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Three-Nucleon Forces and the Trinucleon Bound States

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Abstract

A summary of the bound-state working group session of the "International Symposium on the Three-Body Force in the Three-Nucleon System" is presented.

Introduction

The trinucleon bound state is the natural testing ground for most of our efforts to determine the effects of three-nucleon forces[1-4]. The existence of these forces, which depend on the simultaneous coordinates of three nucleons, arises from neglecting non-nucleonic degrees of freedom, such as the excitation of a nucleon in an intermediate state between two exchanges of mesons. Three-body forces are additional forces which may have to be taken into account to explain the binding energies of nuclei for $A \geq 3$. In the trinucleon system typical three-nucleon forces change the binding energy by 5-15 percent, although they generate a much smaller fraction (1-2%) of the total potential energy. This relative smallness has proven to be a serious problem because, until recently[5], the reliability of calculations was insufficient and there was considerable uncertainty over the accuracy of the wavefunctions (needed to calculate observables) and eigenvalues.

This symposium has shown that considerable progress has recently been achieved. In particular the calculation of the trinucleon bound-state properties due to two-body interactions is now well under control. The different numerical techniques used by various groups show remarkable convergence in the binding energies at a level of accuracy of about 10 keV.

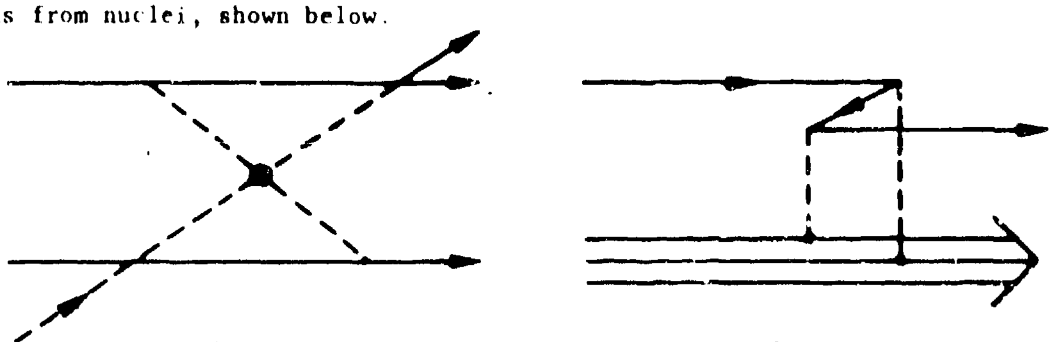
In the traditional Faddeev[6] procedure, the two-nucleon potential is partial-wave projected and written as an infinite series of terms, each term of which acts only in a given nucleon-nucleon partial wave (e.g., $^1S_0$). This infinite series is made finite by truncation, and the truncated problem is solved "exactly" in a numerical sense. Each of these partial-waves for an interacting pair of particles can be coupled to the partial wave of the remaining (spectator) nucleon to form a three-nucleon partial-wave or "channel". A decade ago standard calculations usually included all positive-parity nucleon-nucleon partial waves with total angular momentum $J \leq 1$, or 5 channels. Hajduk and Sauer[5] implemented a very accurate procedure in momentum space for solving the bound-state Faddeev equations with two-body forces, and improved the original 18-channel ($J \leq 2$) calculations of Brandenburg and Kim[7] to high accuracy. Recently, the Los Alamos group[8] (Chen, Payne, Friar, and Gibson) and the Sendai group[9] (Sasakawa and Ishikawa) have extended this to 34-channels ($J \leq 4$). These calculations have established that the partial wave series has converged, and any error due to a truncation of the (infinite) partial-wave series is almost certainly less than 10 keV. Moreover, numerical methods exist[10] where the wavefunction has the same level of accuracy as the eigenvalue, implying a high degree of confidence in the accuracy of matrix elements, or observables.

