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INVESTIGATIONS OF THE STRUCTURE AND ELECTROMAGNETIC INTERACTIONS OF FEW-BODY SYSTEMS

Progress Report

1 July 1992 to 30 June 1993

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INTRODUCTION

This progress report summarizes the work of The George Washington University (GWU) nuclear theory group during the period 1 July 1992 - 30 June 1993 under DOE Grant No. DE-FG05-86-ER40270. During this year, the faculty working under the grant were D.R. Lehman (P.I.), H. Haberzettl, L.C. Maximon, and W.C. Parke (co-PI's), and C. Bennhold (Senior Investigator). Professor Bennhold was added to the group during the Fall semester 1992 after joining the Physics Department faculty in September 1992 as a new assistant professor of physics in theoretical nuclear physics. One postdoctoral research scientist, Hiroshi Ito, has been working with the group since 1 July 1991. Three graduate students, Reyna Pratt Kushner, Mohamed Najmeddine, and Ali Rakei, all supported by the grant, joined the effort as of 1 June 1992 through a supplemental addition of funds from DOE and tuition cost-sharing by GWU. Ms. Kushner is currently preparing to take her general examinations in September 1993, but has been working with Professors Maximon and Bennhold to prepare herself for theoretical work in nuclear physics. Mr. Najmeddine and Mr. Rakei have both passed their general examinations and have chosen to work with Professors Lehman and Haberzettl, respectively. During the summer period, we usually support one or two graduate students for a three-month period to provide them with the opportunity to learn about theoretical nuclear physics, to do a small research project, and to become acquainted with our group. This summer (1993), we are supporting two students, one working with Professor Bennhold (Ms. Zarei) and one working with Professor Lehman (Ms. Rugina). One other graduate student, John Woloschek, who holds a full-time federal government job, has been working under the direction of Professor Lehman, but other than computer time, he is not directly supported by the grant. Outside collaborators with the group during the period indicated were B.F. Gibson of Los Alamos National Laboratory, A. Eiro and A. Fonseca of the U. of Lisbon, J. Haidenbauer of Hannover University, Y. Koike of Hosei University (Tokyo), W. Sandhas of the U. of Bonn, and H. Weller of Duke University.

The format of the Progress Report is as follows:

1. Papers published or in press, submitted for publication, and in preparation;
2. Invited talks at conferences and meetings;
3. Invited talks at universities and laboratories;
4. Contributed papers or abstracts at conferences;
5. Visitors to the group;
6. Research progress by topic.

PAPERS PUBLISHED

H. Haberzettl, "Cluster-Dynamical Approach to N-Body Scattering", Phys. Rev. C46, 687 (1992).

V. Punjabi, C.F. Perdrisat, E. Cheung, J. Yonnet, M. Boivin, E. Tomasi-Gustafsson, R. Siebert, R. Frascaria, E. Warde, S. Belostotsky, O. Miklucho, V. Sulimov, R. Abegg, and D.R. Lehman, "T_{20} in the Inclusive Breakup of 4.5 GeV Polarized ^{6}Li", Phys. Rev.

C46, 984 (1992).

W.C. Parke, "Methods in Few-Body Nuclear Physics", Proceedings of the Hampton University Graduate Studies at the Continuous Electron Beam Accelerator Facility, May 29 through June 16, 1991, published by HUGS at CEBAF, Nuclear Physics Group, Department of Physics, Hampton University, Hampton Virginia, Fall, 1992.

H. Ito, W.W. Buck, and F. Gross, "The Axial Anomaly and the Dynamical Breaking of Chiral Symmetry in the $\gamma^*\pi^0 \to \gamma$ reaction", Phys. Lett. B287, 23 (1992).

H. Haberzettl, "Relativistic Cluster Dynamics of Nucleons and Mesons. I. Kinematics and Covariance", Phys. Rev. C47, 1237 (1993).

Th. Januschke, T.N. Frank, H. Haberzettl, and W. Sandhas, "Neutron-Deuteron Scattering Calculations with Realistic NN Interactions using the W-matrix Representation of the Two-Body Input", Phys. Rev. C47, 1401 (1993).

H. Ito and F. Gross, "Gauge Invariance and Compton Scattering from Relativistic Composite Systems", Phys. Rev. C48, in press (1993); also available as CEBAF preprint #CEBAF-TH-93-10.

A.C. Fonseca and D.R. Lehman, "Full Three-Body Calculation for $\vec{d} + p \to {}^3He + \gamma$ with a Realistic NN Interaction", Phys. Rev. C48, in press (1993).

PAPERS SUBMITTED

T.N. Frank, Th. Januschke, H. Haberzettl, and W. Sandhas, "Neutron-Deuteron Breakup Calculations with Realistic NN Interactions using the W-Matrix Representation of the Two-Body Input", submitted to Phys. Rev. C.

K. Gebhardt, W. Jäger, C. Jeitner, M. Vitz, E. Finckh, T.N. Frank, Th. Januschke, H. Haberzettl, and W. Sandhas, "Experimental and Theoretical Investigation of the ${}^2H(n,nnp)$ Reaction and of the Neutron-Neutron Scattering Length", submitted to Nucl. Phys.

H. Haberzettl, "Relativistic Cluster Dynamics of Nucleons and Mesons. II. Formalism and Examples", submitted to Phys. Rev. C.

H. Haberzettl and W.C. Parke, "Triton Binding-Energy Calculation with a One-Pion-Exchange Three-Body Force", submitted to Phys. Rev. Lett.

A.C. Fonseca, B.F. Gibson, and D.R. Lehman, "Approximate Ways to Treat the Nucleon-Nucleon Tensor Force in the Four-Nucleon Bound State", submitted to Phys. Rev. C.

H.R. Weller, R.M. Chasteler, B.S. Marks, T.G. Seyler, and D.R. Lehman, "Angular Distribution Coefficients for (γ,X) Reactions with Circularly Polarized Photons and Polarized Targets and a Correction to Previous Tables", submitted to Atomic Data and Nuclear Data Tables.

H. Ito and F. Gross, "Isoscalar Meson Exchange Currents and the Deuteron Form Factors", submitted to Phys. Rev. Lett.; also available as CEBAF preprint #CEBAF-TH-93-06.

H. Ito, "SU(3) Flavor Symmetry in the Anomalous Magnetic Moments of Light Quarks", submitted to Phys. Rev. Lett.

PAPERS IN PREPARATION

D.R. Lehman and B.F. Gibson, "Formalism Underlying the $A = 4$ Λ Hypernuclei 1^+ Equations", to be submitted to Phys. Rev. C.

A.C. Fonseca, J. Haidenbauer, D.R. Lehman, and W.C. Parke, "Eighteen-Channel Three-Nucleon Bound-State Wave Function from a Two-Nucleon Separable Expansion Method", to be submitted to Few-Body Systems.

D.R. Lehman, H.R. Weller, and M. Whitton, "Production of E1 Radiation in the $^2H(d,\gamma)^4He$ Reaction at Very Low Energies", to be submitted to Phys. Rev. C.

A.C. Fonseca and D.R. Lehman, "Radiative Capture of Polarized Deuterons on Protons", to be submitted to Few-Body Systems.

H. Ito, "Quark Flavor Mixing and Strangeness Form Factor of the Nucleon", to be submitted to Phys. Rev. C.

H. Ito, "Separable Potential and Gauge Invariance in Compton Scattering", to be submitted to Phys. Rev. C.

Xiaodong Li, L.E. Wright, and C. Bennhold, "Quasifree Radiative Capture in the Δ-Region", to be submitted to Phys. Rev. C.

S.S. Kamalov, L. Tiator, and C. Bennhold, "Photoproduction of Neutral Pions on the Deuteron and the Trinucleon", to be submitted to Phys. Rev. C.

T. Mart, C. Bennhold, and C. Hyde-Wright, "Electromagnetic Production of Σ-Hyperons", to be submitted to Phys. Rev. D.

C. Bennhold and A. Ramos, "$\Delta I=1/2$ Rule Violations in the Weak Hypernuclear Decay", to be submitted to Phys. Lett. B.

L. Tiator, C. Bennhold, and S.S. Kamalov, "The ηNN Coupling Constant in η-Photoproduction", to be submitted to Nucl. Phys. A.

A. Ramos and C. Bennhold, "Vector Meson Contributions to the Nonmesonic Hypernuclear Decay", to be submitted to Nucl. Phys. A

INVITED TALKS AT CONFERENCES AND MEETINGS

D.R. Lehman, "Few-Body Physics -- Electromagnetic Interactions: An Overview (1990-92)", Invited Talk, presented at the Gordon Research Conference on Photonuclear Reactions, (Tilton School), Tilton, New Hampshire, 10-14 August 1992.

C. Bennhold, "Photonuclear Physics with η-Mesons", Invited Talk, presented at the 6th Workshop on Perspectives in Nuclear Physics at Intermediate Energies, Trieste, Italy, 3-8 May 1993, Trieste, Italy.

INVITED TALKS AT UNIVERSITIES AND LABORATORIES

C. Bennhold, "Eta Photoproduction from Nucleons and Nuclei", at the Dept. of Physics, Rensselaer Polytechnic Institute, Troy, NY, April 5, 1993

C. Bennhold, "Photonuclear Physics with η Mesons", at the Dept. of Physics, University of Barcelona, Barcelona, Spain, May 26, 1993

C. Bennhold, "Photonuclear Reactions Involving η Mesons", Nuclear Bag-Lunch Seminar, Department of Physics, The George Washington University, 23 April 1993.

H. Haberzettl, "A Relativistic Scattering Theory for Nucleons and Mesons", Nuclear Bag-Lunch Seminar, Department of Physics, The George Washington University, 23 October 1992.

H. Haberzettl, "A Covariant Relativistic Scattering Theory for Composite Particles", Physikalisches Institut für Theoretische Physik II, Ruhr-Universität Bochum, Bochum, Germany, 22 June 1993.

H. Haberzettl, "A Covariant Relativistic Scattering Theory for Nucleons and Mesons", Institut für Theoretische Kernphysik, Universität Bonn, Bonn, Germany, 6 July 1993.

H. Ito, "Radiative Transition of Vector Mesons", at the Department of Physics, University of Maryland, College Park, MD, 13 May 1992.

H. Ito, "SU(3) Flavor Symmetry in the Anomalous Magnetic Moments of Light Quarks", Nuclear Bag-Lunch Seminar, Department of Physics, The George Washington University, 2 April 1993.

D.R. Lehman, "Few-Body Physics - Electromagnetic Interactions: An Overview (1990-92)", Nuclear Bag-Lunch Seminar, Department of Physics, The George Washington University, 18 September 1992.

D.R. Lehman, "Few-Body Physics - Electromagnetic Interactions: An Overview (1990-92)", Experimental Nuclear Physics Seminar, Department of Physics, University of Maryland, College Park, MD, 12 October 1992.

D.R. Lehman, "Few-Body Physics - Electromagnetic Interactions: An Overview", Seminaro do Mestrado, Departamento de Fisica, Universidade de Lisboa, Lisboa, Portugal, 3 June 1993.

D.R. Lehman, "Radiative Capture of Polarized Deuterons on Hydrogen", Triangle Universities Nuclear Laboratory Seminar, Department of Physics, Duke University, Durham, NC, 17 June 1993.

W.C. Parke, "Lithium-6 Photodisintegraticn", Nuclear Bag-Lunch Seminar, Department of Physics, The George Washington University, 11 December, 1992.

W.C. Parke, "Alpha-deuteron Radiative Capture", Triangle Universities Nuclear Laboratory Seminar, Department of Physics, Duke University, Durham, NC, 27 May, 1993.

CONTRIBUTED PAPERS AND ABSTRACTS AT CONFERENCES

H. Ito, "Dynamical Theory of the Compton Scattering from Relativistic Composite Systems", Annual Fall Meeting of the Division of Nuclear Physics of the American Physical Society, Santa Fe, NM, 14-17 October 1992, B.A.P.S. 37, 1317 (1992).

H. Ito, "Quark Model of π- and ρ-mesons and the $\rho\pi\gamma$-Exchange Current in the Deuteron Form Factors.", Annual Fall Meeting of the Division of Nuclear Physics of the American Physical Society, Santa Fe, NM, 14-17 October 1992, B.A.P.S. 37, 1318 (1992).

VISITORS TO THE GWU NUCLEAR THEORY GROUP

Yasuro Koike
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RESEARCH PROGRESS BY TOPIC

In order to make it easy for the reader to see the specific research carried out and the progress made, the following report of progress is done by topic. Each item has a format layout of Topic, Investigators, Objective, Significance, and Description of Progress, followed at the end by the relevant references. As is clear from the topics listed, the emphasis of the GWU nuclear theory group has been on the structure and electromagnetic interactions of few-body nuclei. Both low- and intermediate-energy electromagnetic disintegration of these nuclei is considered, including coherent photoproduction of π mesons. When the excitation energy of the target nucleus is low, the aim has been to handle the continuum part of the theoretical work numerically with no approximations, that is, by means of full three- or four-body dynamics. When structure questions are the issue, numerically accurate calculations are always carried through, limited only by the underlying two-body or three-body interactions used as input. Implicit in our work is the question of how far one can go within the traditional nuclear physics framework, i.e., nucleons and mesons in a nonrelativistic setting. Our central goal is to carry through state-of-the-art few-body calculations that will serve as a means of determining at what point standard nuclear physics requires introduction of relativity and/or quark degrees of freedom in order to understand the phenomena in question. So far, in the problems considered, there has been no evidence of the necessity to go beyond the traditional approach as yet, but this most likely will not remain the situation in the years to come. In particular, since our work is involved with questions in the intermediate-energy realm and our plans are to be significantly involved with the physics associated with CEBAF, effort is beginning to be directed towards introducing relativity into the few-body dynamical framework. The problems that have been pursued (see publication list) reflect more the need to understand the mechanisms of the reactions and structural questions in the context of full few-body theory. However, contributions to setting up a formalism for relativistic dynamics within a few-body framework is underway as can be seen in the list of publications and papers submitted.

