COO-1573-71

DEPARTMENT OF PHYSICS

NUCLEAR PHYSICS LABORATORY

PROGRESS REPORT

FOR THE PERIOD

NOV. 1, 1969 to OCT. 31, 1970

CASE WESTERN RESERVE UNIVERSITY

UNIVERSITY CIRCLE CLEVELAND, OHIO 44106

DISCLAIMER

DEPARTMENT OF PHYSICS

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The researches described in this report have been supported in part by the U.S. Atomic Energy Commission under Contract No. AT(11-1)-1573.

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EXPERIMENTAL RESEARCH PROGRAM

1. Elastic and Inelastic Neutron Scattering

Accurate differential elastic (typically 3 to 5%)and inelastic (typically 10 to 20%) neutron scattering cross sections have been determined for ^{12}C, ^{54}Fe, ^{58}Ni, and ^{60}Ni between 4.0 and 5.6 MeV. The iron and nickel elastic cross sections have been compared with predictions of the optical model using standard sets of parameters for the potential.[1] As illustrated in Figure 1, calculations using the average potential of Rosen et al. predict the differential cross sections fairly well, with agreement somewhat better for the two nickel isotopes. Coupled-channel calculations for the elastic scattering of neutrons by carbon agree very well with the measurements.

Inelastic scattering to single levels in the residual nucleus can be described adequately with the statistical model. In the case of the first excited levels of the nickel and iron isotopes, which are 2^+ collective states, there is significant evidence for the existence of direct reaction contributions. Figure 2, showing the data and calculations for ^{58}Ni at $E_n = 5.58$ MeV, illustrates the agreement between theory and experiment. Solid curves are Legendre polynomial fits to the data; dashed curves are predictions of the statistical model; and dot-dashed curves are predictions including DWBA calculations of direct reaction contributions.

This work is now complete, and a paper titled "Scattering of Fast Neutrons by ^{12}C, ^{54}Fe, ^{56}Fe, ^{58}Ni and ^{60}Ni" has been submitted for publication in Nuclear Physics. A Ph.D. dissertation[2] describing the work has been accepted by the university.

P. Boschung, J. T. Lindow, and E. F. Shrader

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[1] L. Rosen, J. G. Beery, A. S. Goldhaber and E. H. Auerbach, Ann. Phys. 34 (1965) 96; P. A. Moldauer, Nucl. Phys. 47 (1963) 65; F. Perey and B. Buck, Nucl. Phys. 32 (1962) 353; F. G. Perey, Phys. Rev. 131 (1963) 745; D. Wilmore and P. E. Hodgson, Nucl. Phys. 55 (1964) 673.

[2] J. T. Lindow, unpublished Ph.D. dissertation, CWRU (1970).

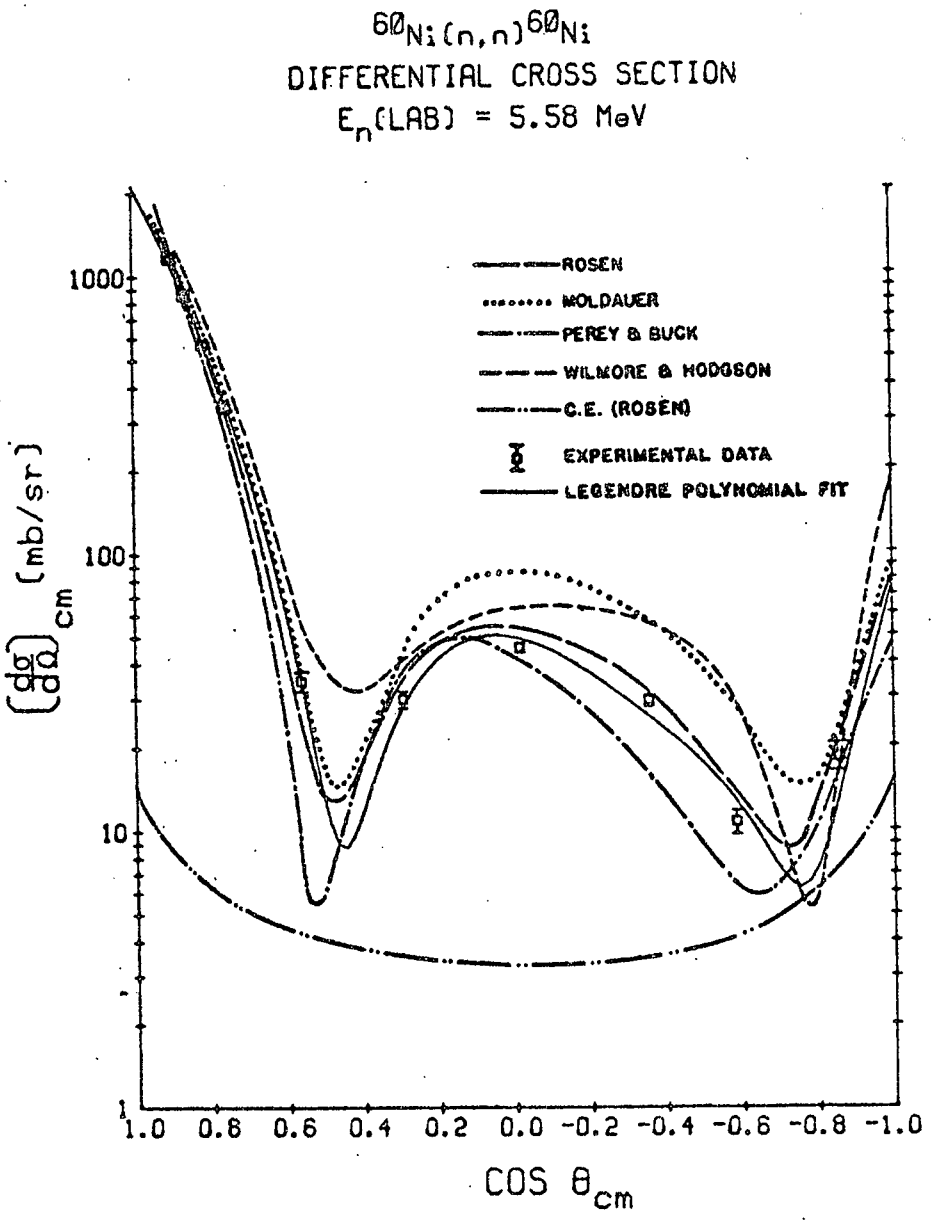

Figure 1. Comparison of optical model predictions for various sets of potential parameters.

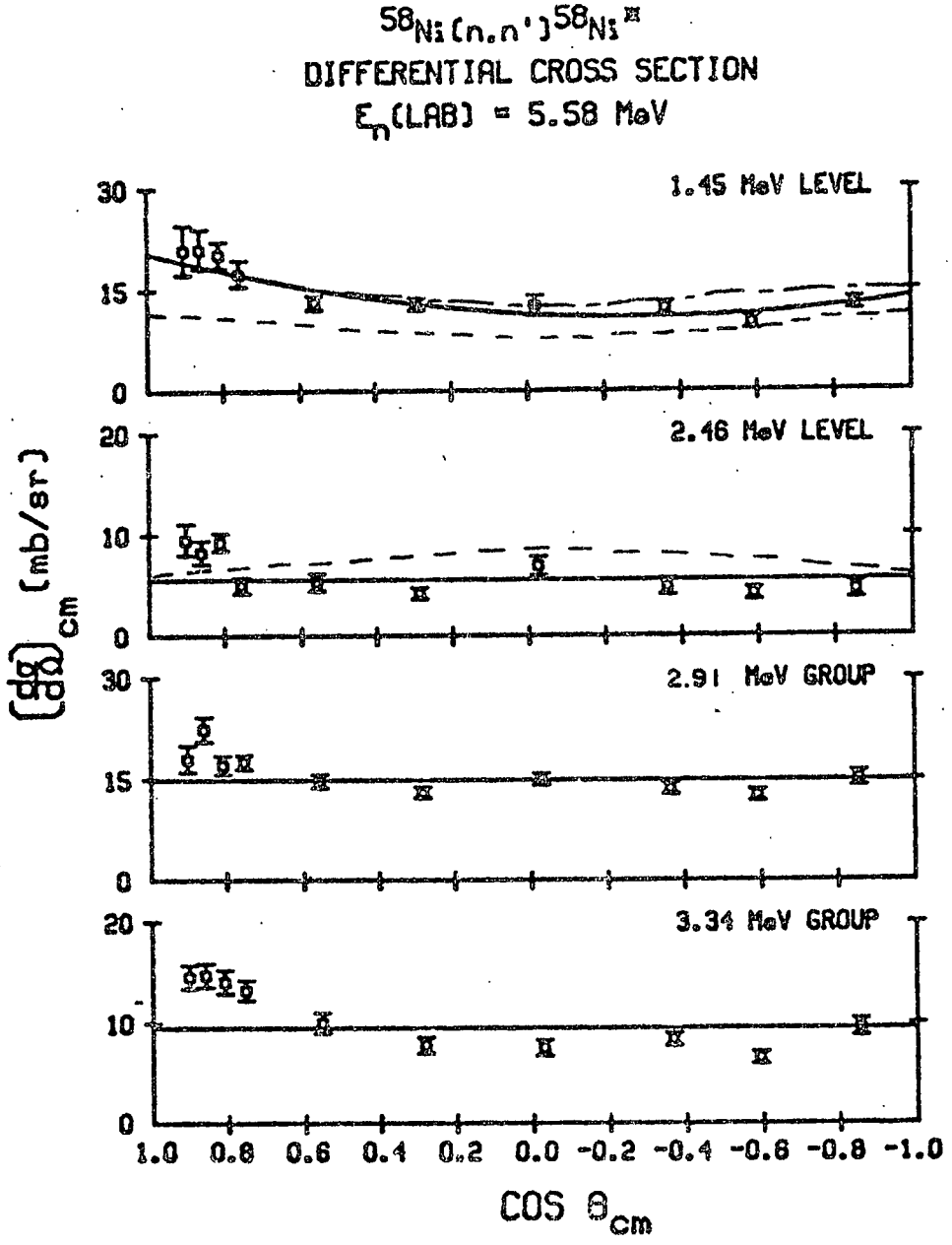

Figure 2. Inelastic scattering cross sections.

2. Normalization of Neutron Scattering Cross Sections

Work has been completed on a technique for absolute normalization of the cross section data from neutron scattering. A paper titled "Absolute Normalization of Neutron Scattering Cross Section Data Using Organic Scintillators as Scatterers"[1] has been published.

Abstract: An improved method for obtaining absolute neutron cross sections from time-of-flight scattering data has been developed which uses organic scintillators as scattering samples and Monte-Carlo, experiment simulating techniques.

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[1] J. T. Lindow, P. Boschung, and E. F. Shrader, Nucl. Instr. and Methods 85 (1970) 151.

3. Investigation of Gamma Rays from ^{54}Fe(n,n') Reactions

Evidence was obtained in the measurement of neutron inelastic scattering by ^{54}Fe described above for neutron groups corresponding to levels in ^{54}Fe near 1.95 and 2.15 MeV. Gamma rays from levels near these energies had been observed in one previous measurement.[1]

In order to obtain more conclusive results, the yield of gamma rays following inelastic scattering of 4.4 MeV neutrons by ^{54}Fe was investigated with a 25 cc Ge(Li) detector. Neutrons were obtained from the D(d,n)^{3}He reaction with a pulsed deuteron beam. Time-of-flight techniques were used to discriminate against events in the detector other than prompt gamma rays from the sample. The sample was $\sim$ 1 mole of 97% enriched ^{54}Fe.

No gamma rays were observed which could be attributed to ground state transitions from the two levels in question or cascades to the well known 1.408 MeV state. An upper limit for the excitation of these two levels can be set at about 5 mb/sr. This work is now complete.

D. E. Velkley, J. T. Lindow, and P. Boschung

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[1] P. Shapiro and R. W. Higgs, Phys. Rev. 108 (1957) 760.

4. Polarization of Neutrons from the $^{13}C(d,n)$ Reaction

The reduction of data from measurements of the polarization of neutrons produced by the $^{13}C(d,n)$ reaction is now completed. The feasibility of analyzing these data by comparison with DWBA calculations is being investigated.

A Ph.D. dissertation[1] describing the experimental methods and results has been accepted by the university.

Abstract: Polarization angular distributions for $^{13}C(d,n)$ neutrons leading to the ground and first five excited states of ^{14}N have been obtained for 1.7, 2.3, and 2.5 MeV incident deuterons. Relative yield excitation functions at 20 and 90 degrees (LAB) have also been measured over this energy range in 50 keV steps. Polarization excitation functions at 20 degrees (LAB) were also obtained for the third, fourth, and fifth ^{14}N excited state groups.

The polarization distributions for the ground state group and the first, third and fifth excited state groups were found to be slowly varying with energy even though considerable compound-nucleus contributions were indicated by yield fluctuations. Polarization predictions may therefore be possible by simple addition of an unpolarized background contribution, varying slowly with energy, to optical model direct reaction calculations.

W. W. Lindstrom and E. F. Shrader

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[1] W. W. Lindstrom, unpublished Ph.D. dissertation, CWRU (1970).

5. $^{16}O(d,n)^{17}F$ Differential Cross Sections

Preparations are almost complete for measurements of the absolute differential cross sections for excitation of the ground and first excited state of ^{17}F via the $^{16}O(d,n)^{17}F$ reaction over the deuteron energy range from 2.8 to 3.8 MeV. Excitation functions will be measured at two angles in intervals of 100 keV, and angular distributions will be taken at average deuteron energies of 3.05, 3.34, and 3.60 MeV, corresponding to the same incident deuteron energies and target thickness as the polarization measurements described below. These results are expected to provide additional information regarding the reaction mechanism which may be pertinent to interpretation of the polarization results. Measurements of cross sections in this energy region have been reported[1] but not at the exact energies and angles appropriate for the desired analysis.

The necessary equipment including an oxygen gas target chamber and neutron detection system has been assembled and measurements are expected to be made in the very near future.

D. E. Velkley, B. D. Anderson, and H. B. Willard

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[1]Dietzsch, et al., Nuclear Physics A114 (1968) 330. Bahnsen, et al. Phys. Rev. C2 (1970) 859.

6. Polarization of Neutrons from the $^{16}O(d,n)^{17}F$ Reaction

Experimental data have been taken to determine the polarization of neutrons from the $^{16}O(d,n)^{17}F$ reaction. Asymmetries in the scattering by helium of the ground and first excited state neutron groups have been measured for a deuteron energy range of 3 to 4 MeV. Three angular distributions and one excitation function have been measured in this region. The experimental apparatus has been described previously[1]. Targets were in the form of Ta_2O_5 and were approximately 200 keV thick for 3 MeV deuterons.

As in previous $^{13}C(d,n)$ neutron polarization measurements performed at this laboratory, the data were stored in a two-dimensional array. The first dimension was time-of-flight (TOF) from the target to a He-Xe cell and the second dimension was the pulse height output of the He-Xe cell derived from the alpha recoils produced by the neutrons scattered into side detectors. Figure 3 shows one of these spectra. The ground state and first excited state groups are seen to be nicely resolved in TOF. The pulse-height peaks, while broad (resolution approximately 30%), are in the correct channels.