This confidence in our calculational techniques for the trinucleon bound states allows us for the first time to investigate the effect of three-nucleon forces in a reliable and systematic way. We also should critically examine the effects of a relativistic treatment of nucleon motion and the presence of explicit non-nucleonic degrees of freedom such as pions, isobars, quarks, etc. One of the difficulties of this problem is that there is a certain overlap between these phenomena, so in principle they should not be treated separately. We should recall that the discovery and demonstration of significant contributions (10-20 percent) to the electromagnetic current from intranuclear pions in few-body systems is one of the major success stories in nuclear physics in the recent past.[4] No such unambiguous demonstration exists for relativistic effects and three-nucleon interactions, and that is one of the reasons for this symposium.

The three-nucleon force is not a fundamental quantity; its description depends on the theoretical approach[11-13]. Two very different techniques are used. The most direct and popular approach[12,13] is to "freeze out" non-nucleonic degrees of freedom and to include them as separate three-nucleon potential operators. A more ambitious approach is to treat explicitly the new degrees of freedom associated with non-nucleonic components. This has the advantage of providing a more unified approach, but at the expense of greater computational complexity. The latter approach has been implemented by Hajduk and Sauer[11], who include (single) Δ components in the wavefunction, so that three-nucleon forces mediated by a single Δ are implicit in their formalism. This unique calculation is truly "un tour de force."

Significant components[4] of the two-pion-exchange three-nucleon force are known to be of relativistic order: $(v/c)^2$. Those components can be viewed schematically as V_π^2/Mc^2, where V_π is the two-body OPEP and M is the nucleon mass. This observation allows one to make an estimate of their size, 1 MeV, since $\langle V_\pi \rangle$ is roughly 30 MeV. This is 2 percent of the total potential energy of approximately 50 MeV.

The mesonic and other non-nucleonic processes in the triton ground state also have their three-body force analogues in the medium-energy scattering of pions and protons from nuclei, shown below.



(a) Figure 1. (b)

The scattering of a pion from the (exchanged) pion cloud in the nucleus shown in (1a) is a true three-body force, while the Z-graph for proton- nucleus scattering depicted in (1b) is a three-body force effect implicitly included in Dirac treatments of the proton projectile.

Experimental Evidence for Three-Nucleon Forces in Trinucleon Ground States

The experimental evidence for three-nucleon forces has centered on two ground-state properties: the tritium binding energy and the trinucleon form factors. We discuss the binding energy first.

The tritium binding energy is 8.5 MeV, while that of ^{3}He is 764 keV less. The binding energy difference has been a persistent problem.[14] The best estimates of the Coulomb energy, ΔE_c, have been by means of the hyperspherical formula, an approximation developed independently by Fabre de la Ripelle[15] and Friar.[16] This approximation, which is accurate at the one percent level, writes the Coulomb energy as an integral over the trinucleon charge form factors. The latter can be taken from experiment, which leads to an estimate of $\Delta E_c \cong 640$ keV. Most of the remaining charge-symmetry breaking (CSB) is believed to arise largely from short-range processes. Estimates of three-body-force CSB contributions have been made by Yang[17] and are typically a few keV.

Five "realistic" two-body potentials have been calculated in the 34-channel approximation by the Los Alamos[8] and Sendai groups.[9] These are the Reid Soft Core, Argonne V_{14}, Super Soft Core (C), de Tourreil-Rouben-Sprung, and Paris potentials. There is not yet complete agreement among results[5,9,18] for the latter case. All of the binding energies are approximately 1 MeV too low. This has prompted intense speculation that three-body forces are responsible for the defect, although all of these calculations have been nonrelativistic and this approximation might also be responsible for a significant part of the discrepancy. We also indicated earlier that a significant component of the two-pion-exchange three-body force was of relativistic order. Those calculations of relativistic corrections (without 3BF) which have been performed to date are inconclusive, with a substantial cancellation between the relativistic corrections to the potential energy (repulsive) and the kinetic energy (attractive).