A significant guiding factor in the work of the GWU theory group is the current experimental effort and capabilities in the areas of interest. The work at low excitation energies is motivated by the beautiful radiative capture experiments with polarized beams being carried out at TUNL, Wisconsin, IUCF, and SIN. At intermediate energies, the capabilities of coincidence experiments at NIKHEF has been a source of inspiration for carrying out detailed three-body calculations. More recently, the existence of a source of polarized gammas at the LEGS facility (Brookhaven) has lead us to examine what can be learned about the D-state of ^{4}He by disintegration into two deuterons by linearly polarized gammas. At the same time, much of the impressive data that has already been obtained at the new higher-duty accelerators, and data which will be forthcoming at the new facilities like CEBAF, depend critically on a full understanding of the QED processes inherent to electron scattering, i.e., the ability to calculate and account accurately for these effects. One member of our group (LCM) contributes significantly in this area as is evident from his putting together of a manual for the CEBAF experimentalists on radiative corrections. Finally, all of us interact and collaborate with the GWU nuclear experimentalists. In fact, the interactions between the GWU nuclear theorists and experimentalists has been on the increase. This tradition has been further augmented by the addition of Cornelius Bennhold to our group who has been working closely with both Professors Briscoe and Berman on the interpretation of their LAMPF pion scattering experiments.

TOPIC: Photo- and Electro-production of η-Mesons on the Nucleon

INVESTIGATORS: C. Bennhold, L. Tiator (U. Of Mainz, Germany), S.S. Kamalov (JINR, Dubna, Russia), R. Pratt (Ph.D. Student), and L.C. Maximon

OBJECTIVE: To develop an operator for η electromagnetic production on the nucleon in the excitation region of the $S_{11}(1535)$ and extract the ηNN coupling constant.

SIGNIFICANCE: In contrast to pions which excite the Δ (with isospin T=3/2) as well as N* (T=1/2) resonances simultaneously, the η-meson, due to its isoscalar nature, can be employed to probe N* states selectively. In the low energy regime, there is significant preference for intermediate excitation of the $S_{11}(1535)$ state in the ηN system which has not yet been understood in quark models. A successful description of the resonance sector in the $\gamma N \rightarrow \eta N$ reaction should permit the extraction of the ηNN coupling constant which via η-η' mixing is related to the $U_A(1)$ anomaly of QCD and the axial flavor singlet coupling measured by recent EMC data.

DESCRIPTION OF PROGRESS: The initial phase of this project focused on the description of the resonance sector of the eta photoproduction process. At low energies, the (γ,η) reaction is dominated by intermediate excitation of the $S_{11}(1535)$, $P_{11}(1440)$ and $D_{13}(1520)$ resonances. The hadronic vertices and resonance propagators were constrained by solving the coupled-channels problem for the $\pi N \rightarrow \pi N$, $\pi N \rightarrow \eta N$ and $\pi N \rightarrow \pi\pi N$ reactions, using available data as input[1]. The electromagnetic vertices, on the other hand, were fixed by the $\gamma N \rightarrow \pi N$ multipoles. Thus, the (γ,η) process can be predicted in a parameter-free calculation and good agreement[1] with the sparse, low-energy data (taken in the 60's and 70's) is achieved.

However, very recent data taken in Bonn[2] (ELSA) and Mainz[3] (MAMI B), which are currently being analyzed require an eta production mechanism that goes beyond mere resonance production. We have therefore started[4] to include background contributions such as the s- and u-channel nucleon Born terms and vector meson t-channel exchanges. The major uncertainty comes from the structure of the ηNN-vertex. In contrast to the πN-interaction, little is known about the ηN-interaction and, consequently, about the ηNN-vertex. In the case of pion scattering and pion photoproduction, the πNN coupling is preferred to be pseudovector (PV), in accord with current algebra results and chiral symmetry. However, because the eta mass is so much larger than the pion mass -- leading to large SU(3) x SU(3) symmetry breaking -- there is no compelling reason to select the PV rather than the PS form for the ηNN-vertex.

The uncertainty in the structure of the ηNN-vertex is equally large regarding the magnitude of the coupling constant. The SU(3) value of $g_\eta^2/4\pi$ is related to the πN constant and is in the range of 1.7 - 1.9, depending on the F and D strengths chosen as the two types of SU(3) octet meson-baryon couplings. Other determinations of the ηN coupling employ reactions involving the eta, such as $\pi^- p \rightarrow \eta\ n$, and range from 0.6 - 1.7. Finally, the η-meson has also been built into one-boson-exchange potentials (OBEP) of the nucleon-nucleon interaction. Typical values obtained in fits with the Bonn potential can lie anywhere between 3 - 7. However, including the η yields only small effects in fitting the NN-phase shifts and, furthermore, provides a small contribution to nuclear binding at normal nuclear densities. Nevertheless, from the above discussion it seems clear that the ηN coupling constant is much smaller compared to the corresponding πN value of 14. Since in our model the resonance sector is well constrained by other related but independent reactions, we use the (γ,η) data to extract information on the ηNN-vertex. While the total (γ,η) cross section on the proton can be well reproduced by either a small coupling constant with PS-coupling or a large value with PV-form, the angular distribution singles out the small constant. Polarization experiments would be helpful to constrain further the magnitude of the ηN coupling.

[1]C. Bennhold and H. Tanabe, Nucl. Phys. A530, 625 (1991); Phys. Lett. B243, 13 (1990); Lect. Notes in Phys. 365, 190 (1990).
[2]G. Anton, Proc. 6th Workshop on Persp. in Nucl. Phys. at Intermed. Energies, Trieste, Italy, May 3-8, 1993 (in press).
[3]B. Krusche, as in Ref. 2.
[4]C. Bennhold et. al., as in Ref. 2.

TOPIC: Exclusive Quasifree Pion Photoproduction in the Δ-Region

INVESTIGATORS: Xiaodong Li (Ph.D. student at Ohio U.), L.E. Wright (Ohio U.), and C. Bennhold

OBJECTIVE: To provide a calculational framework for the reaction (e,e'πN) and (γ,πN) in order to extract Δ properties modified by the nucleus.

SIGNIFICANCE: In the last decade, much has been deduced about the Δ-nucleus interaction indirectly by studying pion-nucleus scattering and photoproduction. The new high-duty cycle accelerators allow for measuring direct Δ-knockout in (γ,Δ) and (e,e'Δ) reactions where the delta is detected as a πN-system in coincidence. Providing a rigorous calculational framework for these processes (which has not been done until now) should at last permit the extraction of Δ properties -- modified by the nuclear medium -- directly.

DESCRIPTION OF PROGRESS: The exclusive A(γ,πN)B reaction offers an ideal laboratory for studying the Δ resonance in the nuclear medium. It allows for more direct access to the Δ than the reaction A(γ,π)B since the final nucleon is no longer bound and the sensitivity to the nuclear structure of the target is thereby greatly reduced. In the past, information on the Δ-nucleus interaction could only be extracted indirectly from reactions like pion elastic and inelastic scattering, and pion photoproduction on nuclei. In descriptions like the Δ-hole model, the delta is treated as an explicit degree of freedom whose propagation in the nucleus is modified by the surrounding medium. These medium corrections are introduced by including terms in the delta propagator that prevent the delta from decaying into Pauli-blocked states and account for coherent multiple scattering of the pion. Furthermore, a phenomenological spreading potential has been included which can be related to an effective two-body ΔN-interaction.

In quasifree pion photoproduction the only information required for the target is the single-particle bound wave function and the spectroscopic factor, which is only an overall factor in the cross section. Kinematically, the reaction provides a great deal of flexibility since the target can take up a wide range of momentum transfer and for finite nuclei, little energy. We propose a kinematic arrangement that can best expose the information from the production vertex by fixing the lengths of each momentum vector in the overall momentum conservation. Encouraged by the success of our previous DWIA approach[1] in the analysis of the A(γ,π)B reaction, our goal is to set up a nonlocal DWIA formalism for the A(γ,πN)B reaction using the same standard physics inputs. Even though previous calculations on A(γ,π)B and inclusive quasifree A(γ,π)X reactions were all performed in a nonlocal framework, no nonlocal computations have been performed for exclusive A(γ,πN)B processes. The theoretical results available up to now[2] employ a factorized impulse approximation. Following the analogous development of A(γ,π)B calculations, we find it important to assess the significance of nonlocal effects. The additional nucleon in the final state adds new computational challenges because additional partial waves need to be summed over.

At the present stage, we neglect possible medium modifications and only use the free production amplitudes, to see if there are significant deviations of experiments from our nonlocal DWIA description. Comparison with the existing data suggest that it contains the correct basic ingredients. We find that the photon asymmetry is a very good observable to complement the cross section measurements. It comes mainly from the Δ resonance, is free from normalization problems, is predicted to be large, and is relatively insensitive to the distortions and nonlocal effects. It should definitely be measured at accelerators with the capability of polarized photon beams. As far as the local DWIA calculation is concerned, the distortions from final state interactions always attenuate the PWIA cross sections. Although distortion plays an important role in getting the correct magnitudes, it does little to change the shape of the curves. Nonlocal effects always enhance the local DWIA cross sections and in some cases they are quite significant. In general, quantitative comparison of theory and experiment requires a nonlocal calculation. We find a great sensitivity[3] of the calculated cross sections and photon asymmetries to the Δ mass. Within our local DWIA analysis, it appears to be able to explain the disagreement between the recent Bates data[4] and theoretical predictions at the forward pion angle if the Δ mass is reduced by about 5%. A dynamical model such as the Δ-hole model may be needed in order to resolve the discrepancy by properly including the medium modifications .

[1]L. Tiator and L. E. Wright, Phys. Rev. C30, 989 (1984); C. Bennhold, L. Tiator and L.E. Wright, Can. J. Phys. 68, 1270 (1990).

[2]J.M. Laget, Nucl. Phys. A194, 81 (1972); I.V. Glavanakov, Sov. J. Nucl. Phys. 52, 205 (1990).

[3]Xiaodong Li, L.E. Wright and C. Bennhold, preprint.

[4]L.D. Pham et al., Phys. Rev. C46, 621 (1992).

TOPIC: The Nonmesonic Weak Decay of Hypernuclei

INVESTIGATORS: C. Bennhold, A. Ramos (U. of Barcelona, Spain) and A. Parreno (Ph.D. student at U. of Barcelona, Spain)

OBJECTIVE: To extract information on the weak hadronic vertices by analyzing the nonmesonic hypernuclear decay.

SIGNIFICANCE: The nonmesonic hypernuclear decay is the only possibility to access the strangeness changing ($\Delta S=1$) weak hadronic matrix elements experimentally. Most previous studies have described this process in nuclear matter which may not be a good approximation to predict decay rates for light hypernuclei. Hypernuclear structure as well as ΛN short-range correlations have to be treated as well as possible in order to extract the underlying $\Lambda N \to NN$ interaction whose coupling is in turn related to the weak parity-violating NN interaction. Furthermore, there have been experimental indications that the $\Delta I=1/2$ rule is violated for the nonmesonic decay.

DESCRIPTION OF PROGRESS: The weak decay of the lambda and other hyperons is of interest since it involves a weak interaction process without leptons. The mesonic decay of the free Λ-hyperon, $\Lambda \to N\pi$, dominates the leptonic one, $\Lambda \to p+e^- +\nu_e$, by more than a factor of 1000 due to the three-body final state in the latter decay mode. Hypernuclei in their ground states also decay via weak interaction mechanisms when they are stable against strong decay modes such as particle emission. However, the final nucleon produced in the mesonic decay of a Λ has a very low momentum ($<$ 100 MeV/c) and is therefore Pauli blocked in the nuclear medium. Thus, the mesonic mode is strongly suppressed inside all but the lightest hypernuclei. It was recognized early[1] that the dominant decay for heavier hypernuclei would be due to the two-body, nonmesonic mode $\Lambda N \to NN$, where the pion may now be viewed as being virtual and absorbed on a second nucleon bound in the nucleus. This process can also receive contributions from more massive mesons whose production threshold is too high for the free-space Λ decay.

Nonleptonic hyperon decays are not yet well understood in terms of the underlying weak dynamics. In the absence of strong interactions, the lowest-order Hamiltonian for the weak quark-quark interaction is given by the V-A theory with the Cabibbo hypothesis[2]. However, this Hamiltonian leads to both $\Delta I=1/2$ and $\Delta I=3/2$ transitions with comparable strength, in contradiction to experimental data on kaon and free hyperon decays which suggest a ratio of these two amplitudes of about 20. In order to explain this empirical $\Delta I=1/2$ rule, strong interaction corrections to the Cabibbo theory have been suggested. Among those are contributions from renormalization and one-loop gluon radiative corrections such as penguin diagrams which contribute only to $\Delta I=1/2$ transitions.

On the hadronic level, the nonmesonic decay mode $\Lambda N \to NN$ will complement the information available from the weak NN-interaction, which is accessible experimentally through parity-violating NN-scattering. The physics of the $\Lambda N \to NN$ decay may be richer since it involves weak strangeness-changing ($\Delta S=1$) interactions. Furthermore, both the parity-conserving (PC) and parity-violating (PV) partial rates can be measured, whereas the strong force masks the PC interaction of the weak NN interaction.