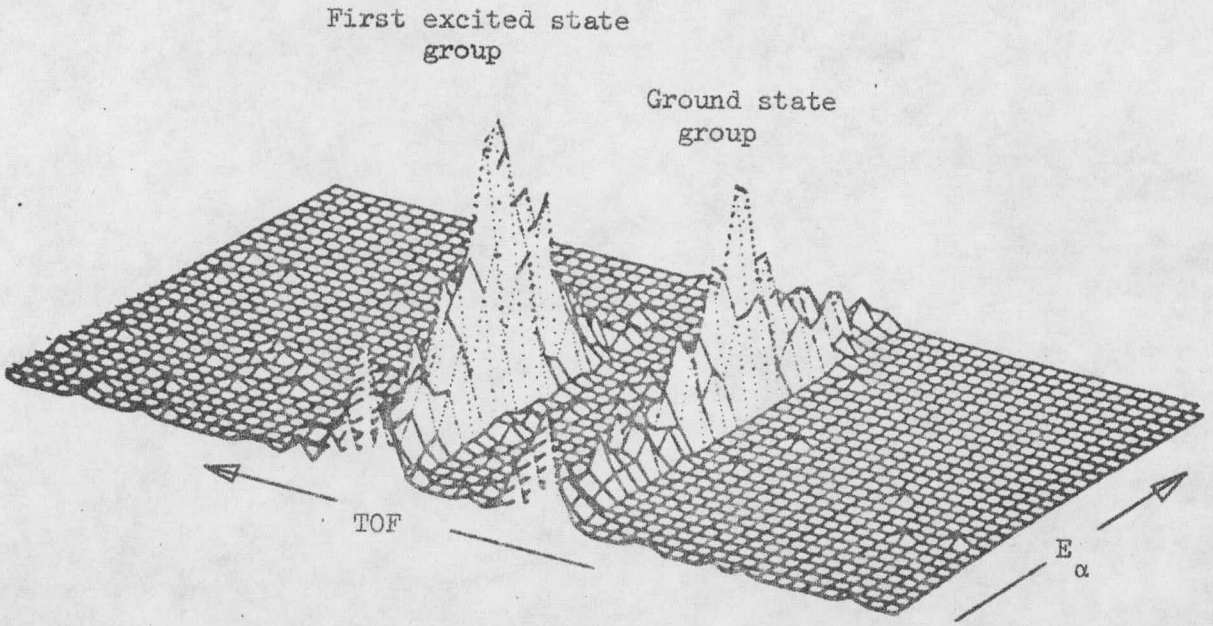

Figure 3. Two dimensional array of $^{16}O(d,n)^{17}F$ neutron polarization data. E_d(av.) = 3.34 Mev, reaction angle = 30 deg.(lab.).

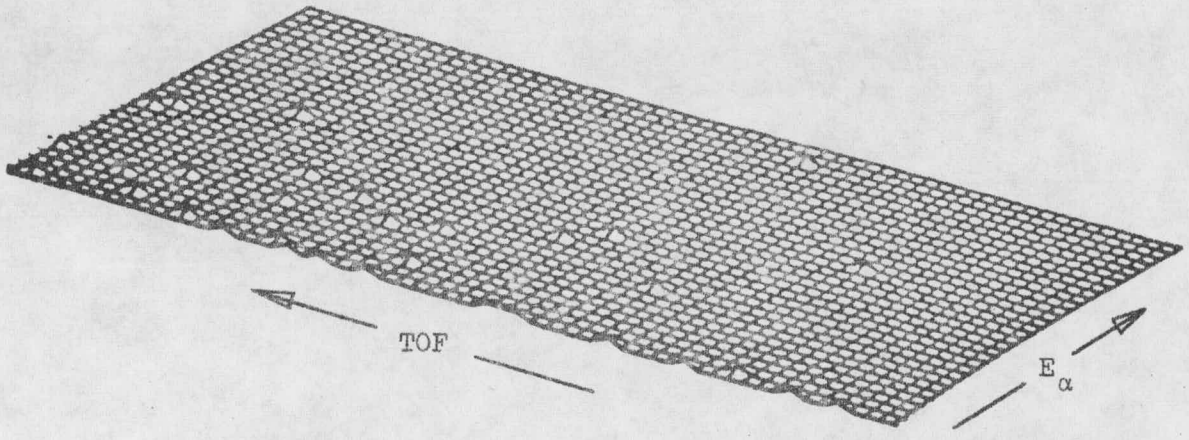

Figure 4. Background run, identical to above run (Figure 3), taken with 39 cm of paraffin in neutron collimator.

Figure 4 shows an identical run with 39 cm of paraffin placed in the neutron collimator. This background is seen to be small and unstructured. An average background is obtained by subtracting the equivalent number of TOF channels on both sides of the two peaks.

Figure 5 shows a blow-up of the ground state sum region of Figure 3. Figure 6 shows this same region viewed from "behind". Figures 3 - 6 are all photographs of the data displayed by a three - dimensional viewing program developed for the CWRUNCH computer. As shown in these photographs, this program provides the opportunity to look at the data in an ideal way which facilitates identification of the peak and background sum regions. Lower-level pulse-height cutoffs in the alpha recoil dimension are also employed.

Periodic checks for false asymmetries were performed throughout the data taking. These checks included: (1) measurements at zero degrees, (2) measurements at both left and right reaction angles for some data, and (3) measurement of the $^{12}C(d,n)^{13}N$ neutron polarization for comparison with the results of Meier et al.[2] The checks were considered to be satisfactory in all cases.

An existing program to determine effective average analyzing power is being modified to take into account a change in the side detector scintillators from NE-213 to NE-102. This modification consists of an improved calculation of the absolute neutron detection efficiencies and is aided by comparison with the results of a Monte-Carlo code which simulates events in a proton-recoil neutron detector.

It is expected that experimental asymmetries will be determined by early this fall and the polarizations soon after. A DWBA analysis with the program DWUCK[3] is in preliminary stages.

B. D. Anderson, D. E. Velkley, R. C. Nerbun, Jr., and H. B. Willard

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[1] W. W. Lindstrom and E. F. Shrader, CWRU Progress Report, COO-1573-63, p. 12 (1969).

[2] M. M. Meier, L. A. Schaller, and R. L. Walter, Phys. Rev. 150 (1966) 821-825.

[3] P. D. Kunz, University of Colorado.

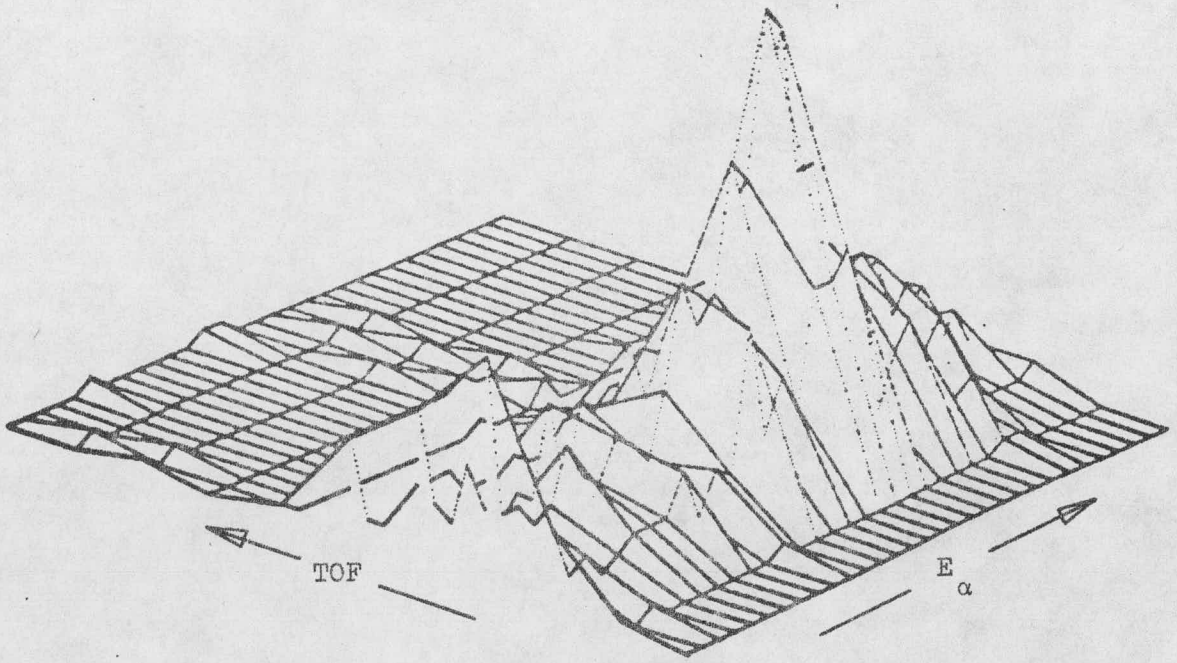

Figure 5. Enlargement of region for summation of ground state in Figure 3.

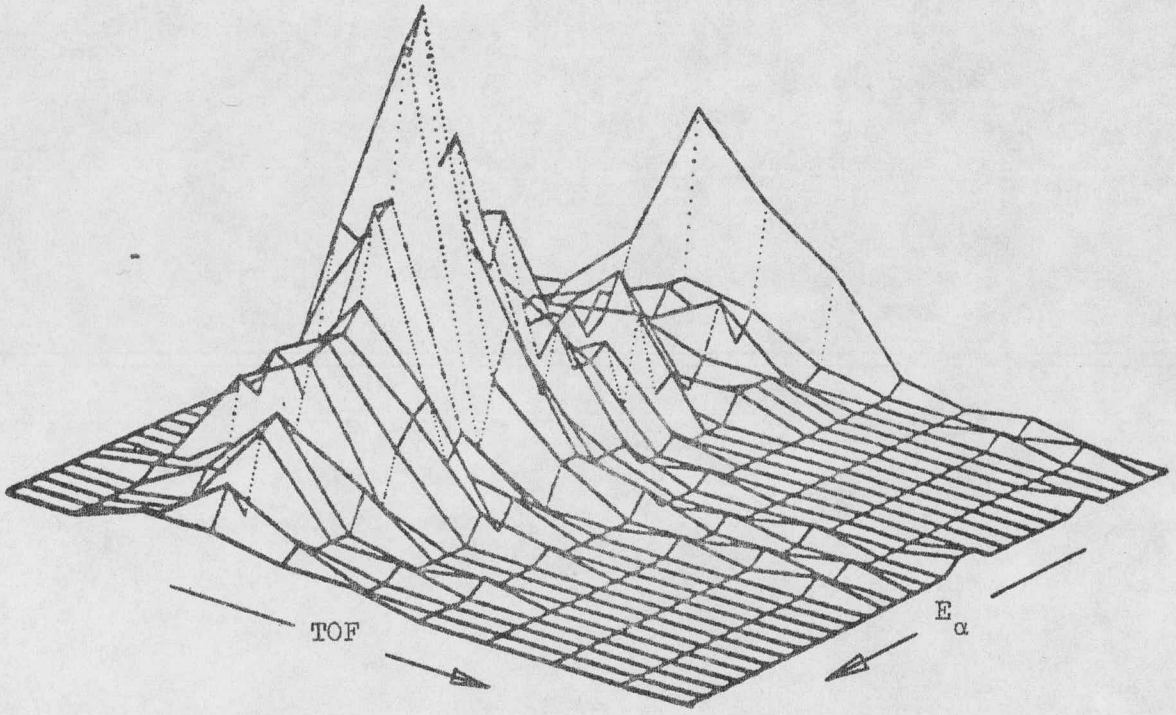

Figure 6. Figure 5 viewed from 'behind'.

7. Cross Section Measurements of the (^{3}He,n) Reaction

An investigation of the cross sections for (^{3}He,n) reactions for target nuclei in the s-d shell region is in progress. Almost all modifications to existing apparatus necessary for these measurements have been completed. Measurements of ^{20}Ne(^{3}He,n) cross sections are scheduled to begin in February, 1971.

A computer program RATE (Reaction Analysis of Time-of-Flight vs. Energy) has been developed to simulate the time-of-flight spectra for nuclear reactions as a function of Q values, geometry, and kinematics. The program displays the resultant spectrum on the oscilloscope of the CWRUNCH computer, with provisions to alter any of the experimental conditions via teletypewriter or card reader, so that the effect of each parameter on the resolution of various peaks may be studied visually. The program has been utilized to select experimentally feasible target nuclei and to optimize conditions such as detector size and distance, target thickness, etc., as well as to analyze preliminary measurements with the accelerator to identify contaminants in the target.

The shielding of the existing LiOH collimator, which presently has a 6 in. diameter central shaft, has been improved by the fabrication of a hollow paraffin cylinder 30 in. long, with a conical interior, designed to minimize contributions to background from multiple scattering from the collimator.

A liquid NE-213 bubble-free scintillator 5 in. in diameter and 3 in. long has been obtained[1] which is larger than that used in preliminary measurements and is expected to increase the counting rate by nearly an order of magnitude. The complete assembly of scintillator, photomultiplier tube, and electronics is being constructed with low mass and with considerable attention to optimizing scintillator response.

An existing gas target has been modified to conform to the desired geometry of this experiment. A computer program ELOSS was written to determine the proper thickness for the entrance window; Ni foils 25 μin. thick and free of pinholes have been successfully attached and found leak tight. A gas filling system has been constructed, including a zeolite trap to absorb and contain the gas, an oven for the trap to emit the gas in a controlled manner, and a pressure gauge.

For timing with doubly charged ^{3}He^{++} ions at energies above 4 MeV, a pick-up loop to synchronize external bunching of the beam with internal burst times has been installed ahead of the energy-stabilizing magnet; it takes advantage of the higher current of the singly charged ^{3}He$^+$ ions in the beam before they are separated out by the magnet.

One of the experimental problems encountered in preliminary measurements of (^{3}He,n) cross sections was that of carbon contamination of the target system, including apertures and target backings. Various methods of cleaning Ta were evaluated, using the ^{12}C(d,n) yield to determine the level of contamination. Best results were achieved by dipping the Ta into a mixture of nitric, sulphuric, and hydrofluoric acids in the proportion 9:24:8 for about fifteen seconds. Apertures in the gas target have been cleaned and enlarged to reduce contributions from carbon in (^{3}He,n) spectra.

In order to estimate the neutron yield from (^{3}He,n) reactions in the s-d shell at energies below 4 MeV, time-of-flight spectra were obtained with a target of Mg, which is one of the most easily fabricated targets. The spectra were so dominated by the yield from carbon that Mg peaks were not discernible. Investigation with the (d,n) reaction (to minimize the use of expensive ^{3}He) indicated that the carbon contamination was deposited along with the Mg, as indicated in Figure 7, where the yield from the Ta backing is more than an order of magnitude smaller than that from the target itself. Since the carbon contamination appears to be linear with Mg deposition, both for evaporation and for MgO smoking, the study of Mg as a representative benchmark has been abandoned.

S. K. Bose, A. Kogan, and P. R. Bevington

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[1] Nuclear Enterprises, Inc., San Carlos, California.

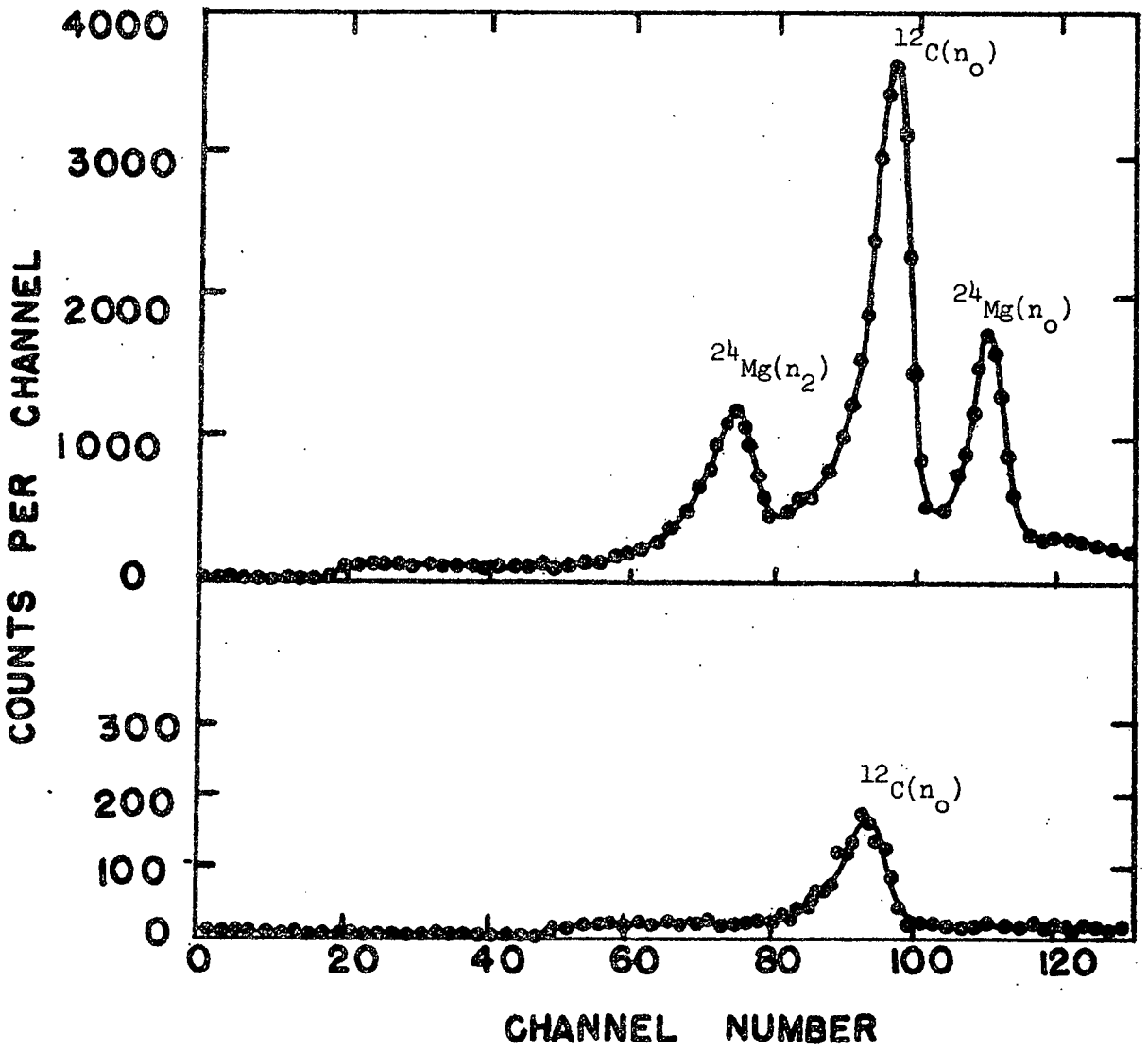

Figure 7. A time-of-flight spectrum for the $^{24}Mg(d,n)^{26}Si$ reaction at E_d = 2.5 MeV, θ_{Lab} = 45° and flight path = 2 meters. A spectrum with clean Ta is shown for comparison. The time scale is 0.75 nsec/channel.