Calculations using three-body forces are still in their infancy. Early efforts involved first-order perturbation theory and 5-channel wavefunctions. It was later shown[19] that both approximations are inadequate. A minimum of 18 channels is required for a reasonable approximation to the correct answer, and the 34-channel approximation is much better. Moreover, at least third-order perturbation theory is required for certain of the three-body force models. The calculations with explicit three-body potentials, such as the Tucson-Melbourne[12], Brasilian[13], and Urbana-Argonne[20] forces, have yielded roughly 1.5 MeV additional binding, largely independent of the two-body potential, for the most commonly used versions of these models. Unfortunately the calculations have indicated a high degree of sensitivity to the short-range behavior, mediated by the π-nucleon form factor. The calculations indicated above[19] used a monopole form factor mass of roughly ($\Lambda \cong$) 800 MeV, which is equivalent to a Goldberger-Treiman (G-T) discrepancy[21] of 3 percent. Using the full 6 percent G-T value ($\Lambda = 500$ MeV) leads to much less additional binding, while the value of Λ = 1200 MeV from N-N potential fits leads to much more binding. None of these calculations included the momentum-dependent terms[22], and the TM and Brasilian forces in their original forms did not include short-range components from the exchange of heavier mesons. Both groups have extended their techniques[23,24] to include $\rho\rho$ and $\rho\pi$ 3BF with the 2π3BF (typical components are shown below in Fig. 2), but no realistic calculations of their contributions have yet been made. Crude estimates[25] indicate contributions of roughly 20 percent of the 2π2BF contributions.

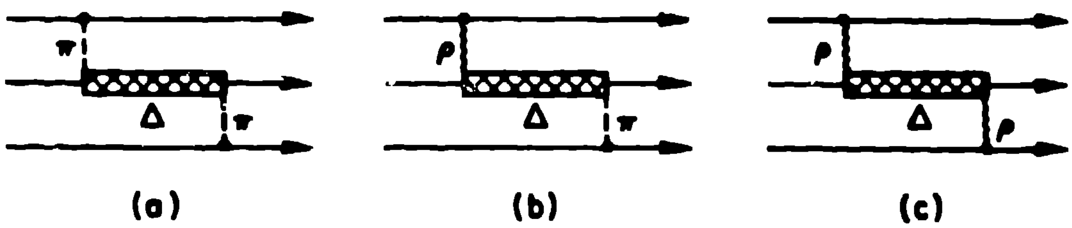


Figure 2.

The other calculational technique which has been implemented is the Hajduk-Sauer method[11] employing explicit Δ's. Their result also gave a large Δ-mediated 3BF contribution when the Δ was forced to be static, but this was reduced when the complete Δ-propagator was used. Moreover, the two-body force contribution is modified when Δ's are added, and a "dispersive" correction must be made to account for this. The net result is a small (.3 MeV) increase in binding for this model. The wide discrepancy between this method and the previous one is discussed further in the next section.

The other traditional observables of the trinucleon are the rms charge radii, the probabilities of various wave function components, and the asymptotic normalizations of various wave function components. All of these are expected to be sensitive to the binding energy. In particular, the mean-square radius should be heavily dependent on the asymptotic form of the wave function $\sim e^{-\kappa\rho}/\rho^{5/2}$, where κ is proportional to $E_B^{1/2}$ and E_B is the triton binding energy. Thus, we expect that $\langle r^2\rangle^{1/2} \sim 1/E_B^{1/2}$. This has been found to be approximately true by the Los Alamos group,[26] and the rms charge radii extrapolated to the physical binding energy are in agreement with the most recent Saclay data and analysis, presented at this symposium by Martino.[27] For ^{3}He, all of the data sets agree within the quoted experimental uncertainties; the largest renormalization factor is less than 3%. For ^{3}H, on the other hand, the disagreement between the normalization of the different data sets may exceed 10%. The experimental values of the charge rms radii which correspond to the best fit are the following:

^{3}H: $\langle r^2 \rangle^{1/2} = 1.81(5)$ fm ,
^{3}He: $\langle r^2 \rangle^{1/2} = 1.93(3)$ fm ,

and charge radii for pointlike nucleons,

^{3}H: $\langle r^2 \rangle^{1/2} = 1.66(6)$ fm ,
^{3}He: $\langle r^2 \rangle^{1/2} = 1.74(3)$ fm .