This study was motivated by new experimental results from Brookhaven and KEK in Japan. New measurements of total and partial hypernuclear decay rates for $^{5}He_{\Lambda}$ and $^{12}C_{\Lambda}$ with reduced experimental uncertainties have been obtained at Brookhaven. A recently completed experiment at KEK[3] measured the asymmetry of the angular distribution of protons coming from the decay of polarized hypernuclei produced via the (π^+, K^+) reaction. Most theoretical studies, reviewed recently in Ref. 4, have analyzed the nonmesonic decay mode in nuclear matter, assuming the lambda to be at rest and keeping only the relative ΛN s-wave contributions. These calculations have focused mainly on the structure of the $\Lambda N \rightarrow NN$ amplitude as well as the sensitivity to form factors and ΛN short-range correlations (SRC). However, as has been shown recently[5], a direct calculation of the hypernuclear nonmesonic decay rate in finite nuclei yields a substantially different answer than applying the local density approximation to nuclear matter results. In our study, we develop the formalism for relativistic calculations of the nonmesonic hypernuclear decay in a shell-model framework. Since we will study polarization observables involving the ejected nucleons, we have chosen the relativistic approach which has successfully predicted spin observables in elastic proton-nucleus scattering. In order to minimize the model dependency, the details of the nuclear structure input are treated as well as possible. In this spirit, we avoid the transformation into the relative ΛN two-body frame and can therefore easily incorporate nucleon orbitals with arbitrary n, l, and j. Final-state distortions of the outgoing nucleons with the residual nuclear state were generated using a relativistic optical potential. The nucleon and lambda bound-state wave functions are solutions of the Dirac equation with scalar, vector and tensor potentials which were adjusted to reproduce binding energies and charge form factors. Appropriate spectroscopic factors, corrected for center-of-mass (c.m.) motion, are employed to include properly the shell structure of the hypernucleus under study. Short range correlations are accounted for by using a ΛN correlation function that is based on the Nijmegen YN-potential. The elementary $\Lambda N \rightarrow NN$ amplitude is given by one-pion exchange whose weak vertex function is constrained through the mesonic decay of the free lambda, as well as one-kaon exchange whose weak KNN couplings are obtained using $SU(6)_W$ symmetry and a pole model.

Our results for the total and partial decay rates of the A=5, 11, and 12 hypernuclei underestimate the experimental data by a factor of 2-4. The most dramatic reduction in the total rates is due to the ΛN correlation function while the effects of final state interaction and vertex form factors are less pronounced. We find a significant change in the total rates when kaon exchange is included. However, the ratio Γ_n/Γ_p is barely affected by SRC and kaon exchange. The calculated asymmetries, on the other hand, are in reasonable agreement with the measurements once the hypernuclear polarization obtained via the (π^+, K^+) reaction has been corrected for hypernuclear structure and finite detector resolution effects.

[1]W. Cheston and H. Primakoff, Phys. Rev. 92, 1535 (1953).
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TOPIC: Higher Configurations in the Wave Functions of p-shell Nuclei

INVESTIGATORS: C. Bennhold, L. Tiator (U. of Mainz, Germany), S.S. Kamalov (JINR, Dubna, Russia), R. Mach (INR, Prague, Czech Republic), and S. Karataglidis, D. Koetsier, K Amos (all at U. of Melbourne, Australia)

OBJECTIVE: To find signatures of $2\hbar\omega$ admixtures (contributions from the (2s,1d) and (2p,1f) orbitals) in the ground state wave functions of p-shell nuclei through a variety of electromagnetic and pion-nuclear reactions.

SIGNIFICANCE: For many years nuclear physics has used the wave functions of Cohen and Kurath in order to describe the properties of p-shell nuclei. While these wave functions -- limited to configuration mixing within the 1p-shell only -- have given good account for static properties such as binding energies, decay rates and magnetic moments, a number of reactions can only be explained by including $2\hbar\omega$ admixtures beyond the 1p-shell. Especially the isovector, non-spin-flip transition at finite momentum transfer appears to be sensitive to these higher configurations.

DESCRIPTION OF PROGRESS: For over twenty years theoretical calculations have employed the matrix elements of Cohen and Kurath[1] as the nuclear structure input for reactions on p-shell nuclei. Their transition amplitudes were extracted from a global fit to energy spectra and static properties of a range of nuclei throughout the 1p-shell using different forms for a phenomenological NN-interaction. Their coefficients allowed for configuration mixing between the $1p_{1/2}$ and $1p_{3/2}$ orbits and, thus, the description of reactions was improved compared to using simple pure shell-model configurations. One serious drawback, however, was the restriction to the 1p-shell only. A number of high-precision elastic and inelastic electron scattering experiments provided data that could not be satisfactorily reproduced by using Cohen and Kurath amplitudes. Theoretical computations attempted to improve the situation by including contributions from core polarizations. Recently, however, nuclear structure calculations have become available that pursue a description of nuclei with A=4-16 within a full $(0+2)\hbar\omega$ shell model space[2]. Thus, configuration mixing is not restricted to the 1p-shell, but includes contributions from the 2s-, 1d-, 2p-, and 1f-shell as well. These wave functions achieve a good overall description of the relevant energy spectra.

We have reanalyzed the process $^{13}C(\gamma,\pi^-)^{13}N$ in a nonlocal distorted wave impulse approximation (DWIA) approach which included multi-$\hbar\omega$ configurations from outside the 1p-shell. The photoproduction data for this transition which involves an E0 and an M1 isovector transition due to the quantum numbers of the A=13 isodoublet ground states have resisted theoretical explanations for a number of years. An experiment at NIKHEF which measured the differential cross section at constant momentum transfer[3] found discrepancies between theory and experiment of up to a factor of four. Since the data were taken close to the M1 minimum it was concluded that in particular the E0 contribution was overpredicted by theoretical calculations. Within the 1p-shell there is no flexibility regarding the nuclear structure since the dominant E0 reduced density matrix element is fixed by charge conservation and the nuclear Fermi transition.

Using the theoretical $(0+2)\hbar\omega$ shell model wave function reduced the E0 contribution and yielded good overall agreement with all available (γ,π) and (π,γ) measurements[4] on

^{13}C. The largest effects of higher admixtures were found to be due to the 2p-shell, followed by the 2s-shell. Furthermore, the pion single charge exchange process (π^+,π^o) which is dominated by an isovector non-spin-flip potential revealed the significance of 2p-shell admixtures as well. We have recently extended this work to electromagnetic and pion-nuclear reactions on ^{15}N (Ref. 5), and currently our Australian colleagues are producing new wave functions for the A=14 system[6] which will be used to study various reactions on these nuclei. New experimental data for (γ,π) on ^{13}C, ^{14}C, and ^{15}N are forthcoming from the Saskatoon Accelerator Laboratory in Canada.

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TOPIC: Polarization Observables in Pion Scattering and Pion Photoproduction on the Trinucleon

INVESTIGATORS: S.S. Kamalov (JINR, Dubna, Russia), L. Tiator (U. of Mainz, Germany) and C. Bennhold

OBJECTIVE: To describe all available data for pion scattering, single charge exchange, and pion photoproduction on the trinucleon in a unified framework and make reliable predictions for polarization observables.

SIGNIFICANCE: As one of the few nuclei where exact wave functions are available the trinucleon is well suited as a nuclear target to examine whether the pion-nuclear reactions like pion scattering, single charge exchange and pion photoproduction can all be described in one consistent framework. Using only the elementary $\pi N \rightarrow \pi N$ and $\gamma N \rightarrow \pi N$ amplitudes (as well as three-body wave functions) as input, we find a good description of the available data, except at large Q, and therefore use our formalism to predict polarization observables.

DESCRIPTION OF PROGRESS: Pion photoproduction on the trinucleon is an ideal testing ground to investigate the interaction of pions and photons with nuclei and search for possible modifications of delta properties in the nuclear medium. Nuclear structure uncertainties in the trinucleon wave function are under control since correlated three-body amplitudes can be obtained by solving the Faddeev equations with realistic nucleon-nucleon potentials. This is in contrast to reactions on p-shell or heavier nuclei where single particle wave functions are computed in the shell model while nuclear structure coefficients are constrained by beta-decay rates, electromagnetic form factors and other observables. Ambiguities remain especially regarding the magnitude of the spin-flip matrix elements.

In this study, we focused on the single polarization observables Σ (photon asymmetry), T (target polarization) and P (recoil polarization) in the reaction $^3He(\gamma,\pi^+)^3H$. The calculations are performed within a recently developed coupled-channel framework[1] that can consistently describe π^+ and coherent π^o photoproduction as well as elastic and charge-exchange pion scattering on ^3He. After properly including pion final-state interactions (FSI) with the important two-step process $^3He(\gamma,\pi^o)^3He(\pi^o,\pi^+)^3H$ a very good description of the (γ,π^+) data for the differential cross section was achieved over a wide range of photon energies and nuclear momentum transfers.

One of the interesting effects we found[2] has to do with the contribution of the E2 amplitude, which is of a particular interest because its resonance part describes the E2 transition in the $\gamma N\Delta$ vertex. It is well known that the electromagnetic excitation of the delta is mainly magnetic dipole since it proceeds through a quark spin flip. However, its quadrupole component, showing up in the E2 and L2 amplitudes, is sensitive to the tensor force in the quark-quark interaction and gives a measure of the deformation of the delta and subsequently also of the nucleon. We found that there occurs an interference of the E0 and E2 multipoles in the photon asymmetry which is due only to the D-state component in the trinucleon wave function. This drastically increases the sensitivity of the photon asymmetry to this E2 transition, in contrast to the free proton case. In the differential cross section, such an enhancement effect is much smaller due to the large background produced by the E0 and M1 multipoles.

Polarized photon- beam facilities which will hopefully be able to verify experimentally this effect will become available in the near future at several laboratories; in fact, the LEGS facility at Brookhaven already uses polarized photons in experiments with ^{3}He.

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TOPIC: Covariant Relativistic Cluster Dynamics of Nucleons and Mesons

INVESTIGATOR: H. Haberzettl

OBJECTIVE: To formulate a complete, consistent covariant description of relativistic scattering processes involving nucleons and mesons.

SIGNIFICANCE: Apart from the perturbative approach of old-fashioned perturbation theory, with its rather limited applicability, to date there exists no consistent dynamical formulation of the relativistic scattering problem. It is evident, therefore, that such a formulation is of considerable significance from both theoretical and practical points of view.

DESCRIPTION OF PROGRESS: A time-ordered relativistic scattering theory for nucleons and mesons based on clusters rather than individual particles was derived. The S-matrix-type approach provides a recursive hierarchy of Lippmann-Schwinger equations, each describing the dynamical evolution of the two-cluster configurations at different levels of the many-body problem. The first published manuscript[1] provides a clarification of the kinematic aspects of the problem. It is shown there that the on-shell results of the formalism are covariant, without requiring anti-particle contributions. This was achieved by constructing off-shell T matrices as invariants under a set of nonlinear transformations which reduce to Lorentz transformations for on-shell energies. The transformation elements can easily be shown to form a group homomorphous to the Lorentz group. Spin degrees of freedom are dealt with by introducing positive-energy cluster spinor projectors. Apart from the treatment of the spin, this relativistic formulation is formally equivalent to the non-relativistic N-body approach of Ref. 3. This equivalence may be of considerable importance from a practical point of view since it easily allows for a mixed treatment of situations in which some constituents must be treated relativistically while others may be incorporated nonrelativistically. (As an immediate application of such an approach, we discuss elsewhere in this report the relevant three-body forces for a three-nucleon system.)

The details of the full implementation can be found in a recently completed manuscript[2]. It is shown that when including particle absorption and creation, the present approach leads to a recursive hierarchy of nonlinear scattering problems, where each hierarchical level is determined by the (conserved) number of baryons with the nonlinearity entailing contributions from infinitely many virtual mesons. The basic problem to be solved is pion-nucleon scattering; it is at this lowest level of the hierarchy that contact with field-theoretical approaches is made and that one needs to renormalize vertices in the usual way. At higher levels, renormalization will not be necessary. Furthermore, it is shown in Ref. 2 that the full exploitation of the nonlinearity inherent in the formalism leads to a fully crossing symmetric solution of the pion-nucleon problem, which in turn may be used to obtain an equally fully crossing-symmetric formulation for the pion-deuteron problem.

The essential aspects of this formulation are understood and completed. There remain, however, a number of very interesting and potentially far-reaching theoretical and mathematical questions which will continue to be investigated.

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TOPIC: Calculation of Pion-Nucleon Scattering within the Relativistic Cluster-Dynamical Approach

INVESTIGATOR: H. Haberzettl

OBJECTIVE: To solve the pion-nucleon problem within the cluster dynamical framework of the relativistic N-body problem described elsewhere in this report and to represent the resulting pion-nucleon amplitudes such that they may serve as input in other problems with explicit mesonic degrees of freedom.

SIGNIFICANCE: As is described elsewhere in this progress report, pion-nucleon scattering is the basic problem to be solved for all applications of the relativistic cluster-dynamical (RCD) approach; it is at the same level of importance as the two-nucleon problem for the nonrelativistic N-body problem. Without its solution, applications of the RCD approach to higher-order processes, like nucleon-nucleon and pion-deuteron scattering, cannot be done consistently.

DESCRIPTION OF PROGRESS: As mentioned earlier in this report, the nonlinearity inherent in the RCD approach is one of its most essential aspects. At present, we are engaged in a numerical study of these nonlinearities for several simplified versions of the pion-nucleon problem. One important result for these simple models is that the convergence of the iterated nonlinearities depends crucially on which of several possible functions one chooses to iterate. The finding that only dimensionless combinations of functions can be expected to have sufficiently benign convergence properties to be of practical usefulness can presumably be expected also to be true for more complicated realistic cases. The simple models will successively be made more complex and realistic. This careful approach is warranted since there exists very little experience for the solution of nonlinear integral equations.