8. Polarization of Neutrons from (^{3}He,n) Reactions

Interest in obtaining more information about diproton transfer in the (^{3}He,n) reaction for s-d shell nuclei leads one to consider the polarization of the outgoing neutron in addition to angular distributions and excitation functions for this reaction. The measurement of (^{3}He,n) polarization is of interest for the following reasons: (1) to provide additional information for the determination of average optical model parameters for ^{3}He particles; (2) to determine a consistent set of J^π assignments of the residual nucleus; (3) to study the compound nuclear contribution in competition with direct processes; and (4) to provide data of two-nucleon transfer reactions useful to theorists interested in sensitive tests of nuclear wave functions.

With singly charged ^{3}He ions, (^{3}He,n) reactions can be investigated to 4 MeV with the newly installed accelerator tube. The feasibility of producing a pulsed He^{++} beam to extend this energy range to 8 MeV is being investigated. A test-bench duplicate of the accelerator ion source is being studied to maximize the available ^{3}He current.

Work has begun on the design of new side detectors for neutrons scattered from the ^{4}He polarimeter. Because the flux of neutrons produced will be smaller than that from (d,n) reactions previously studied in this laboratory, the side detector size must be increased to make a polarization measurement feasible.

The new larger side detectors will increase the polarimeter efficiency because (1) neutron transmission through the side detectors will be decreased by a factor of 2 to 4 as compared to the present side detectors, and (2) the solid angle subtended by the detectors will be larger. The larger solid angle will be partially offset by the fact that a larger time window is needed to separate in time neutrons and gammas traveling from the ^{4}He polarimeter to the side detectors.

The detector shape is being optimized to minimize the decrease in analyzing power of the polarimeter. A computer program AVPOL will be used to determine the effective average analyzing power. In order to eliminate the larger background, lead shielding will be provided for the side detectors.

A program RUNT is being written to calculate the running time necessary for several different counting statistic percentages in a polarization experiment with a gas or solid target, given polarimeter geometry, etc.

During the past year a thorough study was undertaken of s-d shell nuclei as targets for diproton stripping via (^{3}He,n) reactions. Simulated TOF spectra were observed for these reactions on the oscilloscope of the CWRUNCH computer calculated by program RATE (Reaction Analyzer for Time-of-Flight vs. Energy). The reaction ^{20}Ne(^{3}He,n)^{22}Mg was found to be one of the best from a physics standpoint. Work is now under way to measure the neutron polarization for this reaction.

The computer simulation was done for expected experimental geometry, and Figures 8-11 show TOF spectra for the reactions $^{20}Ne(^{3}He,n)^{22}Mg$ and $^{12}C(^{3}He,n)^{14}O$ as seen on the oscilloscope. The time scale for all spectra is .75 nsec/channel, with time increasing to the left. The position in time of the gamma peak is marked by the crosses and all spectra are calculated for a reaction angle of 0^{o}.

Simulated TOF spectra for ^{3}He incident energies of 3.0, 4.0, 5.5, 7.0, and 8.0 MeV on ^{20}Ne are shown in Figures 8-10. The separation and resolution of TOF peaks for given expected experimental conditions indicate that measurements of neutron polarization are possible for: (1) the ground state for ^{3}He energies of 20 to 8.0 MeV, (2) the 1^{st} excited state for energies of 3.0 to 8.0 MeV, (3) the 2^{nd} excited state for energies of 5.5 to 8.0 MeV, and (4) the 3^{rd} excited state for energies of 6.5 to 8.0 MeV. Even at the maximum accelerator energy of 8 MeV for doubly charged $^{3}He^{++}$ ions the TOF peaks are resolved for the lowest four final states of ^{22}Mg, illustrating the advantage of TOF measurements over alpha recoil-energy determinations for separation of different neutron groups.

Figure 11 indicates the danger from carbon contamination. The ground state neutron group from the reaction $^{12}C(^{3}He,n_{o})^{14}O$ has nearly the same TOF as the 1^{st} excited state neutron group from $^{20}Ne(^{3}He,n_{1})^{22}Mg$. Work is in progress to decrease the carbon contamination in the gas target assembly.

R. C. Nerbun, Jr., V. Burke, and P. R. Bevington

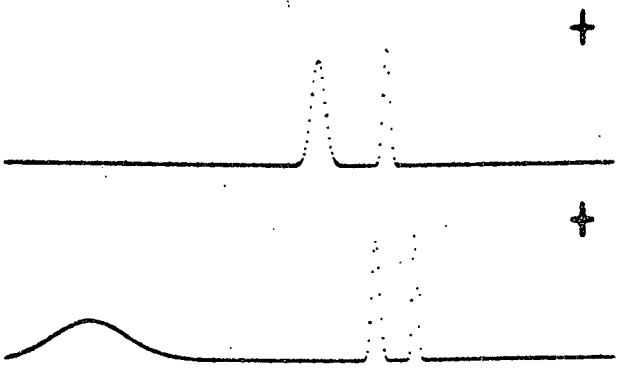

Figure 8. Simulated TOF spectra of $^{20}Ne(^{3}He,n)^{22}Mg$ for E_{He} = 3.0 MeV (top) and 4.0 MeV (bottom).

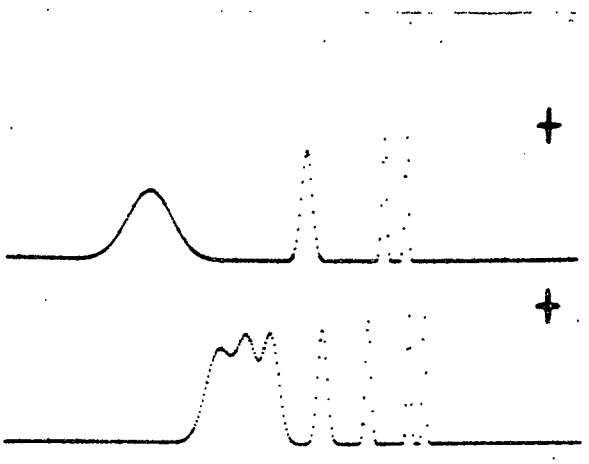

Figure 9. Simulated TOF spectra of $^{20}Ne(^{3}He,n)^{22}Mg$ for E_{He} = 5.5 MeV (top) and 7.0 MeV (bottom).

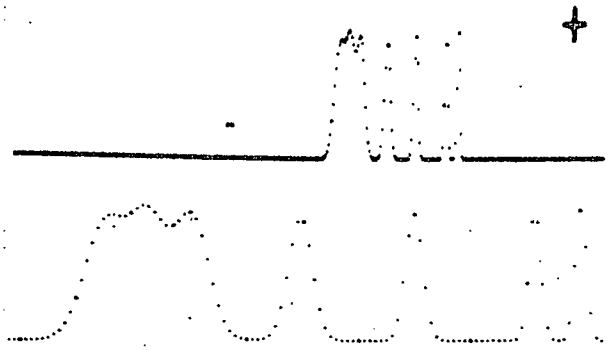

Figure 10. Simulated TOF spectra of $^{20}Ne(^{3}He,n)^{22}Mg$ for E_{He} = 8.0 MeV (bottom; time scale expanded).

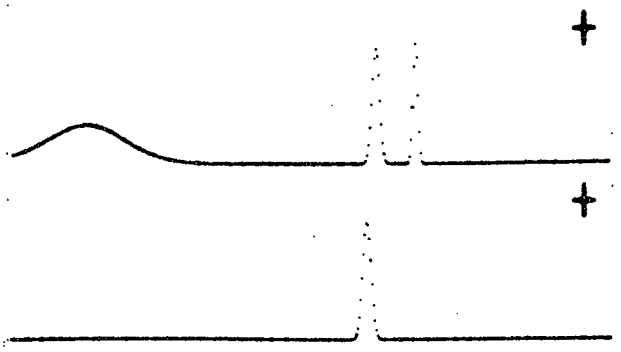

Figure 11. Simulated TOF spectra for E_{He} = 4.0 MeV of $^{20}Ne(^{3}He,n)^{22}Mg$ (top) and $^{12}C(^{3}He,n)^{14}O$ (bottom).

9. Study of the (^{4}He,^{6}He) Reaction on s-d Shell Nuclei

The (^{4}He,^{6}He) reaction on s-d shell nuclei was investigated by measuring the energy spectra of ^{6}He nuclei emitted after bombardment of various targets by alpha particles. Targets of ^{18}O, ^{22}Ne, and ^{26}Mg were bombarded with the 42 MeV alpha particle beam from the 60-inch fixed-energy cyclotron of the Lewis Research Center of NASA.[1] Energy spectra were measured over the angular range of 15° to 70° in steps of 2.5° with a particle-identifier system containing four detectors. Cross sections accurate to about 10% were extracted from the data with the help of an interactive display program written for the CWRUNCH computer.

Angular distributions for half of the energy groups detected appear quite smooth, varying by only about one order of magnitude over the angular range studied, while the rest of the angular distributions are quite oscillatory in nature, with very pronounced minima. In general, those for the excited states tend to have less structure. The average magnitude of all cross sections for states in the same nucleus are approximately the same. That is, no one state is excited preferentially over the angular range studied, and in particular the ground state cross section is of the same order of magnitude as that of the first several excited states, which is not the case for (p,t) stripping reactions. This difference may be attributable to the effects of inelastic scattering in the entrance and exit channels, or the structure of the neutron pair in the outgoing particle.

DWBA predictions were calculated for two-neutron pickup on ^{18}O with a computer code[2] for zero-range approximation and one-particle transfer, modified by the inclusion of a form factor describing the nuclear structure information. Given a Woods-Saxon potential which reproduces the single-particle levels in ^{17}O, a set of two-particle states were found, and the residual interaction (of Yukawa form) was diagonalized in this set of states. Optical potential parameters for ^{6}He were extrapolated from data for elastic scattering of ^{6}Li, but the resulting ^{6}He-^{16}O potential, which is the least reliable potential used in the calculations, appears to have the most influence on the calculated angular distributions.

DWBA predictions for the ^{18}O(^{4}He,^{6}He)^{16}O reaction could not even reproduce qualitatively the main features of the experimental data, even with considerable freedom in choice of the ^{6}He parameters, although this $0^+ - 0^+$ transition should be the simplest to describe. Possible reasons for the discrepancy include: 1) finite-range effects may be important

for two-nucleon transfer; 2) correlations of the transferred neutrons with the alpha particle may be important; 3) shell model continuum states included in the calculation of two-particle form factors may significantly alter their shape in the region extending outward from the nuclear surface; and 4) there may be a sizable compound nuclear contribution to the reaction.

A Ph.D. dissertation[3] describing the work has been accepted by the university.

J. Arnold and H. B. Willard

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[1]Work supported in part by the National Aeronautics and Space Administration; research conducted in part under the direction of R. Bercaw, Lewis Research Center, NASA.

[2]W. R. Gibbs, V. A. Madsen, J. A. Miller, W. Tobocman, E. C. Cox, and C. Mowry, unpublished NASA Technical Note No. D-2170 (1964).

[3]J. Arnold, unpublished Ph.D. dissertation, CWRU (1970).

10. Analysis of Direct Reactions

Since many of the experiments performed recently and proposed for the future in this laboratory and referenced in this report lend themselves to analysis in terms of direct reaction mechanisms - (d,n) and (^{3}He,n) cross sections and polarizations, etc. - considerable effort is being expended in developing the capability of analyzing their results by DWBA calculations. In particular, the computer code DWUCK[1] has been obtained from P. D. Kunz of the University of Colorado, and has been modified to run on the CWRU UNIVAC 1108 Computer. This code, which is capable of handling spin-orbit coupling, finite range interaction, non-locality corrections, and two-particle transfer reactions in addition to the standard DWBA techniques, is expected to be the principle tool to derive information regarding reaction mechanisms and nuclear spectroscopy from the measured cross sections. Extensive familiarization with capabilities and options is in progress.

A. Kogan, D. E. Velkley, and P. R. Bevington

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[1]P. D. Kunz, "Distorted Waves, University of Colorado, Kunz", private communication.

11. Parity Conservation in Strong Interactions

An experiment is under way to test the conservation of parity in strong interactions by a new technique. It is anticipated that a factor of 5 to 10 in increased sensitivity over previous measurements will be achieved. The reaction chosen to be studied is the $^{9}Be(p,\alpha)^{6}Li$ reaction, leading to the 3.56 MeV 0^{+} level in ^{6}Li. This level is forbidden by parity and isospin to break up into an alpha particle and a deuteron. Thus a search for either will determine the extent to which conservation of parity and isospin holds.

In our experiment deuterons are observed with an NE-102 scintillator 1-1/2 mils thick. This thickness was chosen in order to just stop the maximum energy deuterons and minimize the background arising from neutrons and gamma rays produced by proton bombardment of ^{9}Be. Time-of-flight deuteron spectra are observed with the elastically scattered protons gated out to reduce the dead time to essentially zero. Backgrounds are obtained by interchanging the beryllium target with an aluminum foil.

Preliminary results indicate that we can observe a limit of 10^{-13} on F^2 (F is the ratio of parity-violating to parity-conserving amplitudes). Final runs requiring about 0.25 Coulombs of beam charge are now under way.

A. Kosiara and H. B. Willard

12. $T(d,n\gamma)^{4}He$ Branching Ratio

This work is now complete, and a paper titled "Gamma Ray - Neutron Branching Ratio in the Triton - Deuteron Reaction" has been published.[1]

Abstract: The cross section for the $^{3}H(^{2}H,\gamma)^{5}He$ process has been measured. At 1025 KeV, 90 degrees (lab) its value is 0.44 ± 0.12 μb/sr and the gamma ray - neutron branching ratio is 2.3×10^{-5}.

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[1] A. Kosiara and H. B. Willard, Physics Letters B32 (1970) 99.

13. Search for a Bound Trineutron

The experimental phase of the search for a bound trineutron has been completed. Natural lithium was bombarded with 19 MeV neutrons, obtained via the T(d,n) reaction. No evidence for a bound trineutron has been found. The cross-section limit for production by the reaction $^{7}Li(n,^{3}n)^{5}Li$ over the lab angle range from 5 to 40 degrees is 0.1 mb/sr. This corresponds to a total cross section of $\leq$ 1 mb if the angular distribution is isotropic, and a smaller value if it is forward peaked. Cross-section limits for two-step reactions, such as $^{7}Li(n,p)^{7}He$, $^{7}He \rightarrow {}^{3}n + \alpha$, are being determined.