The error for ^{3}H is twice the error for ^{3}He. The recent MIT measurements presented by Beck at this workshop should reduce this error by a determination of the absolute normalization of the data to better than 2%. This experiment had just been completed at the time of this workshop, and the results of their analysis are expected in the near future. At present the values of the charge radii presented by Martino are in reasonable agreement with theoretical calculations which give the correct triton binding energy. This indicates that it is the binding energy alone which constrains many of the observables. The Sendai group[28] has analyzed the asymptotic normalizations with the same conclusion: when the binding energies are correct, the calculated asymptotic normalization components agree with experiment, although the trinucleon data are not very accurate. The mixed symmetry S-state (denoted S′) component of the wave function is also very sensitive to the binding energy. It and the D-wave probability are not observables[29], however (i.e., they cannot be measured). The latter for the triton is very close to 3/2 times the corresponding D-wave probability of the deuteron for a given two-body force model.[26] The three-body force tends to increase[8] the latter probability slightly (~10-20 percent).

The remaining ground state observables which have commanded attention lately are the form factors of the trinucleon ground states.[27,30,31] The magnetic form factors are dominated by meson-exchange currents.[4] Their sensitivity to the three-nucleon force is small, and they are studied primarily to learn about the exchange currents. The ^{3}He charge form factor[30] has been a problem for theorists since it was first measured. The original Stanford measurements[32a] showed that this form factor has a diffraction minimum at $q^2 \simeq 11$ fm^{-2}, and a very large secondary maximum. The high-q^2 measurements[32b] at SLAC found suggestions of a second diffraction minimum. The conversion of these form factor data to an "experimental" charge density by Sick[33] led to the appearance of an unexpected, deep "hole" near the origin. The interpretation of this hole is controversial, because it depends on significant theoretical assumptions and somewhat arbitrary extrapolations. Nonetheless, it points graphically to a serious problem: impulse approximation calculations[11] (dashed lines in Fig. 3) underestimate significantly the size of the secondary maximum in the form factor. Recently, after nearly two decades of anticipation, Saclay[27] extended the early Stanford measurements of the tritium charge form factor[31a] to large values of q^2. These eagerly awaited data, and those of the MIT experiment[31d] now being completed, demonstrate that the same secondary maximum