PROGRESS

TOPIC: Triton Binding-Energy Calculation with a One-Pion-Exchange Three-Body Force

INVESTIGATORS: H. Haberzettl and W.C. Parke

OBJECTIVE: To solve the three-nucleon bound-state problem with a novel type of three-body force

SIGNIFICANCE: Triton binding energies calculated with realistic nucleon-nucleon (*NN*) interactions typically fall short of the experimental value of 8.48 MeV by about 0.5-1 MeV. Attempts to resolve this discrepancy in terms of meson-exchange-based three-body forces provide encouraging but, at present, not entirely satisfactory results. The dynamically most detailed description of meson contributions in the three-nucleon system is provided by the coupled-channel approach pioneered by the Hannover group. Using the Paris potential, they find that employing explicit Δ channels raises the binding energy by 0.4 MeV to 7.85 MeV, which still is about 0.6 MeV short of the experimental value. The present novel type of three-body force has never been employed in any bound-state calculation.

DESCRIPTION OF PROGRESS: The cluster-dynamical treatment of meson-nucleon systems described in Ref. 1 also provides a consistent description of three-body forces in a three-nucleon system. It is found that there exists a one-pion-exchange three-body force which, to our knowledge, has never been taken into account in any calculation. In the usual coupled channel approaches, such contributions either cannot be generated at all, or are discarded based on erroneous double-counting arguments.

In order to get an estimate of the importance of this mechanism, we performed a five-channel triton binding-energy calculation using only the new three-body force in addition to the purely nucleonic contributions. The latter were described by the Paris potential in a separable PEST expansion. We find that the purely nucleonic value of the binding energy is increased by about 0.6 MeV. As mentioned above, this value closely corresponds to the amount by which the binding energy obtained in coupled-channel calculations with explicit Δ degrees of freedom differs from experiment. We do not claim that the present result is the definitive solution of the triton puzzle. For a complete answer, one should perform a comprehensive calculation within the cluster-dynamical framework outlined in Ref. 1, and the binding-energy increase reported here may then be altered by the presence of other, competing mechanisms. However, the present finding shows that the one-pion-exchange three-body force is an important mechanism which must be taken into account in a realistic calculation.

A manuscript detailing our findings was submitted for publication[2].

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[2]H. Haberzettl and W.C. Parke, "Triton binding-energy calculation with a one-pion-exchange three-body force", submitted to Phys. Rev. Lett.

TOPIC: Triton Binding-Energy Calculation with Three-Body Forces and Relativistic Effects

INVESTIGATOR: A. Rakei (Ph.D. Student solely supported by grant) and H. Haberzettl (Director)

OBJECTIVE: To solve the three-nucleon bound-state problem with the three-body forces found in the cluster-dynamical treatment[1].

SIGNIFICANCE: Triton binding energies calculated with realistic nucleon-nucleon (*NN*) interactions typically fall short of the experimental value of 8.48 MeV by about 0.5-1 MeV. Attempts to resolve this discrepancy in terms of meson-exchange-based three-body forces provide encouraging but, at present, not entirely satisfactory results. The dynamically most detailed description of meson contributions in the three-nucleon system is provided by the coupled-channel approach pioneered by the Hannover group. Using the Paris potential, they find that employing explicit Δ channels raises the binding energy by 0.4 MeV to 7.85 MeV, which still is about 0.6 MeV short of the experimental value. The results[2] found for the one-pion exchange three-body force discussed elsewhere in this report suggest that the cluster-dynamical treatment may provide a more consistent framework for the calculation of three-body force effects than the usual coupled-channel approaches.

DESCRIPTION OF PROGRESS: This project was started only recently. Only very few preliminary steps related to a rough outline of the work required have been undertaken.

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TOPIC: Gauge Invariance and Comp ¬n Scattering from Relativistic Few-Body Systems.

INVESTIGATOR: Hiroshi Ito and Franz Gross (CEBAF and College of William & Mary)

OBJECTIVE: To develop a theoretical basis for the gauge invariance of inelastic and/or inclusive electron scattering from relativistic composite systems and to solve numerically the problem with tractable models for few-body systems.

SIGNIFICANCE: A structure function of inclusive electron scattering from a composite system is related to the virtual Compton amplitude. To meet the gauge invariance in the amplitude, a consistent dynamical theory is necessary with regard to the bound-state wave function, final-state interactions and two-body current operators. Within the Bethe-Salpeter formalism, we develop a dynamical theory of gauge-invariant Compton scattering from relativistic composite systems. An explicit solution to the problem will be obtained by using covariant separable interactions. This work is expected to shed light on the relativistic dynamics in inclusive electron scattering. For example, the physics of y-scaling will be studied with this consistent relativistic approach.

DESCRIPTION OF PROGRESS: Inclusive electron scattering from a relativistic composite system is of great interest in association with today's high-energy--high-efficiency experimental facilities such as the Continuous Electron Beam Accelerator Facility (CEBAF). Interesting scaling phenomena are observed in this process; for example, x-scaling for the parton model in hadron physics and y-scaling[1,2] in nuclear physics.

The response tensor of inclusive electron scattering can be expressed as an integral over the expectation value of the current commutator

$$W^{\mu\nu} = \int d^4x \; e^{iqx} < gs \,|\, [\; J^{\mu}(x), J^{\nu}(0)] \,|\, gs > , \tag{1}$$

where $|\, gs >$ is the ground-state wave function of the composite system. The response tensor, $W^{\mu\nu}$, can be expressed in terms of the virtual Compton amplitude, $T^{\mu\nu}$, i.e. the elastic-scattering of a virtual photon from the composite systems:

$$W^{\mu\nu} \propto \Im m \, T^{\mu\nu} \; . \tag{2}$$

As a very significant theoretical point, the Compton amplitude must satisfy gauge invariance,

$$q_{1\mu} \, T^{\mu\nu} = \; q_{2\nu} \, T^{\mu\nu} \; = 0, \tag{3}$$

where $q_1(q_2)$ is the four-momentum of the virtual photon 1(2). The gauge invariance will be satisfied only with a dynamically consistent treatment of (a) the bound-state wave function, (b) the final state interactions, and (c) the electromagnetic two-body current operators.

Gauge invariance of the Compton scattering from a composite system has been extensively investigated in the framework of nonrelativistic dynamics[3], but very few[4] of the relativistic studies have ever been explicitly developed. Recently, a very challenging approach has been performed[5] with the use of a covariant separable interaction in the inclusive electron scattering from a relativistic composite system. Though the bound-state wave function and the final-state interactions are explicitly obtained in this approach, the total amplitude is not gauge invariant[5] due to the use of a nonlocal interaction. This indicates the necessity of the systematic study of the dynamical aspect of gauge invariance in Compton scattering. In the previous work[6,7], the investigator and his collaborator developed a theory of gauge invariance in the observables of a one-photon process such as the exclusive electromagnetic form factor. A constraint on the relativistic two-body (interaction) current, J^{μ}_{2-body}, was obtained on a very general basis, where the one-body Ward-Takahashi identity and Bethe-Salpeter equation are applied to the current conservation, $q_{\mu}\ (J^{\mu}_{1-body} + J^{\mu}_{2-body}) = 0$. Furthermore, the explicit form of the two-body current was analytically derived[6] by applying the minimal substitution method[8] to a covariant separable interaction. With the bound-state solution of the Bethe-Salpeter equations, the matrix element of the current operator was explicitly calculated.

With this motivation and experience, we propose to develop a theory of gauge invariant Compton scattering from relativistic few-body systems. Within the Bethe-Salpeter formalism, we follow a similar approach to that taken in Ref. 6. Firstly, we apply the one-body Ward-Takahashi identity to the current conservation of the Compton amplitude, Eq. (3). In Eq. (3), $T^{\mu\nu}$ must include the impulse amplitude, intermediate-state rescattering amplitude, and the contribution from two-photon interaction currents, all in a general form. Secondly, we introduce the Bethe-Salpeter wave equation into the above expression to obtain a general constraint on the two-photon interaction current. This constraint equation (2-body Ward-Takahashi identity) can be expressed in terms of the two-body force in the nuclear dynamics. Next, by using a covariant separable interaction or other models of nonlocal force, we derive the analytical expression for the interaction currents. The result must satisfy the above constraint. Finally, the total amplitude is proven to be gauge invariant, and we calculate the Compton amplitude by using the bound state wave function obtained with the separable interaction.

The Bethe-Salpeter equation has been solved for the two- and three-nucleon bound systems[9] and for the scattering matrix[10] with covariant separable interactions. Meanwhile, a relativistic generalization[11] of the EST-expansion[12], which is an approximate separable expansion of a local potential, has been published. With this successful development of the methods for solving relativistic few-body systems, we expect that the proposed project can be developed on the realistic basis of nuclear physics; for example, the use of realistic One-Boson-Exchange interactions should be possible. Nevertheless, within the proposed time scale, we focus on the basic theoretical development and the application to a simple model of two- or three-body systems in order to clarify the physical significance in the dynamical aspect of the problem.

CURRENT PROGRESS: The theoretical formulation of Compton scattering has been completed for relativistic 2-body systems, and published[14] with the following principal conclusions:

(1) In both electrodisintegration and Compton scattering processes, if nuclear forces are nonlocal, the conventional amplitudes including the Impulse (IMP) and Final State

Interaction (FSI) processes do not conserve current. This violation is induced by the nonlocality in the nuclear forces, and can be expressed in terms of $\Delta = V(k' - \frac{p}{2} + \frac{q}{2}, k - \frac{p}{2} + \frac{q}{2}; p+q) - V(k' - \frac{p}{2}, k - \frac{p}{2}; p)$, where q is the momentum of the photon. The nonlocal potential, $V(k', k; p)$, depends on the total momentum of the two nucleons, p, and the relative momentum $k'(k)$ in the final (initial) state.

(2) The nonlocal force can be expressed as $V(x_1', x_2'; x_1, x_2)$ in the coordinate representation, where x_1' and x_2' (x_1 and x_2) are the coordinates of the first and second particle in the final (initial) state. Within the nonlocal length, $d = |x_1' - x_1| \sim |x_2' - x_2|$, photons may interact with the charged constituents participating in the NN interaction, and this induces 2-body interaction currents. By using typical models of nonlocal nuclear forces, (a) two-pion exchange potential and (b) separable potential[15], we have explicitly derived the 2-body current operators. These operators satisfy the 2-body Ward-Takahashi identity.

The low-energy limit of the Compton amplitude, for example the Thomson-limit, should be given in a model independent way. However, the theoretical derivation of the Thomson-limit is not clear for few-body systems described by relativistic dynamics, rather this may be examined by various three-dimensional reductions of the Bethe-Salpeter equation. Furthermore, the electromagnetic polarizability of a composite system crucially depends on the FSI (intermediate rescattering after the absorption of the first photon). For the 3-body systems described by the Faddeev equation, these reaction mechanisms are not clear even in the nonrelativistic formalism. The theoretical derivations of the Thomson-limit and electromagnetic polarizability are in progress within (a) the Bethe-Salpeter formalism for relativistic 2-body systems and (b) the Faddeev equation for nonrelativistic 3-body systems.

Other progress has been made within a related topic; the investigation of isoscalar meson exchange current in the deuteron. It has been pointed out[16] that the contributions of $\rho\pi\gamma$- and $\omega\sigma\gamma$- meson exchange currents become dominant in the elastic electron scattering at the momentum transfer of q>1GeV/c. In this region, the composite (quark-antiquark) structure of mesons significantly affects the amplitudes through the form factors of $\rho\pi\gamma$- and $\omega\sigma\gamma$- vertices. We have calculated these form factors from quark loop diagrams[17], and the results are significantly quenched from the ones based on the hypothesis of Vector Meson Dominance. This effect can be observed in high-energy electron scattering from deuteron.

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TOPIC: D-State Structure of ^{4}He

INVESTIGATORS: Hiroshi Ito, D.R. Lehman, and Benjamin F. Gibson (LANL).

OBJECTIVE: To solve the four-nucleon bound-state equations by Faddeev methods with realistic two-nucleon interactions in order to investigate the D-state properties of ^{4}He.

SIGNIFICANCE: Solution of the four-nucleon bound-state problem is intrinsically difficult. It has been solved with the tensor force present by Faddeev methods for separable rank-1 interactions of Yamaguchi type,[1] and initially, for realistic two-nucleon interactions, by variational methods,[2] variational Monte Carlo techniques,[3] Green's function Monte Carlo methods,[4] and by the ATMS (Amalgamation of Two-body correlations into Multiple Scattering processes).[5] Very recently, the Bochum[6] and Groningen[7] groups have completed extensive four-nucleon Faddeev-Yakubovsky bound-state calculations with state-of-the-art two-nucleon interactions and obtain identical results for those cases where their calculations overlap. Whereas the simple separable-potential Faddeev solutions should be numerically reliable to investigate the D-state properties of the ^{4}He nucleus, e.g., the $^4\text{He} \rightarrow \text{d} + \text{d}$ asymptotic normalization constants, the underlying interactions have a significant deficit in their representation of the two-nucleon tensor force. On the other hand, the solutions that have been obtained with realistic two-nucleon interactions by methods other than solution of the Faddeev-Yakubovsky equations tend not to be numerically well determined in the asymptotic region[8] where one needs convergence to extract the D-state parameters like the asymptotic normalization constants and the Distorted Wave Born Approximation parameter, D_2. Thus, wave functions obtained for the ^{4}He ground state by Faddeev methods with realistic two-nucleon interactions should permit us to predict reliable values for the asymptotic normalization constants and the DWBA parameter D_2. As can be seen in the review by Lehman,[9] the situation with regard to the D-state properties of ^{4}He is very unsettled both theoretically and experimentally, so the proposed theoretical work should help to clarify the situation. Moreover, the availability of such wave functions permits us to calculate momentum distributions for $^4\text{He} \rightarrow \text{n} + {}^3\text{He}$, $\rightarrow \text{p} + {}^3\text{H}$, and $\rightarrow \text{d} + \text{d}$, all relevant to coincidence electron scattering experiments already carried out at MIT and NIKHEF, and planned for CEBAF.