(a) Experimental Arrangement

The physical arrangement described in last year's progress report (COO-1573-63) was not substantially altered. A gas target filled with tritium to a pressure of 700 mm of Hg was bombarded by 2.7 MeV deuterons. The large (3-1/4 in. long by 4 in. in diameter) lithium target, contained in a thin-walled can, was placed 2-1/4 in. from the face of the gas target. Trineutrons were detected with a high pressure ^{4}He gas scintillator located at 0 degrees, 1 meter from the lithium target. A tungsten shadow cone (2-3/4 in. long by 3/4 in. in diameter) was placed between the lithium target and the detector, effectively producing a ring geometry. Extensive iron shielding around the target and paraffin shielding around the detector were required to minimize background. Fresh tritium gas was utilized in the final runs to minimize deuterium contamination.

The data were taken by alternately bombarding the lithium target for 90,000 microcoulombs and a carbon dummy target for 30,000 microcoulombs. The characteristic signature of a trineutron is a long time of flight together with a large alpha-recoil pulse height. Events satisfying these criteria were found in both types of runs. Data taken at reduced counting rates showed that the number of such events was linearly dependent on the number of high energy neutrons and therefore that the events were not due to pileup.

(b) Analysis of Data

Since it was impossible to eliminate all background events from high energy neutrons, the determination of trineutron yield has to be made by comparing the lithium and carbon runs. Figure 12 shows plots of the number of counts in the trineutron region versus assumed trineutron binding energy. Curves are shown for three different choices of the portion of the $^{4}He(^{3}n,^{3}n)^{4}He$ angular distribution included in the trineutron region. The results from the two types of runs were carefully normalized. In regions of the top and bottom plots the results with carbon slightly exceed those with lithium. The number of counts with lithium does not exceed the number with carbon in any case. Nor is there a tendency for the lithium results to peak around a given binding energy. Therefore, we conclude there is no evidence for the existence of a bound trineutron.

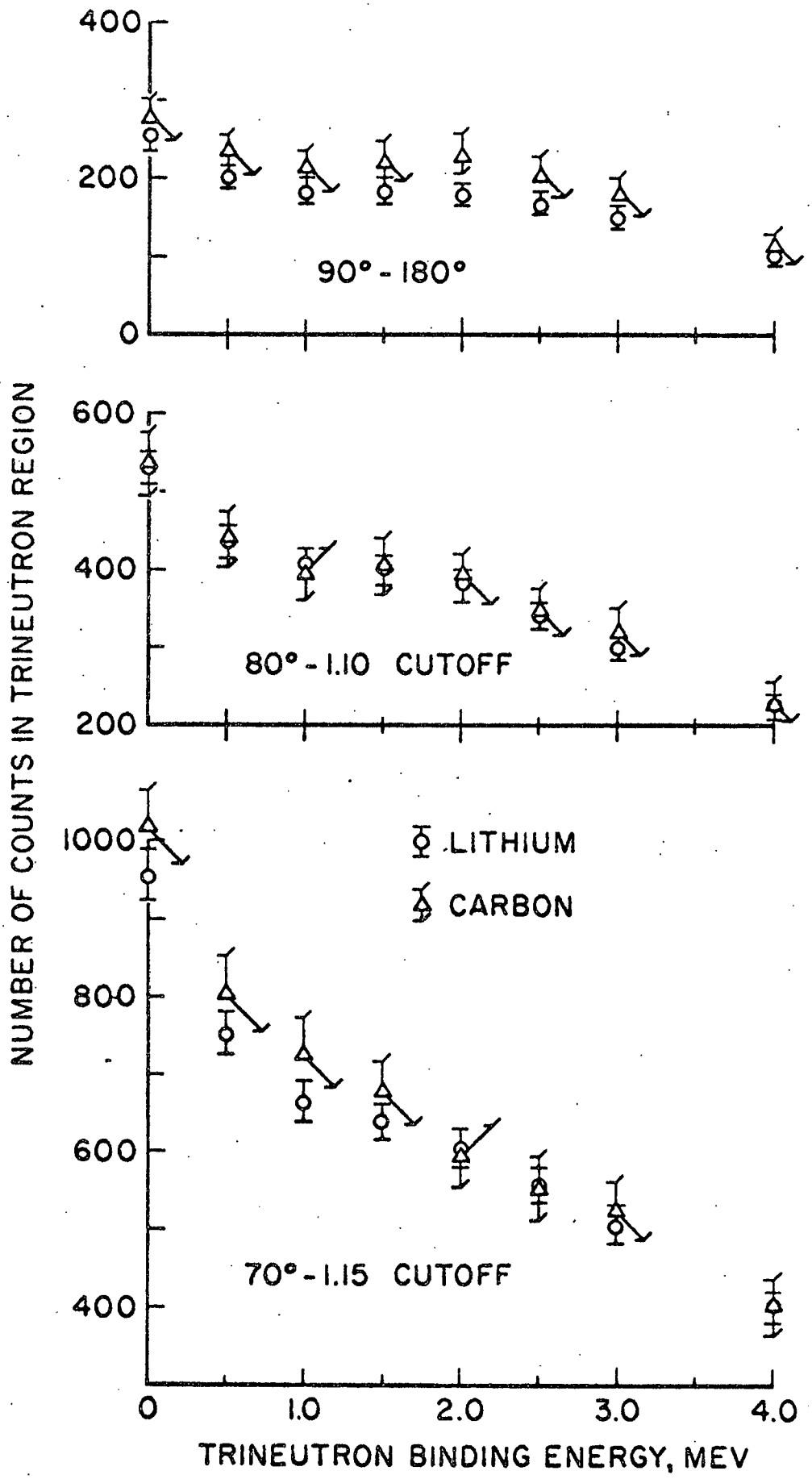


Figure 12. Comparison of results for lithium target versus carbon dummy target for the reaction $^{7}Li(n,^{3}n)^{5}Li$.

(c) Angular Distribution for Elastic Scattering of ^3n by ^4He

A determination of the $^4He(^3n,^3n)^4He$ angular distribution was needed to set a limit on the trineutron production cross section. First optical model potential parameters for $^4He(^3He,^3He)^4He$ elastic scattering were determined at off-resonance energies by fitting available data with the code ELSA.[1] The real and imaginary potential well depths were:

$$V = (69.2 + 1.5E) \text{ MeV}$$

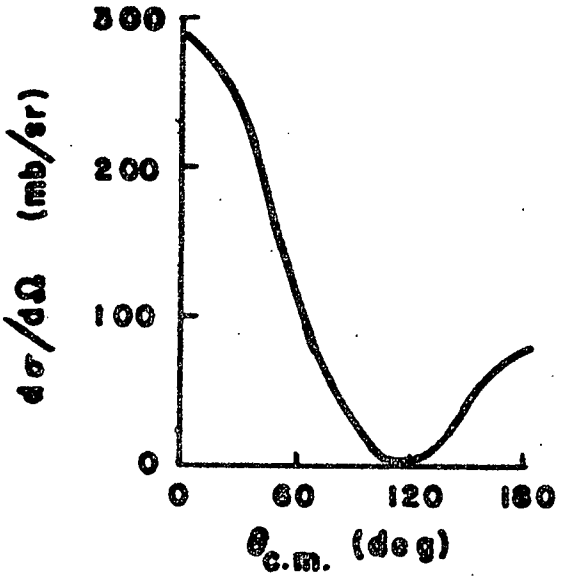
$$W = 0$$

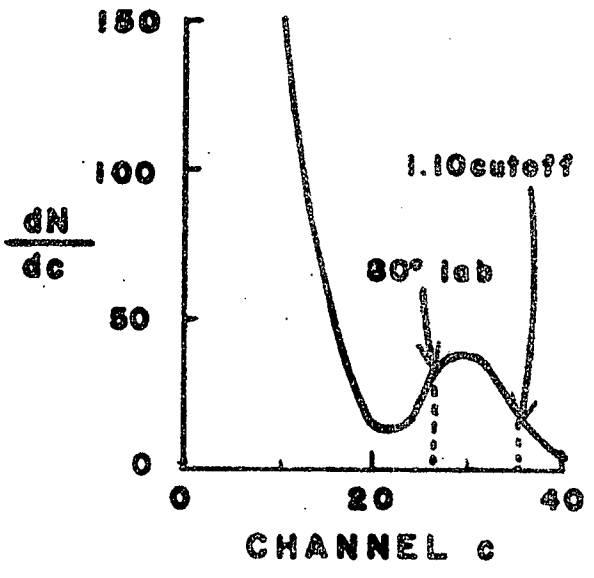
with E the projectile lab energy divided by 1 MeV.

Next the same parameters, without a Coulomb field, were assumed in ELSA for the trineutron scattering except for making W non-zero to account for breakup.

$$W = (0.5E) \text{ MeV}$$

The resulting angular distribution is shown below at the left.





The figure at the right is the expected pulse-height distribution after taking into account the resolution of the scintillator. The channels indicated are for a pulse height corresponding to a trineutron scattering through 80 degrees lab (128 degrees cm) with an ideal resolution scintillator, and for a pulse height which is 1.10 times that corresponding to a trineutron scattering through 180 degrees with an ideal resolution scintillator.

(d) Upper Limit on Trineutron Production Cross Section for $^{7}Li(n,^{3}n)^{5}Li$

Figure 13 shows the effect of 50 trineutron recoils added to the carbon dummy background. This number of recoils is the minimum number that produces a discernible difference between the carbon and lithium results. It is, therefore, an upper limit for the number of trineutron recoils in the given pulse height region. From the angular distribution and the pulse height distribution shown in section (c), the efficiency of the He scintillator is 0.5% and the ratio of trineutron recoils between 80 degrees and 1.10 cutoff to the total number of trineutron recoils is 0.07. The upper limit on the total number of trineutrons produced is therefore 1.4×10^{5}. From an absolute normalization, dependent on the number of high energy neutrons detected, this number corresponds to a cross section limit of

$$\left(\frac{d\sigma}{d\Omega}\right)^{5°-40°}_{\text{Lab}} \leq 0.1 \text{ mb/sr}$$

for the trineutron reaction $^{7}Li\ (n,^{3}n)^{5}Li$.

K. Koral and P. R. Bevington

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[1] C. C. Giamati, W. Tobocman, and D. V. Renkel, "A Fortran Program for Analysis of Spin Zero Elastic Scattering with the Nuclear Optical Model", unpublished NASA document, No. TN D-2120 (April, 1964).

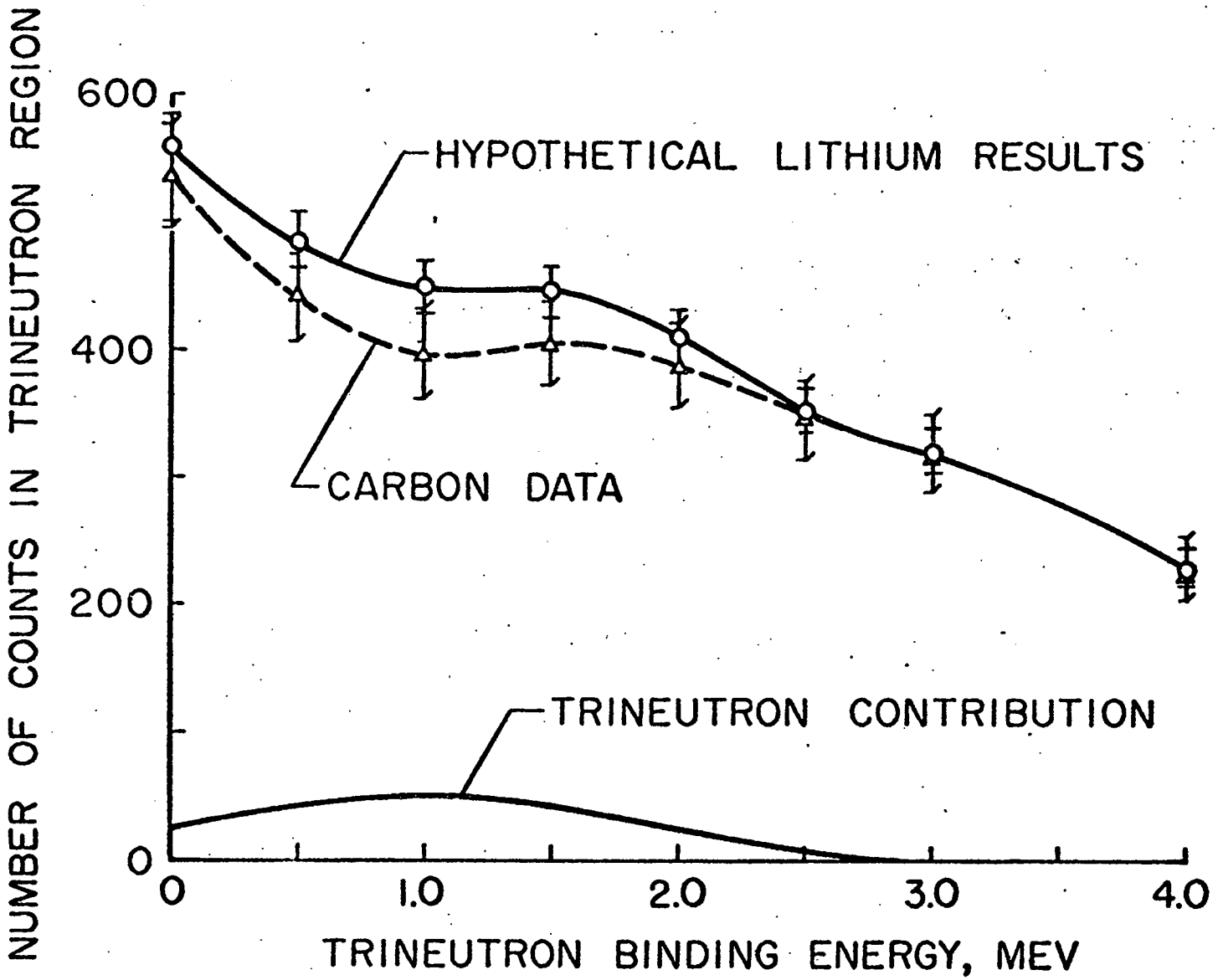

Figure 13. Plot of hypothetical results with the minimum number of trineutrons that produces a discernible difference between the carbon and lithium data.

14. Helium Scintillator Linearity and Resolution

For the analysis of data in the trineutron experiment, it was desirable to know the linearity and resolution of the He scintillator over an energy range of α recoils from 1 to 12 MeV. At the high energies it was difficult to get a direct measurement by adding a detector in coincidence with the scintillator because of the low $^4He(n,n)^4He$ elastic cross section. Instead the entire pulse height distribution was measured for neutrons of various energies. These data were fit to an energy distribution of variable cutoff calculated from the known $^4He(n,n)^4He$ angular distribution and smeared by a Gaussian function of variable FWHM. The fitting was done using the real-time interaction capability of the CWRUNCH computer. The high energy part of the pulse-height distribution was insensitive to Xe(n,p) background contributions. By assuming an energy dependence for the resolution (i.e., for the FWHM of the Gaussian function) and fitting the data for various neutron energies, the true dependence could be found in an iterative manner. One iteration was sufficient. The pulse-height response was given by the dependence of the cutoff on neutron energy.

The results are shown in Figure 14. The scintillator is linear as expected and the resolution is given by

$$R = \sqrt{(20)^2 + \frac{2460}{E_\alpha}} \text{ percent}$$

where $R = \frac{\Delta E_\alpha \text{ FWHM}}{E_\alpha} \times 100\%$

and E_α is the alpha recoil energy divided by 1 MeV.

The resolution is slightly disappointing for a cylindrical scintillator with a phototube at each end, but the gas had not been replaced for over a year and some damage to the coating of wave shifter and reflector is present.