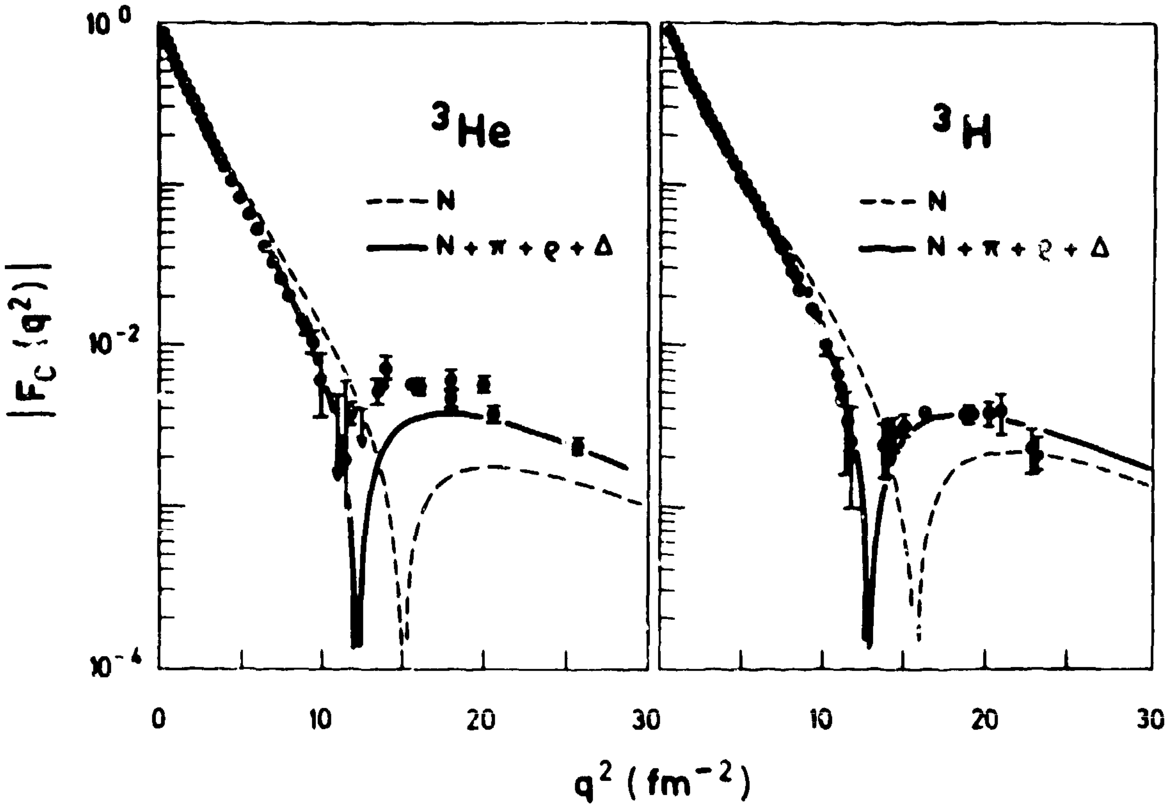


Figure 3.

Fabre de la Ripelle[34] was the first to suggest that the peculiar properties of three-nucleon forces might solve both problems (binding and form factors). In the impulse approximation, the charge density, $\rho_{ch}(r)$, measures the average distance from the trinucleon center-of-mass to a proton. If r is zero, the nucleons are constrained to lie in a straight line. The binding energy is largely determined by the amount of isosceles (roughly equilateral) configuration in the wave function. The latter component can be influenced by different considerations than the collinear configurations which determine $\rho_{ch}(0)$. One of the features of three-body forces which persists in the classical, atomic, solid state, and nuclear domains is that these forces are very angle dependent[4]: they are highly sensitive to the angular orientation of the three objects. It is entirely possible for the three-body force to be repulsive in the collinear configuration and reduce $\rho_{ch}(0)$, while being attractive in the isosceles configurations which largely determine the binding. The commonly used three-nucleon force models have this property.

Calculations of the Grenoble-Montreal[35], Hannover[11], Sendai[28], and Los Alamos groups[19] have shown that the charge form factors are, indeed, increased by the 3BF (by up to 50 percent) in the secondary maximum, while impulse approximation calculations are roughly a factor of 3 too small. The desired effect exists, but is too small, at least for those 3BF models which have been used to date.

Suggestions that meson (pion)-exchange currents in the charge operator, $\rho_\pi(r)$, which are of relativistic order, might significantly alleviate the problem led to early calculational success for ^{3}He.[35] Unfortunately, most of these calculations used the pseudoscalar (PS) π-nucleon coupling model version of the currents. This model is known to make unphysical predictions which are at variance with chiral symmetry.[36] The more realistic pseudovector (PV) model produces smaller effects for ^{3}He, but gives better agreement for ^{3}H (solid lines in Fig. 3). Unfortunately, two further problems with these currents cloud the issue badly.[22,37] One is the fact that $\rho_\pi(r)$ contains a wide variety of momentum-dependent terms, and these have never been calculated for the trinucleons. They are known to be as important as the local terms in the case of deuteron forward photodisintegration.[38] The second problem is that the form of $\rho_\pi(r)$ is ambiguous, as a result of its relativistic origin, and the form used for this operator should be accompanied by a corresponding two-nucleon potential which contains relativistic corrections of a specific form.[22,37] If this scenario is followed, matrix elements are unambiguous. Unfortunately, modern "realistic" potentials have the wrong functional forms to accommodate these relativistic corrections. A resolution of all these problems does not yet exist.

Future Research Theoretical

A number of theoretical problems exist which must be resolved. Several relatively easy calculations with realistic two-body forces need to be performed. The contributions of the various three-body force models need to be broken down into their separate components, and the most important ones identified. In addition, the momentum-dependent terms in the Tucson-Melbourne potential should be evaluated. The new ρ-π and ρ-ρ contributions to the TM and Brasilian forces should be incorporated and their effect determined.