DESCRIPTION OF PROGRESS: In solving four-body, bound-state problems, it is more transparent to begin with Schrödinger's equation and to solve the integral equations for the spectator functions defined below. This is our general direction[10]. It is quite different from the conventional t-matrix works of the original Yakubovsky work[11] and subsequent extensions[12,13], where an approximation of the Bateman or Hilbert-Schmidt expansion type is used in the kernel of the equations. Once the realistic NN interaction is expressed in separable form, the integral equations for the spectator functions are exactly soluble by using today's super-computer facilities. Before reporting the current progress, we describe the method[10] by taking as an example the 4-boson problem with a rank-one separable interaction.

The Schrödinger equation for the four-body bound state is given by

$$(H_o + B)\Psi = -\sum_{i<j}^{4} V(ij)\Psi, \tag{1}$$

where H_o is the kinetic energy, and B is the binding energy. In this work, we assume that the two-body NN force, $V(ij)$, plays the dominant role in nuclear dynamics and that three- and four-body forces are absent or perturbatively treated later. With the two kinds of possible cluster-partitions; (31) $\sim \psi(ab,\ c\ ;\ d)$ and (22) $\sim \psi(ab\ ;cd)$, the total wave function (Ψ) is expressed as a sum of 18 Faddeev components given by the possible distributions

$$\Psi = \sum^{12} \psi(ab,\ c\ ;\ d)\ +\ \sum^{6} \psi(ab\ ;cd). \tag{2}$$

Here, the summations are taken for the possible distributions of particle numbers in the set {abcd}. The rank-one separable potential as a nonlocal operator in momentum space is given by,

$$V(ij) = -\alpha\ g(k'_{ij}) \int d^3k_{ij}\ g(k_{ij}), \tag{3}$$

where k_{ij} is the relative momentum of the i-th and j-th particles. After suitable rearrangements of the Faddeev components, Eq. (1) can be reduced to a pair of coupled integral equations, where we have only two independent functions; the spectator functions $Q(\boldsymbol{p},\ \boldsymbol{q})$ and $R(\boldsymbol{t},\ \boldsymbol{s})$ defined by

$$\psi(12,\ 3\ ;4) = g(k)\ Q(\boldsymbol{p},\ \boldsymbol{q})/(H_0 + B) \tag{4a}$$

and

$$\psi(12;\ 34) = g(k)\ R(\boldsymbol{t},\ \boldsymbol{s})/(H_0 + B). \tag{4b}$$

Here, $\boldsymbol{k}$, $\boldsymbol{p}$, $\boldsymbol{q}$, $\boldsymbol{t}$, and $\boldsymbol{s}$ are the Jacobi momenta of the four particles, so that the other Faddeev components can be obtained by permuting the particle numbers in $Q(\boldsymbol{p},\boldsymbol{q})$ and $R(\boldsymbol{t},\boldsymbol{s})$. After the partial wave expansions, we have

$$Q(\boldsymbol{p},\ \boldsymbol{q}) = 4\pi \sum_l \sqrt{2l+1}\ Q_l(p,q)\ [Y^{[l]}(\widehat{p}) \otimes Y^{[l]}(\widehat{q})]^0$$

and with a similar expression for $R(\boldsymbol{t},\ \boldsymbol{s})$. Now, the pair of coupled integral equations is given by

$$Q_L(p,q) = \int_0^\infty dk\ k^2\ d\Omega_k\ d\Omega_q \times \sum_l \Big\{ X_L(B;\ p, |\boldsymbol{k}+\tfrac{1}{3}\boldsymbol{q}|)\ Q_l(|\boldsymbol{q}+\tfrac{1}{3}\boldsymbol{k}|,\ k)\ P_L(\widehat{q}\cdot\widehat{[k+\tfrac{1}{3}q]})\ \ P_l(\widehat{k}\cdot\widehat{[q+\tfrac{1}{3}k]}) + X_L(B;\ p, |\boldsymbol{k}-\tfrac{2}{3}\boldsymbol{q}|)\ R_l(|\boldsymbol{q}-\tfrac{1}{2}\boldsymbol{k}|,\ k)\ P_L(\widehat{q}\cdot\widehat{[k-\tfrac{2}{3}q]})\ \ P_l(\widehat{k}\cdot\widehat{[q-\tfrac{1}{3}k]}) \Big\}, \tag{5a}$$

and

$$R_L(t,s) = \int_0^\infty dk\ k^2\ d\Omega_k\ d\Omega_s \times \sum_l \Big\{ Y_L^1(B;\ p, |\boldsymbol{k}+\tfrac{1}{2}\boldsymbol{s}|)\ Q_l(|\boldsymbol{s}+\tfrac{2}{3}\boldsymbol{k}|,\ k)\ P_L(\widehat{s}\cdot\widehat{[k+\tfrac{1}{2}s]})\ \ P_l(\widehat{k}\cdot\widehat{[-s-\tfrac{2}{3}k]}) + Y_L^2(B;\ p, |\boldsymbol{k}-\tfrac{1}{2}\boldsymbol{s}|)\ Q_l(|\boldsymbol{s}-\tfrac{2}{3}\boldsymbol{k}|,\ k)\ P_L(\widehat{s}\cdot\widehat{[-k+\tfrac{1}{2}q]})\ \ P_l(\widehat{k}\cdot\widehat{[s-\tfrac{2}{3}k]}) \Big\}. \tag{5b}$$

Here, $P_L(\hat{a}\cdot\hat{b})$ is the L-th order Legendre polynomial, and X_L and Y_L^n are the kernel functions easily obtained by solving inhomogeneous integral equations for the L-th partial wave. Throughout the entire project, we deal with the same type of coupled integral equations as Eqs. (5a and 5b). We solve these integral equations to find the eigenvalue (B) and the solutions $\left(Q_L(p,q) \text{ and} R_L(t,s)\right)$ by the power method on a CRAY.

We point out that Eqs. (5a and 5b) are the coupled integral equations involving the 4-dimensional integral: dk, $d\theta_k$, $d\theta_{q(s)}$ and $d\phi$ with $\phi=\phi_k-\phi_{q(s)}$. As a consequence, we have to interpolate the spectator functions in the integrand; for example, $Q_l(\,|\,q+\frac{1}{3}k\,|\,,k)$ must be interpolated from a few reference values of $Q_l(p_i,\ k)$ at the grid points p_i near by $|\,q+\frac{1}{3}k\,|$. This is a computational difficulty in our exact algorithm. In order to accomplish our objectives, we have divided the work into several levels of development.

[Level-1] Solve the 4-boson problem of Eqs. (5a and 5b) including a few partial waves ($l = 0$, 1, 2) with rank-one separable force to check partial-wave convergence.

[Level-2] Solve the 4-fermion problem with spin-dependent central forces for $l = 0$:
(i) derive the integral equations with the spin degrees of freedom;
(ii) solve the equations in (i) with spin-dependent interactions $V(^1S_0)$ and $V(^3S_1)$;
(iii) take $V(^1S_0) = V(^3S_1)$ limit in (i) and (ii) to check correctness of code;
(iv) normalize the wave function and calculate the S-wave asymptotic normalization constants.

[Level-3] Repeat Level-2 with $l = 0,1,2$ to check convergence with partial waves.

[Level-4] Solve the 4-fermion problem including the tensor and central forces:
(i) derive the integral equations with these forces present;
(ii) solve the equations from (i) and obtain the normalized wave function;
(iii) obtain the D-state probability and the asymptotic S- and D-wave asymptotic normalization constants.

[Level-5] Repeat Level-4 with Paris NN interaction through use of separable-expansion methods as given by Refs. 14-16, for example.

Currently, we are nearly completing the level-3 involving (i) the calculations of wave function normalization for the full Faddeev components, (ii) the magnitudes of mixed symmetry states and (iii) the asymptotic normalizations of (3+1) and (2+2) separations. We have resolved the most oppressive computational difficulty (shown below) inherent in this entire project, and the inclusion of tensor force (level-4) will simply be the matter of computational power. We expect a journal publication to summarize the physical conclusions accumulated up to the current level and to report the important developments in the computational methods in few-body physics.

In calculating the various normalization constants and physical observables of ^{4}He, in principle, we must evaluate integrals with 9-variables,

$$<\Psi|\Omega|\Psi> = \int\int\int d^3k\ d^3q\ d^3p\ \ \Psi^*\ \Omega\ \Psi \tag{6}$$

where Ψ given by Eq. (2) depends on three Jacobi momenta k, q, and p, and Ω is a physical observable including $\Omega = 1$ for the wave function normalization. In our approach, these integral can be reduced to 6-dimensional integrals, where the integrand functions are expressed in terms of $Q_l(|\alpha q+\beta p|,|\gamma q+\delta p|)$ and $R_l(|\alpha q+\beta p|,|\gamma q+\delta p|)$. Here, we are required to interpolate these quantities from $Q_l(p_i,q_j)$ and $R_l(p_i,q_j)$ given on the discrete grid points (p_i, q_j). The magnitude of the D-wave asymptotic normalization is the order of 1/100 relative to the S-wave normalization, and the size of the S-wave mixed symmetry state is the order of 1/1000 relative to the spatially-symmetric S-state. Therefore, the 2-variable interpolation routine must be extremely accurate to complete the project in success. In addition, a way to measure the accuracy of the interpolation is sought.

In completing level-3: (1) We have calculated the normalization constants by the Gauss quadrature method. (2) We have developed a Monte Carlo code to calculate the same normalization constants. These two approaches are quite different in algorithm. As a result, the magnitude of the mixed symmetry S-state is about 0.6%, in agreement for these two different approaches. Calculations of the (3+1) and (2+2) asymptotic normalizations are about to be completed. We are ready to move into the central issue of this project, *investigating the effect of the tensor force in* ^{4}*He.*

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TOPIC: Exact Three-Body Calculation of Polarization Observables in $^1H(\vec{d},\gamma)^3He$

INVESTIGATORS: A.C. Fonseca (U. of Lisbon) and D.R. Lehman

OBJECTIVE: The ultimate scope of this program is to generate theoretical predictions for the key observables in $\vec{d} + p(n) \rightleftarrows \gamma + {}^3He({}^3H)$ from 'realistic' nucleon-nucleon interactions like the Paris potential. Specifically, exact Faddeev calculations (bound-state and continuum) will be performed including the E1 and E2 operators and all components of the ground-state wave function connected through these operators to the allowable continuum states.

SIGNIFICANCE: Attainment of the above objective will permit us to elucidate the mechanism of the E2 rescattering effect and to examine D-state effects in the disintegration process through the data available on the polarization observables.

DESCRIPTION OF PROGRESS: During the period of this progress report, a large amount of progress was made on this project while Professor Lehman was on sabbatical leave at Duke University. For a six-week period in February and March of 1993, Dr. Fonseca was also present at Duke University so total focus on this work during that time was possible. At the time of writing our progress report for last year, we indicated in item 5 on page -15- that a code had been developed to handle arbitrary-rank separable interactions for the above radiative capture reactions. We spent a fair amount of time in the Fall of 1992 checking the code with the EST expansions of the Paris interaction[1]. We confirmed this spring our earlier tentative conclusions that the convergence of the tensor analyzing powers (TAPs) with the rank of the separable expansion is very rapid. Then, in January 1993, we began our production runs on the Florida State University CRAY for the TAPs over the full energy range of the available experimental data. The outcomes of this work have been described in a short article that will be published in Physical Review C as a Rapid Communication in the August issue[2]. We are currently drafting a longer paper with more details of our work that will be submitted to Few-Body Systems.

In summary, the purpose of the most recent work on this project was to obtain results for a full Faddeev calculation of the radiative capture of polarized deuterons on protons over the whole energy range of available data for one representative "realistic" NN interaction (Paris in this case)[3]. The Paris interaction is handled by the EST expansion method in order to reduce the two-variable integral equations to a single variable. The electromagnetic operator is limited to E1, but this is not a serious limitation in that the measurements fall in the domain where the E1 operator dominates for the TAPs. Since we have already explained and justified the power of the EST expansion method in our earlier proposal and progress report writeups, it won't be repeated here. We only indicate that the NN interaction is present in both the initial continuum state and the final three-nucleon bound state in the $^1S_0$, $^3S_1$-$^3D_1$, $^1P_1$, $^3P_0$,$^3P_1$, and $^3P_2$ partial waves. The ground-state wave function has all possible L-S configurations that can be generated from these NN partial waves and the nucleon-deuteron initial state has all possible orbital angular momentum values consistent with total angular momentum and parity of $J = \frac{1}{2}^-$ and $\frac{3}{2}^-$, where the latter are the only states that can connect to the ground state through the E1 operator.

What becomes clear from our overview of the radiative capture data over this fairly wide energy range (deuteron energies from 10 to 95 MeV) is that precision data, both statistically and systematically, will be needed for discrimination of theory versus experiment. This conclusion is reached by looking at the results[4-6] for $E_d = 10$, 19.8 and 95 MeV with the high precision data points[7] at 29.2 and 45.3 MeV. Furthermore, when we compare our earlier simple rank-1 separable interaction results with the Paris interaction results, it appears that it may be difficult to distinguish between different NN interactions. This raises the whole issue as to whether there really is sensitivity to the different NN interactions in the TAPs. Maybe, since they are ratios of amplitudes, such differences can be suppressed.