K. Koral and P. R. Bevington

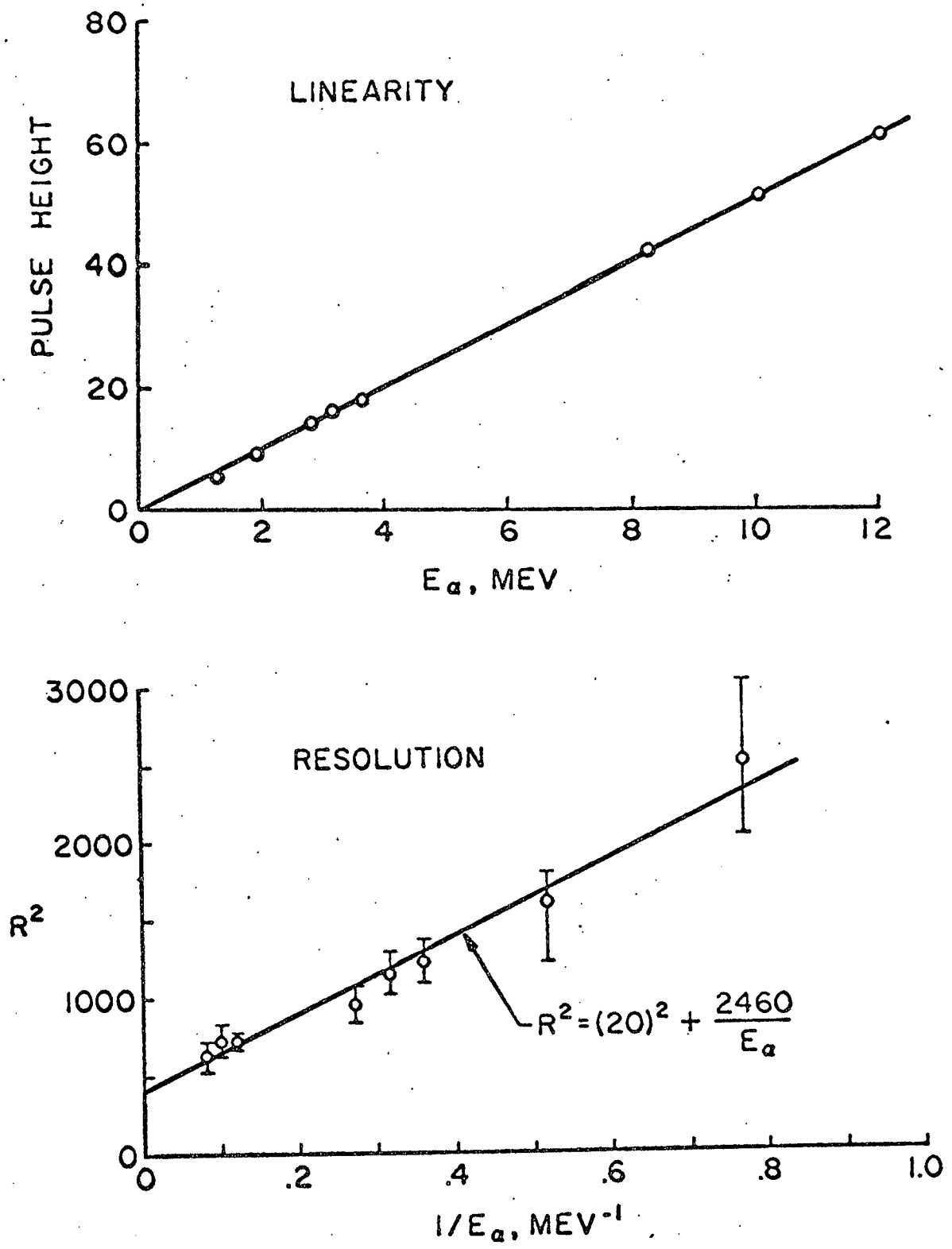

Figure 14. Linearity and resolution of high-pressure helium gas scintillator.

15. Proton Activation for Analysis of Oxygen Diffusion

The temperature dependence of the self-diffusion coefficient of oxygen in ZnO was investigated in the temperature range 950 °C - 1100 °C.[1] Diffusion coefficients for ^{18}O were measured directly and without the combined need for serial sectioning, utilizing proton activation analysis of ^{18}O via the nuclear reaction $^{18}O(p,\alpha)^{15}N$. In this technique, the alpha particle spectrum recorded during proton irradiation is unfolded to determine the ^{18}O concentration profile with a sub-micron resolution. Alpha particle spectra were obtained at back angles with solid state detectors for incident proton energies of about 800 keV.

The feasibility of this approach was demonstrated by studying oxygen self-diffusion in zinc oxide single crystals. With a convolution procedure, the oxygen self-diffusion coefficients, D, could be determined with a relative uncertainty below 20%; the technique is optimum for determining D in the range 5×10^{-11} cm^2/sec. The technique also proved useful for testing diffusion models.

Analysis of the data suggested that the diffusion was partly controlled by a surface exchange reaction of oxygen described by a first order parameter constant K. In the temperature range 940 °C - 1140 °C, D followed the relation below, which is attributed to extrinsic diffusion.

$$D = 1.5 \times 10^{-10} \exp\left(- \frac{30.5 + 3 \text{ Kcal}}{RT} \right) cm^2/sec$$

$$K = 10^5 \exp\left(- \frac{87 \text{ Kcal}}{RT} \right) cm/sec$$

A Ph.D. dissertation[2] describing the work has been accepted by the university. Work is continuing on other targets.

L. H. Hinkley and P. R. Bevington

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[1]Work supported in part by Metallurgy Department, CWRU; research of R. C. Robin conducted under direction of A. H. Heuer and A. R. Cooper, Metallurgy Department, CWRU.

[2]R. C. Robin, unpublished Ph.D. dissertation, CWRU (1970).

16. Detector Efficiency Measurements and Calculations

Relative neutron detection efficiencies of 5.08 cm diameter by 5.08 cm thick cylinders of NE-102 and NE-213 uniformly illuminated perpendicular to their axes have been measured for the neutron energy range 0.2 MeV to 2.0 MeV. The $T(p,n)^3He$ reaction was the source of neutrons. The relative number of neutrons produced at the various proton energies and reaction angles employed was determined from the differential cross section data of Jarvis et al.[1]

Efficiency data for the NE-102 and NE-213 scintillators were obtained simultaneously with the same target filling of tritium gas, etc. Thus the relative ratios of NE-102 and NE-213 detector efficiencies have been determined consistently. Data were obtained using time-of-flight techniques with a discriminator bias to reject all events producing a linear output from the detector smaller than a minimum pulse height. A discriminator bias of pulse height equivalent to 3/4 that of the total absorption peak of 60 keV gamma rays from ^{241}Am was employed on both scintillators as well as data with a bias of 1/2 of the ^{241}Am peak on the NE-102 detector. The results of these data are shown in Figures 15 and 16.

A previous report[2] described modifications made on a Monte-Carlo code capable of simulating the detection process in a proton-recoil neutron detector. This code was used to fit the observed data described above. As input, the code requires the equivalent number of photo-electrons at cutoff. This number was determined from the shape of the total absorption peak from the 60 keV ^{241}Am gamma rays. A Poisson distribution with a mean of 19.0 was observed to have the same resolution as the "One ^{241}Am" peak for the NE-102 detector while a mean of 18.5 was required for the NE-213 detector. The NE-213 data were fitted by varying the program parameter of "average photoelectrons per light unit" until the rapid rise near "cutoff" was reproduced. The NE-102 data were reproduced by changing the scintillator density, the H/C ratio, and the relative light output curves in the code. The scale factor was not changed.

The agreement of the code with the observed data is seen to be excellent. The accurate simulation of efficiencies for different scintillators and different discriminator biases indicates that most of the major physical processes are being handled correctly.

W. W. Lindstrom, B. D. Anderson, and E. F. Shrader

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[1] G. A. Jarvis, A. Hemmendinger, H. V. Argo, and R. F. Taschek, Phys. Rev. 79 (1950) 929-935.

[2] W. W. Lindstrom and E. F. Shrader, CWRU Progress Report, COO-1573-63, pp. 15-19 (1969).

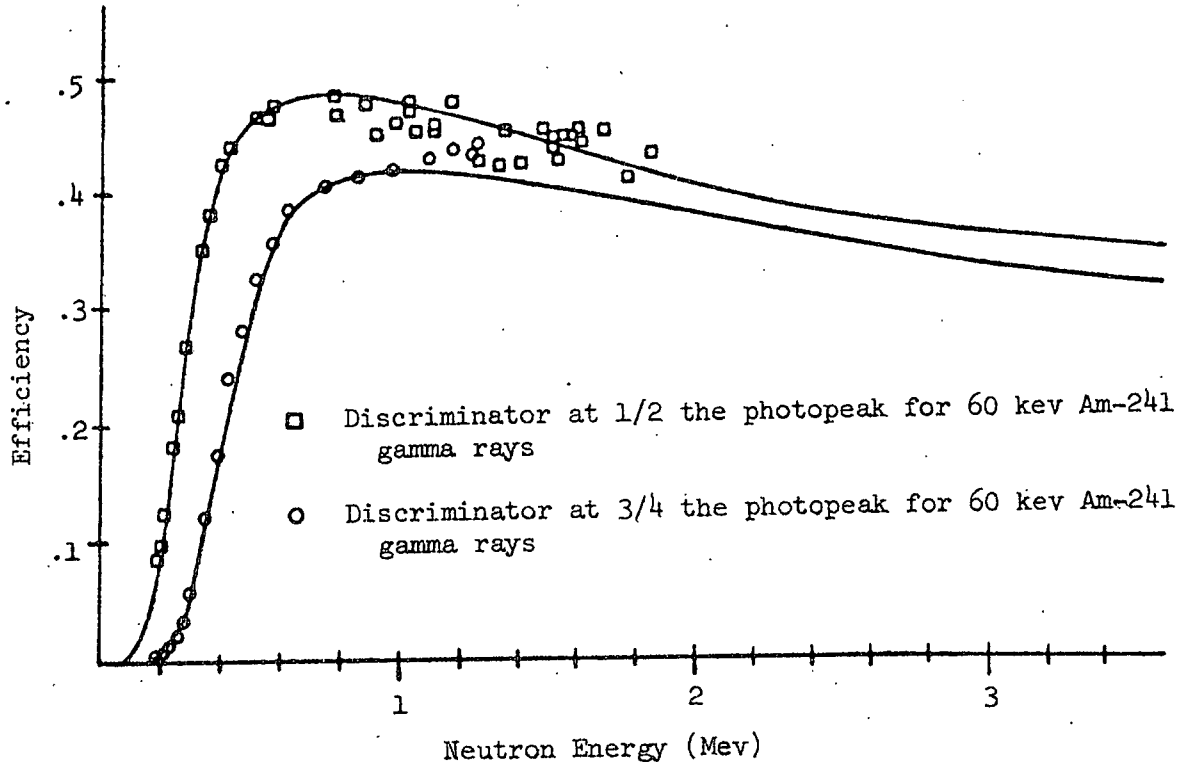

Figure 15. Comparison of measured relative efficiency (data points) and calculated absolute efficiency (solid lines) for a NE-102 detector, 5.08 cm dia. x 5.08 cm high cylinder unifromly illuminated perpendicular to its axis.

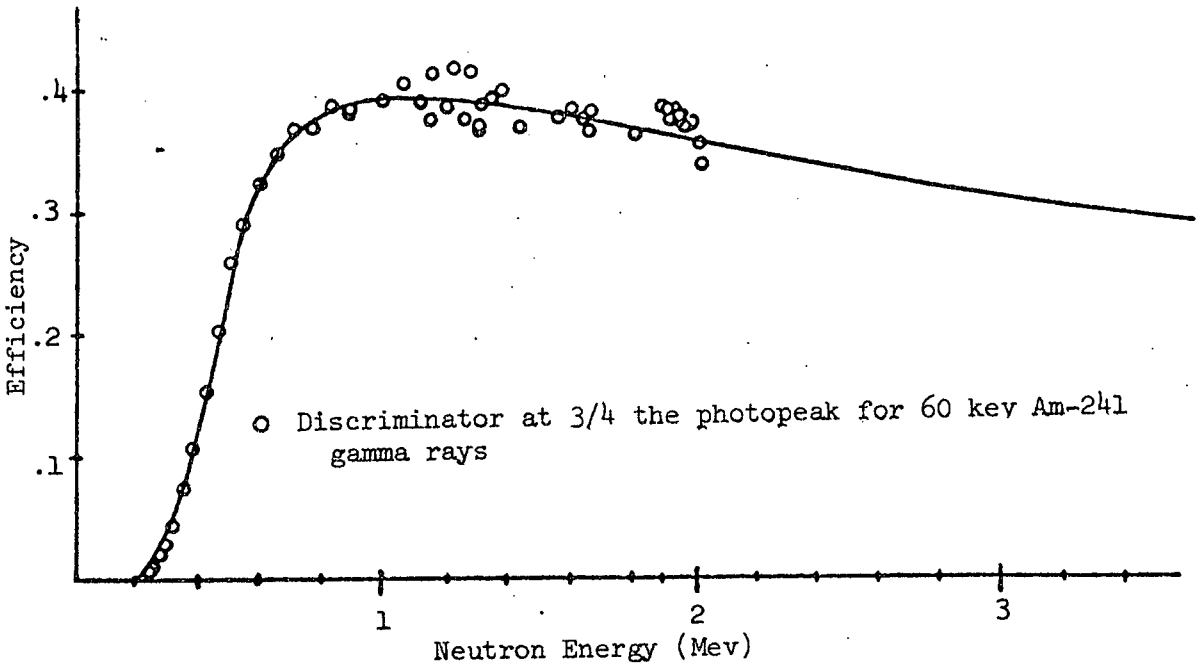

Figure 16. Comparison of measured relative efficiency (data points) and calculated absolute efficiency (solid line) for a NE-213 detector, 5.08 cm dia. x 5.08 cm high cylinder uniformly illuminated perpendicular to its axis.

17. Neutron-Gamma Discrimination

An existing n-γ discrimination circuit[1] is presently being modified in order to increase the efficiency of discrimination, cut the present count-rate dependency, and improve the circuit design.

Present work is centered about the feasibility of adding transistorized stacked emitter followers before the diode stretching networks in order to perserve pulse shapes from the dynode string, thus extracting the short and long time-constant components without distortions.

R. C. Nerbun, Jr. and P. R. Bevington

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[1]W. L. Rogers and E. F. Shrader, Nuclear Physics Report, (COO-1573-7) CIT, Nov. 1965 to Oct. 1966.

18. Photomultiplier Signal Processing

A transistorized tandem stacked emitter follower (based on the White cathode follower circuit) has been devised for feeding low-level linear signals into a 50-100 ohm coaxial cable. Output signal swing is ± 2 volts with a gain of .96, input impedance of 100 kΩ, output impedance of 2 Ω, and rise time of less than 4 nsec. A short paper has been submitted to Electronics.

Constant-Fraction Pulse-Height Discriminators based on a design of D. A. Gedcke and W. K. McDonald[1] have been constructed and successfully used in several of the experiments reported here.

R. A. Leskovec and P. R. Bevington

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[1]D. A. Gedcke and W. J. McDonald, Nucl. Instr. and Methods 58, (1968) 253.

19. Nuclear Instrument Module

A 1 MHz crystal clock has been constructed in a dual-width NIM package. Intended for general purpose timing applications, the clock contains divide-down circuitry to produce outputs of 1 MHz, 100 kHz, 10 kHz, 1 kHz, 100 Hz, 10 Hz, 1 Hz, and 0.1 Hz, with an additional 1-2-5 divider switch. Provisions are included to gate the oscillator pulses going into the divider for preset-count applications. The output circuitry can be gated for simple start-stop applications where it is necessary that the output state always be low when no pulses are coming out. Outputs of square waves and 100 nsec pulses are available, both with amplitude of +12 volts, DC coupled, series terminated for 50 Ω lines.

R. A. Leskovec

20. Accelerator Modifications

The operating range of the Van de Graaff accelerator has been extended from the previous upper limit of 3 MV by installing a new HVEC "stainless steel" accelerator tube with improved breakdown characteristics, and by the addition of SF_6 to the insulating gas. The new tube is now operational, permitting maximum machine voltages of over 4 MV. Beam focus and performance at high voltage have been improved by decreasing the voltage gradient across the top four sections of the tube by a factor of 2. An improved procedure for removing water vapor from the machine permits operation to 3.75 MV without the use of SF_6.

L. H. Hinkley

21. Accelerator Operations

An extensive effort was made to calibrate accelerator voltage with magnetic field and RF bunching settings, after installation of the new accelerator tube. Of special importance was the determination of the proper RF deflection for optimum bunching as a function of accelerator voltage for various ions. A program VDGCAL was written for the CWRUNCH computer to calculate (with relativistic corrections) and tabulate values of the NMR oscillator frequency associated with the flux of the analyzing magnet field for normally accelerated ions.