Several more difficult problems remain. The short-range behavior of the 3BF dominates the bound-state binding. If anything approaching a definitive answer to the question of how much binding is due to three-body forces is to be found, we must thoroughly investigate ways to categorize and treat this problem. The current results are problematic.

The differences between the Hajduk-Sauer approach[11] and the more standard 3BF approach utilizing explicit potentials must be resolved. The HS calculation, because of its enormous complexity, involved a number of compromises. It also treated certain aspects of the physics better than they have been treated by others. The strength of this method is that it is a unified model, with physical input ranging from the bound-state regime to the intermediate-energy regime. It is capable of treating the Δ as a nonstatic object, because the Δ's kinetic energy, T_Δ, is included in the Δ propagator together with the kinetic energy of the nucleons,

T_N, and the Δ-N mass difference, ΔM: $[-E + T_\Delta + T_N + \Delta M]^{-1}$. This propagator is approximated by ΔM^{-1} in conventional 3BF models. In addition the HS approach included the potential energy of the remaining two nucleons in the propagator, but not the Δ-N interaction, which is not well known in any event.[4] Nevertheless, the large effect of the kinetic energies (>0) in the Δ-propagator, found by HS to reduce the Δ's contribution, is partially cancelled by the potential energy. The standard approach assumes that the cancellation is complete. This should be thoroughly investigated. Moreover, the "dispersive" two-body effect which also subtracts from the binding is at least partially reflected in standard formulations[22,37] as shorter-range three-body forces. This relationship should also be thoroughly investigated. It is imperative that the relationship between the standard model Δ-contributions and those of the HS model be well understood.

Finally, in the long term a fully relativistic formulation of the Faddeev equation for Dirac particles needs to be developed and implemented. If this model is capable of incorporating sufficient phenomenology, many questions can be answered. At present only boson formulations have proven tractable.[39] Because over 50 percent of the binding comes from the tensor force, the latter exercises are useful, but not definitive.

Future Research Experimental

We believe that the future of 3 nucleon physics lies in the continuum. There are nevertheless several experimental improvements which can be made that will improve and strengthen our knowledge of the bound states.

The recent experiments[31] on the tritium form factors at Saclay and MIT will provide new challenges to theorists, will eliminate uncertainties, and constrain theoretical predictions. It would be worthwhile to extend these measurements to very high q^2 ($\lesssim 100$ fm^{-2}), corresponding to the ^{3}He measurements at SLAC. It would also be very worthwhile to measure the ^{3}H and ^{3}He form factors together at low q^2, so that the rms radii could be accurately determined together. This would complete our (experimental) understanding of these form factors. In addition, the asymptotic normalization constants are not very well known and do not seriously constrain theoretical models.

A recurring question about the credibility of the theoretical calculations of the trinucleon binding energies is: how well do we know the nucleon-nucleon forces? Ignoring the problem of off-shell behavior, which to some extent is addressed already in 3BF construction[22,37], the primary concern lies in the tensor force determined by the on-shell data. More than 50 percent of the binding energy of the trinucleons comes from the tensor force, and much of the variance between two-body force model results can be traced to the tensor force. New experimental information on tensor observables in the two-body problem would be very welcome. One experiment of this type has begun at SIN, and was presented at this symposium by Picker.[40]

Conclusions

A dozen years ago virtually nothing was known about three-nucleon forces. In the intervening years we have learned to solve routinely the trinucleon bound-state Faddeev equations for what amounts to the complete (model) nucleon-nucleon potential, and to include complicated three-nucleon forces as well. The art of constructing those forces has dramatically improved, and modern versions of these forces contain components derived from the exchange of heavy mesons, in addition to pion exchange. Experimental sophistication in probing the trinucleon ground states has made similar improvements. The recent Saclay and MIT tritium form factor experiments have finally unravelled the isospin structure of the trinucleon charge densities, and have generated new challenges for theorists. Although there are few definite conclusions yet and much remains to be done, the progress has been exceptional. Perhaps it is not too pretentious to quote the final frame of the movie[41], Destination Moon: "This is the end of the beginning."

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