In a global sense, we can say that up to $E_d \sim 30$ MeV, the TAPs data can be well explained with a theory that involves only E1 radiation, NN partial waves through P-waves, and the NN interaction obtained from the Paris potential. However, above ~ 30 MeV, it appears that higher multipoles (at least E2) must be added to the theory. Moreover, we found that the NN P-waves have different significance in different energy regions. Though the Paris interaction does a reasonable job of describing the TAPs over the full energy range, the simple rank-1 separable models do reasonably well also. However, we have to keep in mind that the differential cross section and the vector analyzing power generally are not reproduced by the present E1 theory. At this stage, we take this latter disagreement to originate from the limitation to E1 radiation as opposed to a shortcoming of the Paris interaction. Clearly, these latter issues indicate the importance of extending the present calculations to include at least the E2 multipole as originally planned, and possibly the M1 multipole as well.

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TOPIC: The Quadrupole Moment and the Ratio of the D-wave to S-wave asymptotic normalization constants of ^{6}Li

INVESTIGATORS: J.P. Woloschek (Ph.D. Student) and D.R. Lehman

OBJECTIVE: To explain the quadrupole moment of ^{6}Li within the framework of three-body models.

SIGNIFICANCE: The quadrupole moment of ^{6}Li is one of its most difficult properties to predict. Its small negative value seems to imply, at least within the context of effective two-body (α-d) models, a subtle interplay between the S- and D-wave components of the ^{6}Li wave function. Successful prediction of this observable should lead to a deeper understanding of the D-wave component of the ^{6}Li wave function.

DESCRIPTION OF PROGRESS: One aspect of our previous work[1] on the elastic electromagnetic form factors of ^{6}Li was to extract the quadrupole moment from the slope of the quadrupole form factor as the electron momentum transfer goes to zero. Unfortunately, this turned out to be a numerically difficult problem due to the fact that the expressions for the form factors are five-fold integrals. Nevertheless, it appeared that the three-body models predict a positive quadrupole moment of ≈ 0.5 e-fm^2 in contrast to the experimental value of -0.0644 ± 0.0007 e-fm^2. To get a better grasp of this result, the alpha-deuteron-component contribution to the quadrupole moment was extracted from the three-body model. When only the alpha-deuteron contribution is present, the ^{6}Li quadrupole moment essentially originates from two terms: 1.) The intrinsic quadrupole moment of the deuteron reduced by the fraction of alpha-deuteron component in the three-body wave function; 2.) An interference contribution that originates from the possibility of either s-wave or d-wave relative motion between the alpha-particle and deuteron. In the three-body models, both these terms are positive! However, it has been argued recently,[2,3] on the basis of alpha-deuteron cluster models, that the interference contribution must be negative. For this alpha-deuteron-projected term to be negative in the three-body models, the s-wave and d-wave effective alpha-deuteron wave functions must have opposite signs, especially at large distances. This is not the case; in particular, the s-wave and d-wave alpha-deuteron asymptotic normalization constants are of the same sign. As a consequence, it emphasizes the importance of having a reliable experimental determination of the d-wave alpha-deuteron asymptotic norm, relative to the s-wave, to check this prediction and indicate the plausibility of the alpha-deuteron cluster-model explanations of the ^{6}Li quadrupole moment.[5] Nevertheless, one must keep in mind that the three-body wave functions also have a contribution coming from the alpha-(correlated np pair in the continuum) projection that makes up 35-40% of the norm.

As a consequence of the last point in the previous paragraph, we first carried out a standard calculation of the ^{6}Li quadrupole moment, i.e., directly from the quadrupole operator expectation value with the original three-body ground-state wave functions. The aim was to confirm the results extracted from the quadrupole form factor extrapolations. We found that the previous results are confirmed, i.e., the quadrupole moment does turn out to be positive with magnitude ≈ 0.4 e-fm^2. Next, we improved the representation of the $^3S_1$-$^3D_1$ np interaction used in generating the three-body ground-state wave function. The np interaction underlying the original three-body ^{6}Li wave function is that of Yamaguchi-Yamaguchi[4] which is known to give a poor representation of the mixing parameter ϵ_1 and the wrong sign for the barred D-wave phase shift. Our improvement was to allow for an arbitrary-rank separable interaction so that an interaction that gives a reasonable representation of ϵ_1 can be used. Interestingly, even with an excellent representation of the np interaction, the EST expansion of the Paris potential,[6] the quadrupole moment value is predicted to be positive with a magnitude of approximately ≈ 0.53 e-fm^2. In addition, the s-wave and d-wave alpha-deuteron asymptotic normalization constants retain the same sign though their values change somewhat compared to the original models. Thus, the inadequacy of existing three-body models in explaining the quadrupole moment of ^{6}Li cannot be attributed to the simplicity of the original np interaction. On further reflection and backed up by our new calculations, this should not be surprising. Our new calculations with the Paris interaction indicate that the bulk of the quadrupole-moment value is already given by the alpha-deuteron-projected piece, i.e., approximately 80%. Thus, since the main component of the effective interaction between the alpha and deuteron comes from the alpha-nucleon interaction folded with the deuteron wave function, it immediately becomes clear that the np interaction enters at a secondary level.

Based on the above conclusions, we next looked at the question of inelasticity effects in the alpha-nucleon interaction. On the basis of a set of separable, but coupled-channel, alpha-nucleon interactions originally developed by Miyagawa, et al.,[7] we extended the three-body model to handle these more sophisticated interactions. The new alpha-nucleon interactions couple to a single hybrid deuteron-triton channel with a threshold at 18.4 MeV. With such an approach, the alpha-nucleon phase shifts and inelasticities are reproduced up to nucleon energies of approximately 60 MeV; whereas, our original alpha-nucleon interactions reproduced the phase shifts up to 20 MeV and ignored the inelasticities since the alpha-particle was considered to be elementary. Moreover, in the new interactions, some of the partial-wave couplings are intriguing from the viewpoint of the quadrupole moment and the angular momenta involved. For example, the alpha-nucleon $^2S_{1/2}$ partial wave couples to the deuteron-triton $^4D_{1/2}$ partial wave. In addition, we have now included the $^2D_{3/2}$, $^2D_{5/2}$, $^2F_{5/2}$, and $^2F_{7/2}$ partial waves of the alpha-nucleon interaction besides the original $^2S_{1/2}$, $^2P_{1/2}$, and $^2P_{3/2}$ partial waves. Such an approach recognizes the fact that the alpha-particle is not an elementary particle. We find that when the underlying NN interaction is that of the rank-1 Yamaguchi-Yamaguchi case, the D- to S-wave asymptotic-normalization ratio is already negative with only the S- and P-wave alpha-nucleon interactions present. Addition of the $^2D_{3/2}$ partial wave of the alpha-nucleon interaction to this framework leads to the most negative value of the asymptotic-norm ratio. As the other alpha-nucleon partial waves are added, the asymptotic-norm becomes less negative. However, upon changing the NN interaction to the rank-6 EST expansion of the Paris potential, the asymptotic-norm ratio becomes positive for all alpha-nucleon partial-wave cases considered above. Even when the asymptotic-norm ratio is negative, the alpha-deuteron contribution to the ^{6}Li quadrupole moment is *positive.*

The above model gave hope, but is limited in the sense that once the alpha-nucleon system makes the transition to the "deuteron-triton" channel, there are no interactions between the 'spectator' nucleon and either the deuteron or triton. As a result, three-body-force effects are not generated. The so-called 'dispersive' effect of the channel coupling is present, but no three-body-force component appears. As a consequence, most recently, we constructed a rank-1, coupled-channel interaction where the alpha-nucleon system can make a transition to a pseudo-alpha-particle state that we call alpha* with the same threshold as indicated above. Our hope was that such a model would not only have the 'dispersive' effect of the channel coupling, but that the interaction would not preclude generation of three-body-force contributions. While the investigation of the presence or absence of three-body-force contributions was underway, results for the asymptotic normalization ratio and the full ^{6}Li quadrupole moment calculation were obtained. The results for the asymptotic norm ratio are similar to the "deuteron-triton" channel-coupling model, while the values for the alpha-deuteron component of the ^{6}Li quadrupole moment move to smaller values. The values for the full calculation of the ^{6}Li quadrupole moment are significantly reduced compared to the model where no channel-coupling is present, but they are not negative. Meanwhile, a careful analysis of the issue of three-body-force contributions in coupled-channel problems where the interaction is rank-1 has demonstrated the absence of such terms. Three-body-force-effect contributions require at least rank-2 in the channel coupling[8].

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TOPIC: Angular Distribution Coefficients for (γ,X) Reactions with Circularly Polarized Photons and Polarized Targets

INVESTIGATORS: H.R. Weller and R.M. Chasteler (Duke University), B.S. Marks (N.C. State), R.G. Seyler (Ohio State), and D.R. Lehman

OBJECTIVE: To present in convenient form the formalism for the case of linearly or circularly polarized photons on polarized targets.

SIGNIFICANCE: Presentation of the formalism for incident linearly or circularly polarized photons on polarized targets allows one to generate expressions for cross sections and analyzing powers in terms of reduced matrix elements. Such equations are extremely useful in planning experiments with an aim towards extracting specific physically observable effects.

DESCRIPTION OF PROGRESS: Our earlier work in this area dealt with the angular momentum formalism of linearly polarized photons in (γ,X) reactions on unpolarized targets[1]. The main intention of the present work is to investigate the general formalism of Welton[2] for the case of linearly or *circularly* polarized photons on *polarized* targets, to verify his results in detail, put them into a convenient form, and illustrate their use by an example. One of the strongly motivating factors behind this work is the recent interest in the Drell-Hearn-Gerasimov (DHG) sum rule[3]. Direct experimental test of the DHG sum rule will require measurements employing circularly polarized photons and polarized proton targets. In re-deriving Welton's expressions, we discovered an error in a phase factor, which affects the Tables of Ref. 1. This correction to Welton's equations has been carefully verified and is explained in our preprint submitted to Atomic Data and Nuclear Data Tables.

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PROGRESS

TOPIC: Long-range behavior of the effective nucleon-deuteron interaction for the three-nucleon system

INVESTIGATORS: D.R. Lehman, L.C. Maximon, Walid Younes (former undergraduate physics major at GWU, now graduate student at Rutgers U.), and B.F. Gibson (Los Alamos National Laboratory)

OBJECTIVE: The aim of this work is to derive rigorously the asymptotic behavior of the effective interaction between a nucleon and deuteron within the bound three-nucleon system.

SIGNIFICANCE: One goal in attempts to understand the low-energy properties of the three-nucleon system is to determine whether these properties can be understood within the framework of two-body models with effective interactions. Until recently, such two-body models have met with no success. However, Tomio, Delfino, and Adhikari,[1,2] recently published an analysis of the low-energy properties of the three-nucleon system based on an ad-hoc effective two-body interaction that has an attractive $e^{-\mu r}/r^2$ long-range tail which is essential for the success of the description (r is the separation distance between the center-of-mass of the deuteron and the neutron). In particular, their effective, three-parameter, potential is found to predict correctly the value of the doublet p-d scattering length obtained from exact three-body calculations and to reproduce the correlation between the doublet scattering length and the three-nucleon binding energy found in exact three-body calculations for both the n-d and p-d systems, after having been fit to the experimental values for the ^{3}H and ^{3}He binding energies and the n-d doublet scattering length. In an attempt to justify the long-range behavior of the n-d effective interaction used by Tomio et al.[1,2], Delfino, Frederico, and Tomio[3] have derived the asymptotic behavior starting from a zero-range representation of the three-nucleon bound-state wave function. The essence of their approach is to project the bound-state wave function with a nucleon-deuteron state (freely moving relative to each other) and then substitute this resulting two-body wave function into the two-body Schrödinger equation to derive an effective potential that would lead to the assumed form of the effective n-d wave function within ^{3}H. They find by this approach that the effective n-d potential at large separation distances behaves as $-e^{-\lambda r}/r^{3/2}$. Though their result differs from that of Tomio et al.[1,2], they argue that it is similar in that both contain the qualitative feature of depending on a range associated with the size of the deuteron (through μ and λ). They also argue that their result must be valid for any short-range interaction since it is based on minimal assumptions about the three-nucleon wave function, i.e., a zero-range form. However, it is particularly this assumption about the form of the three-nucleon wave function which casts doubt on the reliability of their conclusions. It is well known that in zero-range approximation, the three-nucleon system has infinite binding energy.[4] Historically, it was this fact that led the early workers on the two-nucleon interaction to the conclusion that the two-nucleon interaction has a short, but finite, range.[5] Therefore, it is important to attempt another approach towards deriving the asymptotic behavior of the effective n-d potential in the three-nucleon system.