B. D. Anderson and R. C. Nerbun, Jr.

22. CWRUNCH PDP-9/L Computer

Work is progressing on providing communication between data-acquisition systems and the CWRUNCH (Case Western Reserve Nuclear Computation Handler) PDP-9/L computer.

A remote terminal has been installed in the Van de Graaff accelerator control room and consists of: A Tektronix Model 611 oscilloscope with control of storage mode and X- and Y-axis expansion, an IDIOT (Indicating Digitizer for Input/Output Transformations) switch panel, and a Model 33ASR teletypewriter. A means has been devised and installed to electronically switch the remote terminal teletypewriter to function as the main teletype of the computer. The remote terminal greatly facilitates reduction and analysis of data during the progress of an experiment and therefore provides improved quality control of experiments.

Interfacing of the high-speed paper tape reader at the remote terminal to the PDP-9/L computer has been completed.

R. A. Leskovec and P. R. Bevington

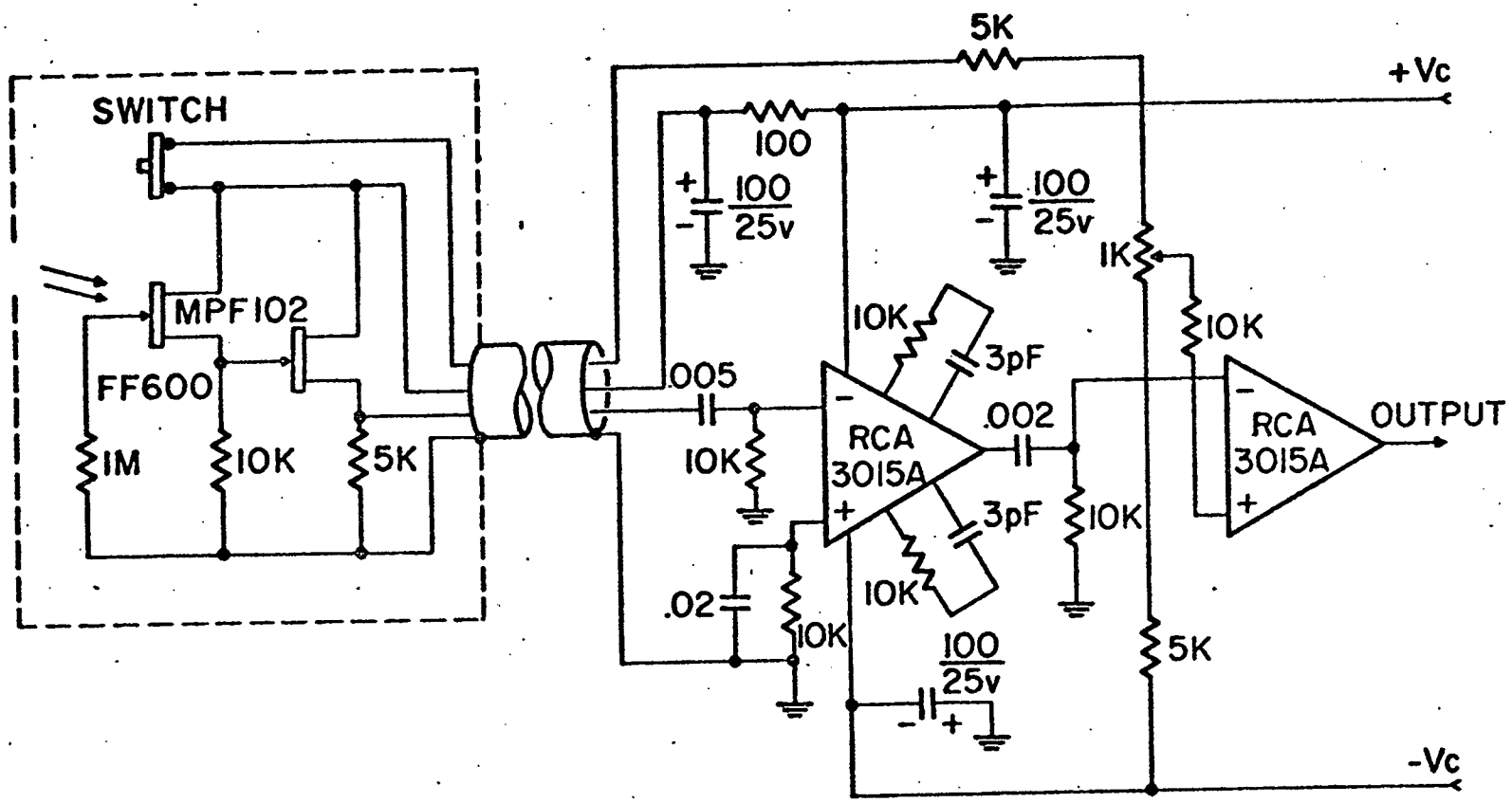
23. Solid State Light Pen

A completely solid state light pen has been developed for the CWRUNCH computer system which is compatible with the Tektronix 611 Storage Oscilloscope. A paper has been submitted to The Review of Scientific Instruments.

A Crystalonics FF600 PFET (photo-field-effect transistor) proved to be the best readily available detector for this application. The signal passes through an FET source-follower and is differentiated to minimize effects of slow phosphor decay and interference from 60 Hz fluorescent room lighting reflecting off the screen. As shown in Fig. 17 the signal is amplified by an RCA 3015A operational amplifier operating open loop with 70 dB gain. The peak output from this stage (150-300 mV) is still substantially a linear representation of the dot intensity. The signal is differentiated again and fed to a second 3015A operating as an open-loop comparator. A small amount of internal positive feedback inherent in the 3015A produces hysteresis in the comparator and minimizes oscillations while still exhibiting large gain. A switch located in the light pen probe enables the comparator by shifting the input bias positive to a preset threshold level. The comparator output is normally minus 2.4 V, swinging positive to 6.8 V during a pulse. This signal swing easily accommodates various output buffers such as the one shown in Fig. 18. The emitter follower drives 150 ft. of RG-62 cable between a remote terminal and the computer. Note that well regulated power supplies are not required, although adequate power supply decoupling is important.

The solid state light pen performs reliably without the need for specially selected or expensive components. It works equally well with the 611 oscilloscope in both the storage and non-storage modes under normal room lighting conditions. Performance has been optimized for the 611 through the choice of the FF600 gate resistor and the differentiation time constants.

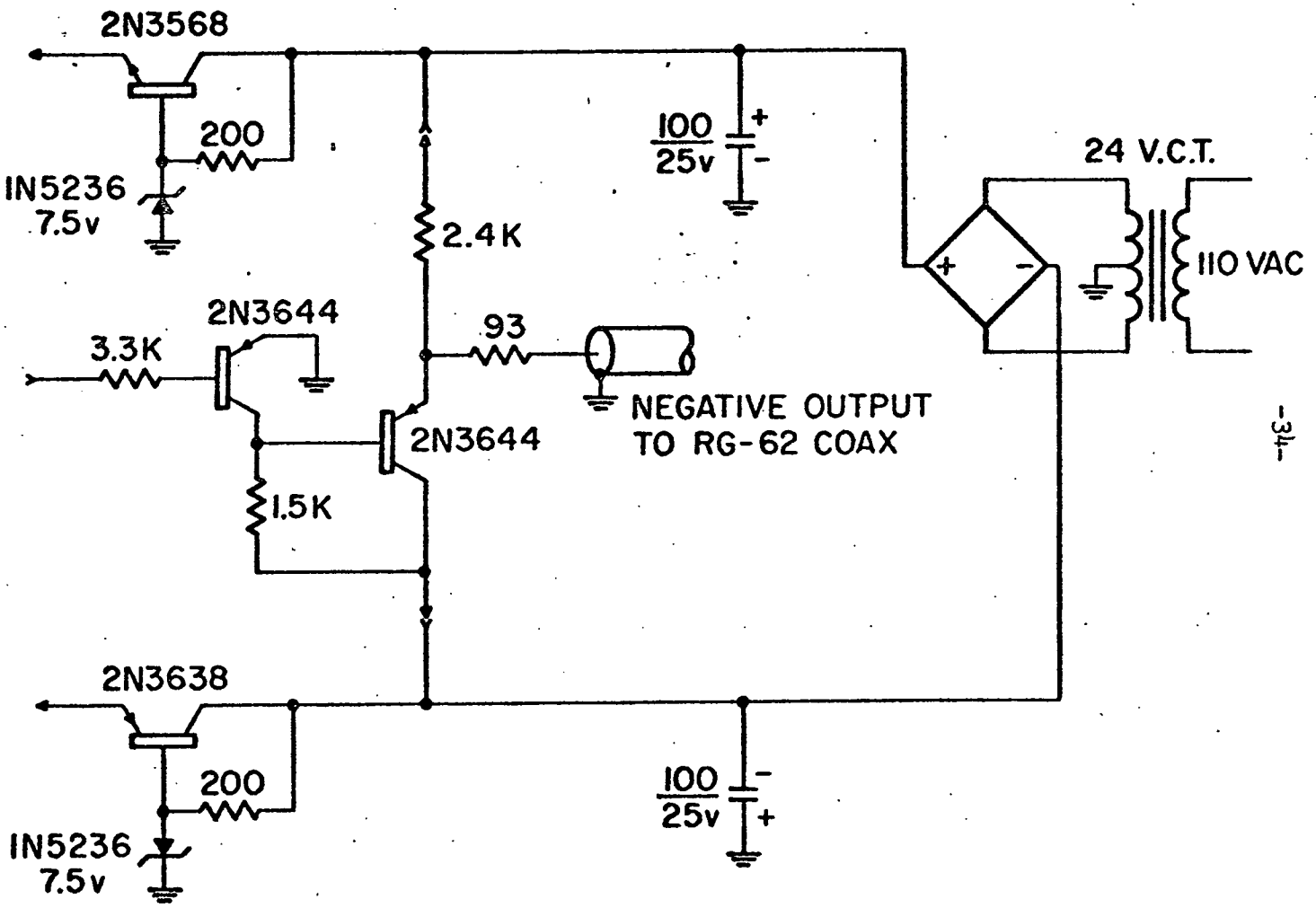
R. A. Leskovec and P. R. Bevington



SHIELDED PROBE ASSEMBLY

LINEAR AMPLIFIER

COMPARATOR



POWER SUPPLY AND NEGATIVE OUTPUT BUFFER.

THEORETICAL RESEARCH PROGRAM

THEORETICAL RESEARCH PROGRAM

1. Charged Gas in the Low Density Limit

Further calculations on Wigner lattices have now demonstrated that while a phase transition from a body-centered cubic to a face-centered cubic lattice does not occur at zero temperature as a result of increasing density, there does exist a line of coexistence in the density-temperature plane and hence the possibility of a direct phase transition from the former to the latter lattice at low densities but with increasing temperature. The coexistence line extends into the region where the validity of the harmonic approximation is established. Thus the direct phase transition must occur unless a third phase is stable over a region which entirely covers the line, in which case one can still assert that some phase transition must occur with increasing temperature at sufficiently low densities. The latent heat of the transition is very small, however. In view of the possibility that Wigner-like lattices may occur in white dwarfs and pulsars, the possibility of these phase transitions may be of astrophysical significance. A manuscript covering the work so far carried out in this area is nearly completed and will be submitted soon for publication. Further work on the hexagonal close-packed lattice is being considered.

L. L. Foldy

2. Electromagnetic Interaction of Composite Systems

The complete solution to the problem of the interaction of an arbitrary N-particle composite system with an external electromagnetic field appropriately expressed in terms of operators which can consistently be identified with non-relativisitic internal variables but correct to terms of order $(\text{mass})^{-2}$ has been obtained subject to the proviso that the effect of interaction between the particles is neglected. The result accommodates any spins, masses, charges, and magnetic moments for the particles, and orbital as well as spin magnetic moment contributions to the total magnetic moment of the system. The validity of the low energy theorem for Compton scattering and of the Drell-Hearn-Gerasimov sum rule has been established without explicit use of space inversion invariance. An account of these results has been published in Physical Review Letters, and detailed calculations are contained in the doctoral dissertation of one of the investigators (Richard A. Krajcik).

In order to extend the results to full compatibility with the effects of interaction between particles and to accommodate many-particle terms in the interaction (such as exchange current effects) a more direct way of testing a form than the full deduction of the low energy theorem appeared desirable. Since the basic problems which had arisen earlier in the work of Barton and Dombey and of Barton arose from a failure to treat internal

states of the system covariantly, one can isolate the problems by examining whether the implications of Lorentz invariance for the matrix elements of the charge and current between states of the system belonging to the same irreducible representation of the Poincare group are satisfied. (It was by this means that a proof of the low energy theorem by Lapidus and Kuang-Chao was constructed for particles of arbitrary spin.) That these conditions are satisfied for the charge and current density operators implied by our form of the electromagnetic interaction has been verified. A manuscript covering this latter work is in preparation.

It now appears that the fully consistent treatment of interaction between particles of the composite system to order $(\text{mass})^{-2}$ in dealing with the electromagnetic (and other external) interactions of the system can be achieved by the method employed by one of the authors (L. L. Foldy) previously to describe relativistic interacting particle systems. The extension to exchange and other many particle contributions to electromagnetic interactions as well as the possibility of extending the results to higher order in inverse mass remain to be explored.

R. A. Krajcik and L. L. Foldy

3. A Generalized Spin Algebra

Since the last Progress Report, the two papers entitled "Spin Algebras and the Poincare Group" and "The Poincare Group and the Lambda Representation" have both appeared in the Journal of Nuclear Physics.

H. J. Braathen and L. L. Foldy

4. Wigner Supermultiplet Model Applied to Nuclear Binding Energy Formulae

This work is directed toward an attempt to obtain the structure of a semi-empirical mass formula containing the maximum information available from symmetry of group state nuclear wave functions. The prime assumption is SU(4) symmetry for the spin-isospin part of the wave function while other approximate symmetries are taken to be consistent with the SU(4) structure. Assumptions about the detailed characteristics of nuclear forces are kept at a minimum. Most of the theoretical development is completed but the few remaining points are difficult to treat without complications inappropriate to the spirit in which the model is constructed. Complementing the theoretical development has been an analysis of up-to-date data on nuclear binding energies. An isobar-by-isobar analysis of the dependence of the binding energies on the SU(4) quantum numbers is largely completed. To extract Coulomb energy from the binding energy, current results on locations of isobaric analogue resonances are used; work on nuclei up to A = 40 has been completed. The remaining data analysis will be directed toward fitting the parameters of the obtained mass formula to experimental binding energy data between magic

numbers. It is expected that this work will provide information on the validity of the supermultiplet model and on the use of SU(4) quantum numbers for specifying the ground states of nuclei as well as yielding an effective semi-empirical mass formula for light nuclei.

R. E. Prael and L. L. Foldy

5. Multiple Resonance Scattering

As reported in the last Progress Report several models for multiple scattering of a projectile with the occurrence of resonances were studied including a potential model and the Lee model. For these cases there was no essential difference between results for the examples considered other than differences in kinematics. While the appropriate equations have been derived for the static model with several sources, the resultant equations have so far resisted any effort to solve them in a reasonable approximation. Thus the potentially important effects of crossing symmetry on resonance multiple scattering are not at all understood at the present time, nor is a clear approach to the problem presently available.

J. Thakur and L. L. Foldy

6. Study of the Migdal Theory for Finite Fermi Systems for Application to Coherent Nuclear Excitation Processes

The independent particle model of the nucleus fails to give an adequate account of nuclear phenomena in which an external probe coherently excites the nucleus to giant resonance states. Examples are photoabsorption, inelastic electron scattering, and ordinary as well as radiative muon capture. Shell model calculations with internucleonic interactions have demonstrated the important role of the latter in explaining some of these difficulties. Another proposed method for taking into account internucleonic interactions is Migdal's theory of finite Fermi systems, and, principally in the hands of Bunatyan, has also accounted for the removal of the difficulties with the independent particle model. Attempts to correlate the two approaches seems to indicate, however, that the Migdal theory has features which are quite substantially different from the shell model theory and in particular fails to reproduce the essential supermultiplet symmetry in O^{16} and Ca^{40} of the shell model picture. The objectives of the present investigation are to understand, if possible, the origin of these differences and to critically analyze the applicability of Migdal's theory to these phenomena in the light of the above results.