It should be noted, however, that Tomio, Frederico, and Delfino[6] do extend their approach to a more general assumed form for the three-nucleon bound-state wave function. They extend their zero-range model to include a parameter that, in some sense, accounts for the finite-range of the two-nucleon interaction. This parameter is set by requiring reproduction of the triton binding energy and the doublet n-d scattering length with the deuteron binding energy set at its experimental value. This time, the problem of finding the effective n-d potential must be approached numerically. They argue that their numerical results justify the phenomenological potential of Tomio, Delfino, and Adhikari.[1,2]

DESCRIPTION OF PROGRESS: The approach taken in the current work is to begin from the three-body Schrödinger equation for the bound-state wave function without making specific assumptions about the two-nucleon interactions (possible three-nucleon interactions are neglected). The equation is projected with a bra state composed of a nucleon plus deuteron moving freely relative to each other (no detailed form for the deuteron wave function is assumed). The aim is to obtain an equation for this effective n-d wave function within ^3H, i.e., for the overlap amplitude of the n-d state and the three-nucleon bound state. Except for the two terms containing the potentials in the coordinates that involve the 'external' nucleon and one of the nucleons in the deuteron, this falls out directly. In the latter 'permuted-potential' terms, a complete set of nucleon-correlated-pair states is inserted to affect the sought after equation. (The correlated-pair terms are the deuteron and an n-p scattering state.) It is then immediately apparent that we must deal with a coupled set of effective two-body equations, one corresponding to the effective nucleon-deuteron wave function and the other to the effective nucleon--n-p--continuum wave function. By iterative substitution, the effective nucleon--n-p--continuum wave function can be eliminated from the equation for the effective n-d wave function at the expense of having an infinite series of terms containing successively increasing powers of the two-nucleon interaction. In the effective n-d wave function equation, the leading term of the effective interaction is local (assuming the two-nucleon interactions are local), while the succeeding terms are nonlocal. These latter terms involve, in the simplest case, a Green's function with the two-nucleon interaction on either side. Initially, we completed a thorough study of the local part of the effective interaction.

Our purpose in investigating the local part of the n-d effective potential was to determine its long-range behavior. The local part of the effective potential is constructed from a matrix element of the 'permuted-potential' terms between deuteron wave functions, sometimes called a 'folding potential'. We started with specific potentials that were analytically tractable (s-waves only): 1. Zero-range; 2. Square-well; and 3. Hulthén. We found that the square-well and Hulthén potentials lead to an asymptotic behavior of $-(\text{constant})\, e^{-4\gamma r}/r^2$, where the binding energy of the deuteron defines γ, i.e., $B_d = \gamma^2/M$. Moreover, the 'constant' multiplying the asymptotic form is given in terms of the potential parameters. Based on these analyses, it was then decided to assume an arbitrary short-range two-nucleon interaction, e.g., with Yukawa behavior at large separation distances, to see if the result can be made potential independent. The answer is that it can. The final expression has the above form with the constant being determined by a particular integral over the potential. The general result has been checked with the specific cases listed above and the previously obtained results have been reproduced. Interestingly, when we start with the assumption of a nonlocal two-nucleon interaction given by the standard Yamaguchi[7] s-wave form, we find an asymptotic behavior of $-(\text{constant})\, e^{-(2\gamma+\alpha)r}/r$, where $B_t - B_d = 3\,\alpha^2/4$, in general agreement with the conclusions of Fonseca, Redish, and Shanley concerning a Yukawa form.[8] At least at the level of the local part of the n-d effective potential, there appears to be a difference in the asymptotic behavior depending on the nature, local or nonlocal, of the underlying two-nucleon interaction.

What has been learned from this investigation so far? First, and most importantly, we found for the zero-range interaction that the local-part of the effective interaction is identically zero. Since it is expected, from our initial study so far, that the nonlocal contribution to the effective potential falls off differently and possibly more rapidly asymptotically than the local piece, and since the authors of Ref. 3 neglected the nonlocal contribution, this demonstrates that the *ansatz* used by these authors is invalid. Secondly, if our tentative conclusion about the asymptotic behavior of the nonlocal piece is correct, our result explicitly substantiates the ad hoc assumption of Tomio et al.[1,2] as to the asymptotic behavior of the effective n-d potential. Moreover, the precise parameter to be used in the exponential is obtained. It differs in numerical value significantly (approximately a factor of 4 larger) from that found by the fits in Refs. 1 and 2. The magnitude of the potential in the asymptotic region is explicitly given by the multiplicative constant. Thirdly, our asymptotic result and the exact expression for the potential can be used in combination to find at what separation distance the asymptotic behavior begins to dominate. This has been done numerically.

In addition to the above, we have been investigating, so far without a definitive conclusion, the question of the Efimov limit in the above framework. The Efimov limit is the situation where γ approaches zero and r is large but less than $1/\gamma$. In this limit, we would expect to find that the interaction approaches a $1/r^2$ behavior -- essential for the explanation of the Efimov effect.[9] Our work on this question and the nature of the succeeding nonlocal corrections to the local part of the effective n-d interaction was minimal this year owing to higher priorities. However, by methods reminiscent of the Feshbach project operators in reaction theory[10], a few months ago it was found possible to rewrite the infinite series on the right-hand side of the equation for the effective nucleon-deuteron wave function in a more compact form. This new form looks potentially more suitable to analysis for the Efimov effect questions.

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TOPIC: Production of E1 Radiation in the $^2H(d,\gamma)^4He$ Reaction at Very Low Energies

INVESTIGATORS: D.R. Lehman, H.R. Weller, and M. Whitton

OBJECTIVE: To show that the mechanism of charge polarization of the deuterons in the reaction $^2H(d,\gamma)^4He$ cannot give rise to E1 radiation owing to the identity of the target and projectile.

SIGNIFICANCE: Recent experimental results[1] suggest that over 50% of the cross section in the $^2H(d,\gamma)^4He$ reaction below $E_d = 80$ keV arises from P-wave capture. Analysis of the data implies that this strength arises from E1 radiation. In this work, we consider possible origins of this E1 radiation and show that its origin must arise from the spin-dependent isoscalar part of the E1 operator.

DESCRIPTION OF PROGRESS: Our work begins by assuming that the $^2H(d,\gamma)^4He$ reaction contains a large P-wave capture component which leads to E1 radiation at $E_d = 80$ keV. This is at first sight a surprise, since isovector E1 transitions are known to be forbidden in self-conjugate nuclei if $\Delta T = 0$. Since the d + d channel has T=0, as does the ^4He ground state, the E1 radiation in this reaction should be isoscalar. The question then arises as to possible origins of E1 radiation in the $^2H(d,\gamma)^4He$ reaction. Since the entrance channel is composed of identical Bosons, we must have L + S even so that the 1^- state (which is needed to generate E1 radiation to the 0^+ ground state of ^4He) must have L=1 and S=1. If the ground state of ^4He is purely L = 0, S = 0, the E1 transition must arise from the spin-dependent isoscalar part of the E1 operator. However, another possible mechanism exists: Charge polarization of the deuterons. This would correspond to a specific mechanism of isospin mixing due to the Coulomb force. It arises because of the fact that the charge of the deuterons does not reside at their respective centers-of-mass, but rather on the proton within each deuteron. Thus, one deuteron in the Coulomb field of the other deuteron has a preferential orientation owing to the induced electric-dipole moment. Since the resulting state must have a mixed parity, symmetry requires that it have a mixed isospin. The two fused deuterons could thereby form a state of ^4He which would have a T=1 component, and isovector E1 radiation could evolve.

In this work, we show that the mechanism of deuteron charge polarization cannot produce E1 radiation in the $^2H(d,\gamma)^4He$ reaction. This occurs because the polarization-potential matrix element vanishes identically for the ^4He reaction owing to the identity of the projectile and target nuclei. This is not the case for $^2H(\alpha,\gamma)^6Li$, because the initial state contains unlike particles. Therefore, so long as isospin is conserved, any E1-radiation produced in this reaction must be due to the spin-dependent part of the E1 operator. A manuscript describing this work is almost in final form[2].

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TOPIC: Approximate Ways to Treat the Nucleon-Nucleon Tensor Force in the Four-Nucleon Bound State

INVESTIGATORS: A.C. Fonseca (U. of Lisbon), B.F. Gibson (LANL), and D.R. Lehman

OBJECTIVE: To show how to include as much of the nucleon-nucleon tensor force as possible in the dominant S-state component of the four-nucleon wave function for the purpose of optimizing the starting point in the iterative solution of the full four-body problem.

SIGNIFICANCE: Until the initial work of Fonseca[1] and the more recent work of Kamada and Glöckle[2], the two-nucleon tensor force in the four-nucleon system had always been treated approximately[3-6], leading to four-nucleon bound-state equations where all relevant orbital angular momenta are zero. As a consequence, the resulting four-nucleon wave function is reduced to the $\mathcal{S} = 0$, $\mathcal{L} = 0$ components with symmetric and mixed-symmetric spatial configurations. At the time, the question was "how close to the exact four-nucleon binding energy can these approximate methods lead us?" The purpose of this work is to answer that question for several approximation methods tested in the four-nucleon bound-state problem as means to understand how the two-nucleon tensor force propagates through the underlying $(2) + (2)$ and $(3) + 1$ subsystem amplitudes to yield a final four-nucleon binding energy.

DESCRIPTION OF PROGRESS: This work has been completed and a manuscript submitted to Physical Review C.[7] Since the various approximation methods discussed in the manuscript are rather tedious to delineate, suffice it to say that of the six approximations considered for handling the nucleon-nucleon tensor force in the four-body problem, two turn out to be of good quality and essentially equivalent. Of these two, the so-called t_{00}/t_{00} approximation becomes the recommended one owing to its simplicity. The t_{00} approach was first initiated by John Tjon[4] in the three-body problem and amounts to use of the full two-body t-matrix truncated to the $l = l' = 0$ element in the three-body equations. The t_{00}/t_{00} approximation in the four-body problem has the same starting point and is applied in both the $(2) + (2)$ and $(3) + 1$ subamplitudes of the four-body equations. The aim would be first to generate the four-body wave function and binding energy in the t_{00}/t_{00} approximation and then use that wave function and binding energy as the starting point for solving the full four-body equations without approximation. The latter approach gives an almost optimal starting point in comparison to starting with an arbitrary initial wave function and a guess at the starting binding energy.

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Physical Review C.

TOPIC: Neutron Halo Few-Body Nuclei

INVESTIGATORS: Mohamed Najmeddine (Ph.D. Student solely supported by grant) and D.R. Lehman (Director)

OBJECTIVE: To apply few-body methods to those neutron-halo nuclei that naturally cluster into three- or four-body systems in order to study their structure, weak, and electromagnetic interaction properties.

SIGNIFICANCE: It is now known[1] that ^{6}He and ^{11}Li exhibit large neutron halos or dilute neutron skins (long neutron tails extending well outside the nucleus), especially ^{11}L. Experiments that make it possible to measure interaction cross sections and/or reaction cross sections at a range of energies for light radioactive nuclei provide data on the nuclear sizes of these neutron-rich nuclei. The above two nuclei exhibit halo-type structure with two loosely bound valence neutrons and only one bound state. They are interesting as three-body systems in that none of the two-body systems within the three-body framework are themselves bound. Therefore, the opportunity exists to study true three-body features associated with the neutron-halo structure.

PROGRESS: Mr. Najmeddine accompanied Professor Lehman during his sabbatical leave at Duke University. During this period, Mr. Najmeddine spent about 50% of his time learning about techniques and methods in few-body physics and about 50% studying the literature concerning neutron-halo nuclei. The purpose of this effort is for Mr. Najmeddine to define a research problem for his Ph.D. dissertation. At this point in time, the choices have been narrowed to three possibilities: 1) Develop an improved three-body model of ^{6}He going beyond that of Ghovanlou and Lehman of 20 years ago[2]; 2) Develop a three-body model of ^{11}Li using the latest experimental information on the n-^{9}Li system to develop a good phenomenological interaction for this two-body subsystem. 3) Carry out a complete (full three-body dynamics for the both the bound and continuum states) three-body calculation of ^{6}He β-decay into the α-deuteron continuum. The aim for the first two calculations would be to use the wave functions obtained to examine the neutron momentum distributions within these nuclei compared to experimental data and to calculate their neutron radii. In the third item, it is believed[3] that this beta decay process should be sensitive to the neutron-halo structure of ^{6}He because the Gamow-Teller transition will emphasize overlap between the deuteron in the α-deuteron continuum and the di-neutron configuration in ^{6}He. However, since the measured values for the branching-ratio momentum distribution are very small, it will be essential to handle the few-particle dynamics of the reaction fully before information about the neutron-halo structure of ^{6}He can be extracted. An existing calculation[3] does not treat the α-deuteron continuum as an exact eigenfunction of the three-body Hamiltonian and this might be the source of their over-estimate of the data by an order of magnitude.

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TOPIC: User's Guide to Radiative Corrections

INVESTIGATOR: L.C. Maximon

OBJECTIVE: This work was originally requested by B. Mecking and J. Mougey, group leaders at CEBAF, who viewed it as essential theoretical support for their experimental programs. It has received strong support from L.S. Cardman, Deputy Associate Director for Physics at CEBAF, who views it as providing an important tool for the entire CEBAF research program. The goal of the User's Guide to Radiative Corrections is two-fold. First, it aims to present, in an easily accessible form, a review of the state of the art expressions for the various radiative corrections which must be applied to high energy electron scattering data if one is to extract accurate nuclear information, at the one percent level. The review will include a list of relevant references for each of the corrections, accompanied by commentary indicating what approximations have been made, what would be the next most important correction to investigate, and an estimate of the accuracy of the formula presented. The radiative corrections to be considered fall under the general headings of Landau straggling, thick-target (external) bremsstrahlung, and the Schwinger radiative correction. Each one of these general topics will have subsections. For example, under the heading Schwinger radiative correction, we will consider recoil corrections, exponentiation, Coulomb corrections, multiple photon emission, photon emission by the target nucleus, and vacuum polarization. Moreover, there will be further subheadings indicating whether the expression for the cross section in question refers to polarized or unpolarized beams, polarized or unpolarized targets, and, very importantly, whether the corrections apply to single arm or coincidence experiments. The second aim of the User's Guide concerns the Schwinger radiative correction in particular, this being the largest correction that must be applied to electron scattering measurements. In this case, we intend to make significant improvements in the currently available expressions for the corrections to both elastic scattering and coincidence experiments (for which no expressions currently appear in the published literature).