J. Thakur and L. L. Foldy

7. Observation of Nonlocal Effects in Nuclear Scattering

A paper with this title has been published in the Physical Review. Phys. Rev. C 1, 1924 (1970). The abstract of this paper follows: The question of how nonlocal effects might be observed in elastic scattering is investigated under the assumption that the interaction is describable by a Hamiltonian. The energy dependence of the real part of the forward scattering amplitude is related to a dynamic quantity with dimensions of length, which we refer to as the nonlocal distance. Possible off-energy-shell effects can be discussed in terms of this nonlocal distance. Work on this problem still continues.

R. M. Thaler and J. Monahan

8. Study of the T-Matrix Off the Energy Shell

The technique of employing unitary transformations to generate elastically equivalent interactions is being studied in detail. A number of new results have already been developed. The method of Baranger is also under critical investigation. Applications to nucleon-nucleon bremsstrahlung and the nuclear many body problem have been proposed and are under study. A critical discussion of current practices in the nuclear many body problem is in preparation. The role of invariance principles in elastic and inelastic scattering is also under investigation by these methods.

R. M. Thaler, C. M. Shakin and J. Monahan

9. Nucleon-Nucleon Scattering at LAMPF Energies

The general program described under this title in last year's Progress Report is still being carried out. The work reported in the entry which follows is a direct outgrowth of our interest in nucleon-nucleon scattering at LAMPF energies.

R. M. Thaler and J. T. Londergan

10. One-Pion Contribution to Neutron-Proton Charge-Exchange Scattering

This work has been published in Physical Review Letters 25, 1065 (1970). The abstract follows: Recent measurements of neutron-proton charge-exchange scattering showed a change in the behavior of the cross section at u=0, near the one-pion production threshold. The slope of the backward cross-section also increased rather rapidly, with a maximum also near the one-pion threshold. We point out that the on-pion-exchange (OPE) amplitude, interfering with a slowly varying amplitude at u=0 gives qualitatively the same behavior as observed in the experiments. A similar explanation has been suggested to account for the n-p charge-exchange data above 2 GeV.

J. T. Londergan and R. M. Thaler

11. Pion Electromagnetic Form Factor from π - ^{4}He Scattering

The use of $\pi^{\pm}$ - ^{4}He scattering to determine the pion electromagnetic form factor (or, more precisely, the second moment of the pion e.m. form factor) was suggested first by Sternheim and Hofstadter. SInce then, a few experimental measurements have been made, and the most recent and precise value obtained by the Berkeley group has been $r_\pi \simeq 3$ fm. This value, considerably larger than the vector dominance prediction of 0.6 fm, suggests that perhaps the electromagnetic effects are not being properly separated in the analysis of π - ^{4}He scattering. Christensen has suggested that inclusion of relativisitic off-shell effects may drastically alter the apparent value of the pion charge radius. The sensitivity of the pion charge radius to second-order corrections to the π - ^{4}He strong interaction, and the energy dependence of the relativistic effects, are now being examined. We hope that we will be able to show that the analysis of $\pi^{\pm}$ - ^{4}He elastic scattering at the higher LAMPF energies will be free of the ambiguities which hamper the lower energy work.

R. M. Thaler and J. T. Londergan

12. Reaction Theory Treatment of the One Dimensional Three Body Problem

As a first step in our program of applying the extended R-matrix formalism to the one dimensional three body problem with δ-function interactions, we have carried out a first order calculation of the T-matrix and the K-matrix. The derived transmission and knockout probabilities are compared with the exact values. The influence of the breakup channels were ignored. Our results indicate that the first order K-matrix treatment is a great improvement over the first order T-matrix treatment. The latter is just the usual distorted wave Born approximation. This shows that rescattering effects are important in three body processes and that the first order K-matrix calculation succeeds very well in describing them. We are now extending the calculation to include the effects of the breakup channels. These results are being reported at the October 15, 1970 meeting of the American Physical Society at Houston.

W. Tobocman, G. K. Tandon and D. Rodjak

13. Recoil Effects in Particle Transfer Reaction Calculations

Our finite range DWBA program for calculating particle transfer reaction cross-sections has been generalized to include certain recoil effects neglected in the original program. The local plane wave approximation was used for this purpose. Calculations with the modified program have been useful in verifying the validity of the no-recoil approximation for nucleon transfer between heavy ions. However, when applied to alpha particle transfer, the recoil effects prove to be so great that the local plane wave approximation cannot be trusted. Thus this approach has been abandoned for the time being. A laboratory report describing this work is being prepared.

F. Schmittroth and W. Tobocman

14. Neutron Transfer in the $^{13}C(^{14}N,^{13}N)^{14}C$ Reaction

We have used our finite range (no recoil) DWBA program for calculating the cross-section for the $^{13}C(^{14}N,^{13}N)^{14}$ reaction in the energy interval 12-20 MeV. Comparison with the experimental results of Toth and Gaedke at Oak Ridge is satisfactory above 14 MeV and should allow the determination of the neutron spectroscopic factor for ^{14}C. There is a discrepancy between theory and experiment below 14 MeV which we have not been able to explain.

W. Tobocman

15. Comparison of R-Matrix Nuclear Reaction Theories

A number of nuclear reaction formalisms were tested and compared by their application to a simple model of s-wave scattering from a two-state nucleus. These formalisms include the extended R-matrix theory of Garside and Tobocman, the Bloch-operator formalism of Lane and Robson, and variations of the Brown-de Dominicis theory. We find that the Hüfner-Lemmer version of the Brown-de Dominicis theory gives the best results in the few level approximation. A report on this work will be presented at the October 15, 1970 meeting of the American Physical Society at Houston, and an article has been submitted for publication in the Physical Review.

F. Schmittroth and W. Tobocman

16. ^{7}Be System Reaction Calculation

The scattering reactions of the ^{7}Be system are being calculated by means of a DWBA treatment of the K-matrix of the three body system $^{7}Be=\alpha+d+p$. Work is still confined to the determination of suitable elastic channel wave functions to be used in the reaction calculation.

H. Gintner and W. Tobocman

17. Shell Model Calculation of Ti^{49}

The energy levels and wave functions of ^{49}T have been calculated in the space of the (1f-2p) shell using the two body reaction matrix elements of Kuo and Brown. The log $f\tau$ for the β-decay of ^{49}Sc has been calculated. The spectroscopic factors for the pick-up reactions $^{50}Ti(p,d)^{49}Ti$ and $^{50}V(t,\alpha)^{49}Ti$ as well as for the stripping reaction $^{49}Ti(d,p)^{50}Ti$ have been calculated. The agreement with experiment was observed to be good. Attempts to improve the results by modifying the calculation are continuing.

A. J. Baltz, M. A. Nagarajan and W. Tobocman

18. Use of the Boundary Condition Constraint Method for Nuclear Bound State Calculations

The boundary condition constraint method (BCCM) of Nagarajan and Tobocman is a modification of the shell model method for doing nuclear structure calculations. The BCCM should be a useful method for calculating form factors needed for particle transfer calculations. A feasibility study was carried out using s-wave particles in square wells. The results were very encouraging. Application to ^{41}Ca and ^{42}Ca is being contemplated.

M. A. Nagarajan, F. Schmittroth and W. Tobocman

19. Extension of the Riemann Lebesque Lemma

This work has been completed and is accepted for publication in the Journal of Mathematical Physics. The abstract reads: The behavior of integrals of the form

$$\int_a^b f(x)[u(x)+e^{i\lambda x}]^{-1}\,dx$$

is discussed for large values of λ.

P. B. Kantor

20. High Energy Scattering from a Composite System

A preliminary note has been published in Physical Review Letters. The question of the validity of the eikonal limit for energy dependent potentials is now under examination. Abstract of Letter: We present a heuristic argument suggesting that at high energies the effect of multiple scattering off the energy shell becomes important for an understanding of the propagation of one elementary particle through another.

P. B. Kantor

21. Decays and Branching Ratios of the η

It was found that the high rate for $\eta \to 3\pi$ can be most readily discussed in terms of final states of mixed symmetry and the width Γ_η can be related to ρ-ω mixing and f_0-A_2 mixing using a 4π model of η. The results are described in the dissertation of K. A. Taggart, who is now in the Air Force. The subject is not presently under active investigation.

K. A. Taggart and P. B. Kantor

22. Algebra of Fields and the $\Delta(1690)$

Work on this problem has been suspended.

P. B. Kantor

23. The Detectability of Exact Symmetries

This work has been published in The Journal of Mathematical Physics under the title "Internal Symmetry Cannot Be Concealed." The abstract reads: We consider the problem of determining whether a given "particle" is elementary or is some member of a degenerate multiplet corresponding to an exact symmetry. We discuss a double-scattering experiment which can make this determination unless the members of the multiplet are unable to distinguish one another. Finally, such an inability is shown to be incompatible with the usual relation between spin and statistics and known analyticity properties of scattering amplitudes for strongly interacting particles.

P. B. Kantor

24. Internal Symmetry Breaking: Mass Terms

In an effort to understand the breaking of internal symmetry a classification of symmetry breaking has been proposed. The simplest form - breaking "only by masses" is presently under investigation.

P. B. Kantor

25. Spin Effects in Nucleon-Deuteron Scattering

An approximate, K-matrix calculation of elastic nucleon-deuteron (N-d) scattering has been completed including the effects of two-nucleon tensor forces. The essential approximation was to take as a K-matrix a sum of impulse and single-nucleon exchange graphs. This generates a N-d scattering amplitude which is exactly unitary below the breakup threshold and consistent with unitarity above this energy. The results of these computations, which were carried out using the simplest Yamaguchi type of N-N interaction, in the energy range from 11.0 to 40.0 MeV, are in reasonable agreement with the experimental elastic nucleon polarizations and N-d differential cross sections. These results represent the first self-contained predictions (i.e. assuming only the N-N interaction as known) of spin-correlation parameters in any multi-particle nuclear scattering problem except for relatively crude impulse approximation calculations (with deuterium targets).

Work is continuing on this problem with the following improvements and extensions in mind. Similar calculations will be carried out using a more

realistic representation of the N-N interaction; this will permit the consistent inclusion of higher N-N and N-d partial waves. In this connection, it is also planned to carry out an eigenphase analysis of the computed N-d partial wave amplitudes. Other elastic spin correlation parameters such as those connected with triple scattering experiments and tensor polarization will also be calculated. Finally, breakup reaction cross sections and associated spin correlation parameters will be computed. We remark that except for the elastic nucleon polarization very little experimental information relating to spin correlation phenomena exists either in the elastic or the breakup channels. It is hoped that these calculations will be of use in determining which out of the many possible spin correlation experiments will be most profitable in elucidating the dynamics of the three-nucleon system at least at energies below the threshold for pion production.

Some of this work has been published in Phys. Letters 31B, 263 (1970) and Phys. Rev. 2C, 1319 (1970).

K. L. Kowalski, J. Krauss and S. Pieper

26. Two Particle Resonance-Pole Dominance Approximations in Three-Particle Scattering

This work has now been published in Nuovo Cimento 67A, 523 (1970).

K. L. Kowalski and D. Bollé

27. Quasi-Unitary Three-Particle Approximations

This work has now been published in Phys. Rev. 188, 2235 (1969); see also the Erratum in Phys. Rev. D2, 812 (1970).

K. L. Kowalski

28. Analysis of Two-Particle Off-Shell Equations

A systematic analysis has been initiated of those features of two-particle off-shell scattering amplitudes which can be exploited in many-particle scattering and bound-state problems. Some of this work is primarily a synthesis of existing techniques particularly those by the present author cited in this Report in previous years. Some new results have been obtained in connection with various proposals for achieving finite-rank approximations and in dealing with amplitudes deriving from singular-core interactions.

K. L. Kowalski

29. Optimal Equations for Three-Particle Scattering

A class of equations has been derived for three-particle scattering for amplitudes corresponding to rearrangement and breakup reactions. In contrast to the usual formulations the unknowns in these equations are simple half-off-shell extensions of quantities which are linearly related to the physical amplitudes with no unphysical auxiliary amplitudes and no reference to the three-to-three process. A special case of these equations realizes in operator form the bound-state scattering equations originally derived by Faddeev using his comparatively complicated residue prescription. An incidental consequence of this last result is the unification of all the various operator formalisms for three-particle scattering and the S-matrix prescriptions of Faddeev and, in addition, the specification of a "natural" off-shell extension of the three-particle amplitudes. Another special case of this class of equations yields completely on-shell equations for the rearrangement (and, of course, bound-state elastic) amplitudes with the breakup amplitudes comprising the input. The associated form of the equations for the breakup amplitudes appears to be the most promising of all extant alternatives for performing exact calculations with arbitrary two-particle interactions. (This work has been submitted for publication in Annals of Physics.)

T. A. Osborn and K. L. Kowalski

30. Unitarization Techniques in Multi-Particle Scattering Problems

Some recent proposals for generating a set of amplitudes satisfying multi-particle unitarity from a corresponding set of amplitudes with no unitary cuts suffer from the defect of the neglect of all disconnected structure. The modifications necessary to include this structure and associated difficulties of non-Fredholm Heitler-type equations are now being investigated. Applications include a viable unitarity-ensuring K-matrix formalism for non-relativistic few-particle scattering problems and a more realistic technique for generating Regge cut structure in high energy two-particle reactions.

K. L. Kowalski

31. Thermodynamics of Systems with Internal Adiabatic Constraints

This work, which was described in the last Progress Report, has been published in the American Journal of Physics 38, 546 (1970).

H. S. Leff

32. Proof of the Third Law of Thermodynamics

The third law of thermodynamics is proved for a large class of Ising models with generalized ferromagnetic many-body interactions. A sufficient condition for the third law to hold is that the model have nearest neighbor couplings which are bounded from below by a positive constant. The proof is based on a spin correlation inequality of Griffiths which implies a corresponding inequality for the bulk entropy per spin. Ground state degeneracy considerations are completely avoided. This work has been accepted for publication in the Physical Review (Dec., 1970).

H. S. Leff

33. Correlation Inequalities for Coupled Oscillators

Correlations in a system of N classical, coupled-oscillators are studied, with a view toward obtaining a more complete understanding of Griffiths-type inequalities. The potential energy is assumed to be $U = \frac{1}{2} \Sigma_i \Sigma_j J_{ij} x_i x_j - \Sigma_k H_k x_k$, with $-\infty \leq x_i \leq \infty$ and $J_{ij} = J_{ji}$. The $N \times N$ matrix with elements $\{J_{ij}\}$ is assumed positive-definite. Sufficiency conditions for the correlation functions to satisfy Griffiths-type inequalities are found to be: (i) $K_{ij} \geq 0$ for all i, j, where $K = J^{-1}$ and (ii) $\Sigma_j K_{\ell j} H_j \geq 0$ for all ℓ. The class of systems obeying (i) and (ii) contains those for which $J_{ij} \leq 0$, $i \neq j$, and $H_k \geq 0$ for all k; these are direct analogs of Ising ferromagnets. It is proved that a necessary and sufficient condition for Griffiths-type inequalities to hold for arbitrary $\{H_k \geq 0\}$ is simply (i) above. The sufficiency conditions (i) and (ii) are broader than those available to date for Ising models (only the sufficiency condition of ferromagnetic coupling is known). The necessary and sufficient condition (i) has no known Ising counterpart at present. This work has been accepted for publication in the Journal of Mathematical Physics.

H. S. Leff

34. The Infinite-Spin Limit of the Quantum Heisenberg Model

The canonical partition function $Q(\vec{H},N,s)$ for a spin-s anisotropic Heisenberg model with N sites, in external magnetic field $\vec{H}$, is examined in the limit $s \to \infty$. The coupling coefficients and the magnetic moment per spin are taken to be inversely proportional to s^2 and s, respectively. It is proved that

$$\lim_{s\to\infty} s^{-N} Q(\vec{H},N,s) = (2\pi)^{-N} Q(\vec{H},N),$$

where $Q(\vec{H},N)$ is the partition function for a corresponding classical Heisenberg model with spins of unit magnitude. This theorem makes precise the widely believed, but heretofore unproved equivalence between the classical Heisenberg

model and the infinite-spin limit of the quantum Heisenberg model. No appeal to the thermodynamic limit is necessary.