SIGNIFICANCE: The analysis of high-accuracy electron scattering measurements at high energies, such as those projected at CEBAF, requires a level of accuracy not previously demanded for the radiative corrections which must be applied to the experimental data, if the full potential of new accelerators and detectors is to be realized. The uncertainties in the theoretical expressions for the radiative corrections often constitute the limiting factor in obtaining accurate nuclear information. The computer programs for the analysis of the scattering data used in the past at most electron accelerator laboratories make use of theoretical work which was carried out almost twenty five years ago, and these computer programs often had inadequate accompanying documentation. Moreover, most of that work referred primarily to single-arm experiments; coincidence measurements, which are generally feasible only with the high-duty-cycle accelerators available within the last few years or currently under construction, were not generally of concern then. The User's Guide will provide a basis for the design of computer programs by making available in a readily accessible form, the most accurate expressions for each of these corrections, together with relevant documentation, comparison with earlier work, and an indication of the accuracy of the expressions given. It will include theoretical work which has appeared only within the last few years, often in unpublished reports.

DESCRIPTION OF PROGRESS: The task of assembling a library on radiative corrections is close to completion. This includes not only published articles, but, for most of the important work, material that has appeared only in unpublished reports and conference proceedings. The work of a number of authors has been examined in detail for the purpose of comparison with the generally used expression for the Schwinger radiative correction, *viz.*, that given by Mo and Tsai[1] for the case of high energy electron proton scattering. A re-derivation of this latter work has been begun, with the aim of simplifying the entire approach, eliminating many of the approximations made, and providing the basis for a calculation of the radiative correction to coincidence measurements. A first draft of the User's Guide, of 90 pages in length, has been prepared. This includes a section on Landau straggling, which is essentially complete, a section on thick-target (external) bremsstrahlung (also essentially complete), and a section on the Schwinger radiative correction to electron proton scattering. In this case, the subsections on vacuum polarization and the electron vertex correction are close to complete, but work remains to be done on the subsections dealing with the hadron vertex correction and the box (two-photon exchange) diagrams. In addition, there are appendices giving references for radiative corrections to deep inelastic electron scattering, references for hadronic contributions to the QED vacuum polarization, references for the method of dimensional regularization, and an appendix giving the essential methods of integration of integrals which appear in doing QED calculations à la Feynman. Finally, there is a section, in only preliminary form, presenting a detailed examination of the work of de Calan, Navelet, and Picard[2].

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TOPIC: Compton scattering of polarized photons from polarized protons

INVESTIGATOR: L.C. Maximon

OBJECTIVE: To provide an accurate, analytic, expression for the cross section for Compton scattering of both linearly and circularly polarized photons from polarized protons below pion threshold, including the effects of π^0 exchange.

SIGNIFICANCE: Recent measurements of the polarizabilities of the proton and of the neutron, as well as theoretical chiral model predictions for the polarizabilities have been the subject of several sessions at the Workshop on Hadron Structure from Photoreactions at Intermediate Energies and the Baryons '92 conference, held in June and July of 1992. In particular, the measurements of Compton scattering on the proton, made with photons in the energy range 32-72 MeV by the group at Illinois[1], and with photons of energies 98 MeV and 132 MeV by the group at Mainz[2], have provided consistent results for the polarizabilities for the first time, but are inconsistent with earlier results from Moscow[3]. Additional measurements using circularly polarized photons are envisaged at facilities having tagged laser backscattered gamma rays, such as LEGS. While nucleon resonances must be taken into account at higher photon energies, it is important to have the cross section correct to order $(\omega/M)^2$, since this provides the major part of the cross section at the energies of these experiments. (Here ω is the incident photon energy, M is the proton mass.) This includes the effects of the proton charge, anomalous magnetic moment, and the electric and magnetic dipole polarizabilities. Although the contribution from t-channel exchange of a single neutral pion is of order $(\omega/M)^4$, it makes a rather important contribution and should be included[4].

DESCRIPTION OF PROGRESS: The basis for this calculation was given in an earlier work on the scattering of linearly polarized photons from unpolarized protons[5]. Furthermore, this work did not include the effects of π^0 exchange. The calculation was thus considerably simpler than that now envisaged. The necessary matrix elements will now have to be programmed using symbolic manipulation programs such as REDUCE or FORM, and this work has just begun. Work on this problem was minimal this year, but significant effort is expected during the coming year.

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TOPIC: Kinematics of the scattering of two particles into three particles

INVESTIGATOR: L.C. Maximon

OBJECTIVE: To describe the kinematics of the scattering of two particles into a three-particle final state with the same pedagogical simplicity as that commonly used to describe the scattering into a two-particle final state.

SIGNIFICANCE: The current and planned high duty-factor electron accelerators facilitate coincidence measurements, and thus increase interest in the analysis of reactions with three-particle final states. Although a number of papers on the kinematics of these reactions have appeared, they lack, in general, the simplicity of the analysis of two-particle final state reactions and certainly do not have the clear geometric picture that is presented in the case of two-particle final states. The pedagogical presentation that is envisaged would be of particular use to both experimentalists and students new to the field.

DESCRIPTION OF PROGRESS: An analysis of the surfaces described by the three final-state particles in various possible frames of reference has been undertaken. The transformation of these surfaces to the frames generally of interest (center of mass, laboratory) is being examined. Work on this problem was minimal this year, but significant effort is expected during the coming year.

TOPIC: Calculation of amplitudes and cross sections for photo- and electroproduction of pions and eta mesons.

INVESTIGATOR: Reyna K. Pratt (Ph. D. Student solely supported by grant) and L.C. Maximon (Director)

OBJECTIVE: To develop computer programs for the comparison of experimental data and theoretical calculations of photo- and electroproduction of pions and eta mesons.

SIGNIFICANCE: The present project is part of a much broader study of baryon resonances, for which there is an extensive experimental program at CEBAF (the N^* program). In particular, this involves both experimental measurements leading to a determination of the amplitudes for photo- and electroproduction of excited baryons and theoretical calculations of these amplitudes, testing the various QCD models of baryon structure. Photo- and electroproduction of eta mesons are of particular interest in that the $S_{11}(1535)$ has a very large decay width to the ηN channel and thus provide an important means of determining the properties of this resonance.

DESCRIPTION OF PROGRESS: Significant progress has been made on the first steps in this project. These comprise
1) Learning the basics of programming in FORTRAN and REDUCE,
2) Learning the tools necessary for performing QED calculations, including
   a) the classification of elementary particles,
   b) decay and conservation laws for elementary particles,
   c) relativistic kinematics,
   d) symmetries and group theory.

Work is continuing on learning QED, – on methods for solving the Dirac equation and the determination of amplitudes and cross sections for scattering and decay. With regard to photodistintegration of η's from protons, work has started on the writing of computer programs, using the kinematic equations, to deduce the energy and momentum of the η and the final proton from the lab system energy of the photon and the angle of the η. These programs will give cms variables in terms of lab system variables, and vice versa.

PROGRESS

TOPIC: $\alpha + d \rightarrow {}^6Li + \gamma$ Scattering Cross Section and Polarization Observables at Low Energies

INVESTIGATORS: W.C. Parke and A. Eiro (U. of Lisbon)

OBJECTIVE: To calculate the cross section and polarization observables for the reaction $\alpha + d \rightarrow {}^6Li + \gamma$ using consistent three-body dynamics in both the initial and final states.

SIGNIFICANCE: Understanding the radiative capture of alpha particles on deuterons (or deuterons on alpha particles) has importance in astrophysics, nuclear physics, and nuclear technology. The capture reaction ${}^2H(\alpha,\gamma){}^6Li$ at low incident energies has been a focus of interest by astrophysicists and nuclear physicists.[1] In astrophysics, the value of the cross section below center-of-mass energies of about 2 MeV is needed to determine the abundance of ${}^6Li$ from the standard big-bang model and by cosmic-ray generation through spallation. Rolfs and Barnes in their review of astrophysically important radiative capture reactions emphasized that the reaction mechanism remains uncertain.[2] Detailed knowledge of the reaction promises to uncover information about the internal structure of the ${}^6Li$ nucleus. With polarized deuterons, or for the inverse photodisintegration process, polarized photons, the D-state properties of ${}^6Li$ can be unveiled. The reaction plays a role in a controlled-fusion plasma. The analysis of the produced gammas can be used to determine the plasma temperature.[3]

Measurements at center-of-mass energies from 1 to 8 MeV have been made, showing a cross section between 4 and 100 nanobarns which seems to be dominated by an E2 direct capture mechanism[4], although some admixture of E1 and possibly M1 may be present. Another series of measurements closer to the reaction threshold is nearly ready for data taking at TUNL.[5]

Besides the cross-section measurement, there has been recent interest in using radiative capture of polarized deuterons on the alpha particle[5,6] to get a handle on the D-state component in ${}^6Li$, and in particular, on the ratio of the D to S asymptotic normalization constants for ${}^6Li \rightarrow \alpha + d$, as well as the difficult-to-predict electric quadrupole moment. The experiments pending at Duke (TUNL) will study the reaction ${}^4He(\vec{d},\gamma){}^6Li$.[5]

As yet, there is no fundamental and fully consistent calculation of the radiative capture reaction, although several effective two-body calculations have been published.[6] A three-body (alpha-particle, neutron, and proton) calculation for both the incoming and outgoing nuclear wave functions, using the same two-body interactions in the three-body scattering state and in the bound state, would satisfy self-consistency, in that the same fundamental dynamics would be used for all parts of the calculation. This approach has already been successful[6] in the case of the calculation of the two-body photodisintegration of ${}^3H$ and ${}^3He$, where effective two-body models have not worked. Moreover, using a three-body wave function in the initial state would automatically include the ${}^6Li(3^+)$ resonance state in the $\alpha - d$ continuum. This state enhances the reaction cross section by almost two orders of magnitude near threshold (at about 700 keV in the center-of-mass). Such an approach should provide the sound footing necessary to delineate the reaction mechanism of this radiative capture reaction, including the role of off-shell two-body rescattering and intermediate three-states.

DESCRIPTION OF PROGRESS: We are currently engaged in a derivation of the full three-body radiative capture amplitude, with the bound-state and incoming scattering states both determined by the same three-body Hamiltonian. Our aim is to carry out a fully consistent effective two-body calculation within the three-body framework. We will then be prepared to compare with the contributions of initial-state rescattering, within a fully consistent effective two-body framework (no effective two-body calculations to date satisfy such consistency), and with the full three-body calculation to see the effects of three-body dynamics. Our effective two-body Born term results already show that the contribution to the reaction cross section can be sensitive to the quadrupole moment of the deuteron, particularly at center of mass energies (near 30 MeV) which probe the radial node in the $\alpha - d$ wave function (this node coming from the underlying Pauli exclusion principle for the nucleons in the two clusters). We have also calculated the tensor analyzing power T_{20}. As expected, this polarization observable is controlled by the D-state components in the $\alpha - d$ system, with the deuteron quadrupole term being the dominant contributor near 90^o, even at center-of-mass energies of 4 MeV. We will be able to reduce the integral equations for the full three-body amplitudes which include rescattering corrections to effective two-body amplitudes. This will give us a clean way to test the contribution of continuum NN states in the intermediate rescattering process.

This summer, W.C. Parke and A. Eiro spent a week at TUNL/Duke to work out the details of the full three-body rescattering formalism needed for our calculation. We plan to have this work completed by late Fall, ready for programming.

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PROGRESS

TOPIC: Eighteen-Channel Precision Triton and Helium-3 Bound-State Wave Functions

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OBJECTIVE: To generate precise three-body bound-state momentum-space wave functions for ^3H and ^3He, using the best available NN interaction potentials for the S, P, D, and F-wave interactions, each represented by converged separable expansions.

SIGNIFICANCE: Our aim is to generate high quality wave functions for the three-nucleon system which can serve as reliable and practical input to full three-body calculations for photodisintegration (radiative capture) and electrodisintegration calculations. It is already known that the P-wave NN interactions are necessary to account properly for the tensor analyzing powers in the polarization measurements for the nucleon-deuteron radiative capture process. Therefore, for completeness, we are using the EST expansion method[1] on the remaining NN partial waves with total angular momentum ≤ 2.

DESCRIPTION OF PROGRESS: We have generated three-body bound-state wave functions for ^3H in momentum space and calculated the binding energy, the percent wave-function components of definite symmetry type and total orbital angular momentum, and the S- and D-wave two-body asymptotic normalization constants. Now included are the NN interactions for total $j \leq 2$, i.e., the $^1S_0$, $^3S_1 - ^3D_1$, $^1P_1$, $^3P_0$, $^3P_1$, $^3P_2 - ^3F_2$, $^1D_2$, or $^3D_2$ partial waves. We have previously found that using PEST separable potentials of rank 5 and 6 for the $^1S_0$ and $^3S_1 - ^3D_1$ NN partial waves, respectively, gives excellent convergence to the Paris potential configuration-space calculations. Keeping these, we tested the P-wave PEST representations with increasing rank. Convergence in the three-body wave-function components and binding energy occurs when the rank of the P-waves reaches 5. This ten-channel calculation was finished last summer, for which the binding energy (7.09 MeV) differs from the Iowa/Los Alamos configuration-space calculation[2] for the Paris potential (7.11 MeV) by 0.3%. For the eighteen-channel code, a completely independent calculation (A.C. Fonseca) of the binding energy gives agreement with the GWU result to the figure 7.34 MeV to within than 0.01% for rank 3 in the P-waves and rank 2 in the D-waves with $j = 2$. We are now confident that the codes are working and will now carry out extensive tests of convergence with rank for the additional partial waves. We plan on having a paper ready for publication shortly which will include these results and those of the S and D-wave asymptotic normalization constants for the 18 channel calculations compared to the Iowa/Los Alamos values.

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