K. Millard and H. S. Leff

35. Statistical Mechanics of the Long-Range Anisotropic Heisenberg Model

See "Phase Transitions for the Anisotropic Heisenberg Model" below.

M. Flicker and H. S. Leff

36. Statistical Mechanics of Spin Systems with Kac Potentials

See "Phase Transitions for the Anisotropic Heisenberg Model" below.

K. Millard and H. S. Leff

37. Phase Transitions for the Anisotropic Heisenberg Model

The results of the previous two entries have been combined in a single manuscript whose abstract reads: The long range, anisotropic Heisenberg model is solved exactly for three cases: (i) Quantum spin-½ systems with constant couplings between all spins; (ii) Classical spin systems with constant couplings between all spins; (iii) Classical spin systems with Kac-couplings. In each case, the thermodynamic behavior is Ising-like if the coupling for spin components parallel to an external magnetic field H dominates, or if H is sufficiently large. If the coupling for spin components perpendicular to H dominates, and if H and the temperature are sufficiently small, an interesting second order phase transition occurs across a phase boundary line in the temperature-field plane.

H. S. Leff, K. Millard and M. Flicker

38. Studies of Local Pressures for Finite Systems

The work described in the last Progress Report has been extended in both breadth and depth. The local pressure definition based on a physical model entailing a pressure sensor (spherical cavity) has led to the following results: (i) The hydrodynamic momentum equation is satisfied for "macroscopic" cavity size and for sufficiently weak external fields. (ii) The low density limit of the local pressure satisfies the barometer formula for sufficiently low external fields. (iii) The local pressure of an almost incompressible fluid is obtained for sufficiently weak fields. (iv) The ranges of validity for results (i)-(iii) above are established using a functional Taylor series expansion of the one- and two-particle canonical distribution functions.

(v) Miscellaneous results have been obtained for the limiting case of "microscopic" cavity size, for the case of pure hard sphere molecular, and for a two phase system separated by an interface.

J. Czika and H. S. Leff

39. Applications of the Microcanonical Ensemble

A final draft of this work, mentioned in the last Progress Report, has not been completed yet. Work on this manuscript has been laid aside in favor of other problems which are of greater current interest.

H. S. Leff

40. Postulational Approach to Entropy: An Analogy with Potential Energy

This work, which was described in the last Progress Report is still in rough draft form.

H. S. Leff

41. Correlations in Lattice and Continuum Classical Fluids

Correlation inequalities, which are similar to Griffiths' inequalities for Ising ferromagnetis, are being investigated for both lattice gases and continuum fluids. This work is in its initial stages. One preliminary result is the following. Consider two classical, continuum fluids with Hamiltonians $H_A=K+W_A$ and $H_B=K+W_A+J\Phi$ (K = kinetic energy, W_A = potential energy, $J\Phi$ = potential energy, $J \geq 0$). Then a sufficient condition for the corresponding entropies S_A and S_B to satisfy $S_B \leq S_A$ is that Φ and W_A be correlated positively (i.e., have positive covariance).

H. S. Leff

42. Intermediate Structure and the Giant Dipole Resonance

Several states which may be described as three-Boson states ($J=1^-$, $T=1$) are found to lie in the energy region spanned by the giant resonance in O^{16}. The coupling of these modes to the giant resonance is considered with the aim of explaining the complex structure of this resonance. The giant resonance is considered to be a doorway both for the electromagnetic transition and the particle emission to the continuum.

C. Shakin and W. Wang

43. Theory of Analog Resonances

An extensive review article is being prepared on the theory of analog resonances. Many topics are treated including extraction of spectroscopic factors, compound contributions to escape amplitudes, direct channel coupling, Coulomb displacement energies, isotopic spin purity, etc. Useful tables of theoretical single particle escape amplitudes, absorption widths, continuum shifts, etc. will be included and application will be made to the barium, strontium and lead nuclei.

C. Shakin, N. Auerbach, J. Hüfner and
A. K. Kerman

44. Channel Coupling and Isobaric Analog Resonances

Work is in progress dealing with the effects of direct channel coupling on the calculation of escape amplitudes. Corrections to spectroscopic factors extracted from the analysis which neglects these effects will be made. Application will be made to Sr^{88} (p,p') Sr^{88} using a particle - core model to describe the parent states.

C. Shakin and M. Saraceno

45. Photo-Disintegration of Pb^{208} Near Threshold

The threshold photo-disintegration of Pb^{208} and the thermal neutron capture by Pb^{207} is considered. It is shown that the magnitude of the thermal capture and the asymmetry of the resonance observed in the (γ,n) reaction at ~ 40 KeV above threshold may be explained by extrapolating the giant resonance amplitude and the amplitude of a sub-threshold resonance into the appropriate energy domains. It is found that the direct (optical) processes are unimportant as compared to the effects of the "resonance tails." A paper describing this work will appear in the Physical Review.

C. Shakin and M. Weiss

46. Single-Particle Resonances in the Unified Theory of Nuclear Reactions

A method for the treatment of single-particle resonances in the theory of nucleon-nucleus scattering is introduced which finds application in the projection operator theory of Feshbach. The method is described in a letter appearing in Physics Letters.

C. Shakin and W. Wang

47. On-Shell Equivalent Potentials and Nuclear Matter

An investigation of the properties of nuclear matter (binding energy, density, single-particle energies, etc.) for various potentials that yield the same on-shell nucleon-nucleon scattering has been started.

C. Shakin and H. C. Pradhan

48. Continuum Effects in Nuclear Structure Calculations

Nuclear structure calculations are usually made with harmonic-oscillator wave functions. This approximation is expected to be poor for single-particle states in the continuum. The effects of using more self-consistent wave functions is being investigated for core-polarization corrections to two-particle spectra. Various reaction matrices will be used.

C. Shakin and H. C. Pradhan

49. Higher Order Corrections in the Axial-Vector Ward Identity Anomaly

Work is in progress on the explicit evaluation of higher order radiative corrections to the anomaly found in lowest order in the Ward identity for the spinor field axial-vector current. The existence or non-existence of such corrections is crucial for the question of whether or not the π^0 decay lifetime can be reliably predicted. That argument which presents strong interactions as an infinite set of Feynman diagrams in, say, the σ - model yields an excellent prediction for this lifetime provided that the aforementioned higher order corrections do not contribute to the anomaly.

R. W. Brown, B. L. Young and T. F. Wong

50. Photon-Photon Scattering and Colliding Electron Beam Experiments

We have recently found that one of the dominant channels in a coincident study of high energy $e^- - e^-$ colliding beams for large energy loss and small scattering angles is related to total photon-photon cross sections. The importance of this is the possibility of extracting heretofore unknown information about one remaining electrodynamic enigma: the scattering of photons by photons. A major complications is the need for calculations of several competitive processes which would interfere experimentally - which we are at present performing.

R. W. Brown and I. J. Muzinich

51. The Intermediate Boson II. Signature Muon Spectra in High Energy Neutrino Experiments

We have calculated the angular and energy distributions for the W-boson and the muons in the reaction $V + Z \rightarrow Z + W + \mu$ including the subsequent decay $W \rightarrow \mu + \nu$. We considered the effects of the W's anomalous magnetic moment and the deep inelastic incoherent contributions. The emphasis was on the energies that will be available at the new National Accelerator Laboratory. A report of these results is in preparation and will be submitted to the Physical Review.

R. W. Brown and J. Smith

52. Three-Body Decays of ${}^{4}_{\Lambda}H$

An investigation of the decays of ${}^{4}_{\Lambda}H$, to final state π + N + nucleus, was published under the title "A Simple Model for the Three-Body Decays of ${}^{4}_{\Lambda}H$" in Nuclear Physics B16, 109 (1970). In this paper, a two-channel reaction matrix model was used to take into account the p-${}^{3}H$ and n-${}^{3}He$ final-state interactions, and the qualitative features of the existing experimental decay spectra were in good agreement with the calculated values. Since publication of this paper, the statistics on the experimental data have been improved, and the new results differ significantly from both the old spectra and from the predictions of the model. The reaction-matrix model is being re-examined to see if the present data are at all compatible with the decay process assumed for ${}^{4}H$.

J. T. Londergan

53. The Λ-N Spin-Orbit Force

Differential cross-sections and polarization in Λ-${}^{4}He$ scattering have been calculated, using a phenomenological central potential and a spin-orbit potential obtained form the Λ-N spin-orbit force. Both differential cross-sections and the polarization were found to be large, and may be amenable to experimental measurement. The results obtained were quite different from results calculated by Gibson and Weiss, who used a Hartree-Fock calculation of Λ-${}^{4}He$ scattering. The approximations used by Gibson and Weiss have been reviewed and the reasons for the discrepancy in the two results have been examined. This work has been completed and submitted for publication in the Physical Review.

J. T. Londergan and R. H. Dalitz

54. Variational Calculation of Three-Body Scattering Amplitudes

A variational formulation of the Faddeev Equations for three-body scattering has been formulated. It has the advantage that even for positive total energies the only non-square-integrable behavior of the trial wave functions is that encountered in the two-body Kohn principle. This is a vast simplification over the asymptotic behavior of the usual three-body wave function. Both elastic and breakup calculations have been made for S-wave scattering using separable potentials of the Yamaguchi type. They have been quite successful and justify further work with this technique. We are currently modifying the program to handle more complicated separable potentials and non-zero orbital angular momentum. We will also include the effects of spin. This work is reported in "Variational Principle for Three-Particle Scattering," Physical Review D1, 1674-1681 and in an article accepted for publication in the Physical Review.

J. Wright, L. Schlessinger and S. C. Pieper

55. Charge Asymmetry in the η Decay

This work has been completed and is accepted for publication in the Physical Review. We have considered the problem of the asymmetry observed in the decay $\eta \to \pi^+ \pi^- \pi^0$. Bernstein, Feinberg and Lee suggested that an asymmetry in the average energies of the charged pions in this decay would be proof of C violation in the electromagnetic interaction among hadrons. Recall, however, that the η is identified as a peak in the invariant mass distribution of three pions from a reaction like $\pi^- p \to \pi^+ \pi^- \pi^0 n$. Yuta and Okubo proposed that the observed effect is due to interference between the η channel for this reaction and direct 3π production background processes. We have calculated the background size and its possible contributions to the asymmetry using a simple model which takes into account only tree (no closed loops) diagrams with constant vertices and ignores the effects of spin. We can account for 40% of the background observed in the experiment of Gormley et al. but find that the largest asymmetry which can be produced through interference is 10^{-5}, as compared to the experimentally observed 1.5×10^{-2}. We conclude that if the observed asymmetry persists, then charge conjugation invariance is violated by the decay. These results agree with the analysis of Stein of the experimental background. He concluded that the background could account for an asymmetry of no more than 2.7×10^{-3}.

K. Taggart

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PUBLICATIONS

Published Papers

1. D. Bollé and K. L. Kowalski, "Two-Particle Resonance-Pole Dominance Approximations in Three-Particle Scattering", Nuovo Cimento 67A, 523 (1970).

2. H. J. Braathen and L. L. Foldy, "Spin Algebras and the Poincare Group", Nuclear Physics B13, 511 (1969).

3. H. J. Braathen, "The Poincare Group and the Representation", Nuclear Physics B15, 477 (1970).

4. R. W. Brown, "Comparison of the Scattering of Electrons and Positrons from Protons at Small Angles", Phys. Rev. D1, 1432 (1970).

5. R. W. Brown, "Neutrinos versus Muons in W-boson Production", Phys. Rev. Letters 25, 257 (1970).

6. D. A. Giltinan and W. Tobocman, "One-Meson-Exchange Calculation of the $\pi + k \rightarrow \rho + k$ Reaction", Phys. Rev. 185, 1849 (1969).

7. P. Kantor, "Internal Symmetry Cannot be Concealed", J. Math. Phys. 11 #6 (1969).

8. P. Kantor, "Possible Difficulty with the Eikonal Picture of High Energy Interactions", Phys. Rev. Letters 24, 1081 (1970).

9. A. Kosiara and H. B. Willard, "Gamma Ray - Neutron Branching Ratio in the Triton - Deuteron Reaction", Phys. Letters B32, 99 (1970).

10. K. L. Kowalski, "Quasi-Unitary Three-Particle Approximations", Phys. Rev. 188, 2235 (1969). See also Erratum in Phys. Rev. D2, 812 (1970).

11. R. A. Krajcik, "Electromagnetic Interactions with an Arbitrary Loosely Bound System", Phys. Rev. Letters 24, 545 (1970).

12. J. Krauss and K. L. Kowalski, "Polarization in Elastic Nucleon-Deuteron Scattering", Phys. Letters 31B, 263 (1970).

13. J. Krauss and K. L. Kowalski, "Polarization in Elastic Nucleon-Deuteron Scattering", Phys. Rev. 2C, 1319 (1970).

14. H. S. Leff, "Thermodynamics of Systems with Internal Adiabatic Constraints", Amer. J. Phys. 38, 546 (1970).

15. J. T. Lindow, P. Boschung and E. F. Shrader, "Absolute Normalization of Neutron Scattering Cross Section Data Using Organic Scintillators as Scatterers", Nucl. Instr. and Methods 85, 151 (1970).

16. J. T. Londergan, "A Simple Model for the Three-Body Decays of $^{4}_{\Lambda}H$", Nuclear Physics B16, 109 (1970).

17. J. T. Londergan and R. M. Thaler, "One-Pion Contribution to Neutron-Proton Charge-Exchange Scattering", Phys. Rev. Letters 25, 1065 (1970).

18. H. Meldner and C. M. Shakin, "Rearrangement Effects and the Parametrization of the Effective Field in Nuclei", Phys. Rev. Letters 23, 1302 (1969).

19. F. Schmittroth, W. Tobocman, and A. A. Golestaneh, "Calculations on Nuclear-Transfer Reactions Between Heavy Ions", Phys. Rev. C1, 377 (1970).

20. F. Schmittroth and W. Tobocman, "Addendum to Three-Particle Channels in Nuclear Reaction Theory", Phys. Rev. 187, 1735 (1969).

21. W. Wang and C. M. Shakin, "Single-Particle Resonances in the Unified Theory of Nuclear Reactions", Phys. Letters 32B, 421 (1970).

Accepted for Publication

1. R. W. Brown and J. Smith, "The Intermediate Boson I. Total Production Cross Section in High Energy Neutrino and Muon Experiments" (Phys. Rev.).

2. P. Kantor, "Extension of the Riemann Lebesque Lemma" (J. Math. Phys.).

3. H. S. Leff, "Proof of the Third Law of Thermodynamics for Ising Ferromagnets" (Phys. Rev.).

4. H. S. Leff, "Correlation Inequalities for Coupled Oscillators" (J. Math. Phys.).

5. C. M. Shakin and M. S. Weiss, "Threshold Photodisintegration of Pb^{208} (Phys. Rev.).

Submitted for Publication

1. "Scattering of Fast Neutrons by ^{12}C, ^{54}Fe, ^{58}Ni and ^{60}Ni", P. Boschung, J. T. Lindow and E. F. Shrader (Submitted for Publication to Nuclear Physics).

2. "The Infinite-Spin Limit of the Quantum Heisenberg Model", H. S. Leff and K. Millard (Submitted for Publication to J. Math. Phys.).

3. "A Solid-State Light Pen and Computer Interface for the Tektronix 611 Storage Oscilloscope", R. A. Leskovec and P. R. Bevington (Submitted for Publication to Rev. Sci. Instr.).

4. "A High Performance Linear Emitter Follower", R. A. Leskovec and P. R. Bevington (Submitted for Publication to Nucl. Instr. and Methods).

5. "Spin-Orbit Coupling for Λ-^{4}He Scattering Using a One-Boson Exchange Model for the ΛN Interaction", J. T. Londergan and R. H. Dalitz (Submitted for Publication to Phys. Rev.).

6. "Optimal Equations for Three-Particle Scattering", T. A. Osborn and K. L. Kowalski (Submitted for Publication to Annals of Physics). See also SLAC-PUB-812, 1970.

7. "Comparison of the R-Matrix Nuclear Reaction Theories", F. Schmittroth and W. Tobocman (Submitted for Publication to Phys. Rev.).

Theses

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