Resonance Detection of Neutron Energy Groups from the $Mn^{55}(p,n)Fe^{55}$ Reaction*†

L. L. LEE, JR., AND F. P. MOORING
Argonne National Laboratory, Lemont, Illinois
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The excitation energies of low-lying levels in Fe^{55} and the Q-value of the $Mn^{55}(p,n)Fe^{55}$ reaction have been measured by determining the proton energies at which 257-kev neutrons are produced in this reaction. The ratio of the number of neutrons scattered by a $\frac{1}{2}$-inch thick lithium slab to the number of neutrons transmitted was measured as the energy of a proton beam striking a thin manganese target was varied monotonically. Peaks in the ratio curve, indicating the presence of 257-kev (the energy for resonant neutron scattering from lithium) neutron groups from the reaction, occur at particular proton energies, and Q-values can readily be computed. A ground-state Q-value of (-1.011 ± 0.005) Mev has been measured for the $Mn^{55}(p,n)Fe^{55}$ reaction and states in Fe^{55} were located at excitations of 437, 936, 1315, 1414, and 2156 kev. Advantages and limitations of the method are discussed.

INTRODUCTION

THE low-lying excited states of nuclides with medium atomic weights have been the subject of numerous experimental studies. One technique which has had considerable success in making precise energy assignments is the detection of slow neutron thresholds by means of the "counter ratio" method.[1,2] In the present experiment a new method, which is able to eliminate some of the difficulties encountered in the "counter ratio" method, has been used to study levels in Fe^{55} by means of the reaction $Mn^{55}(p,n)Fe^{55}$.

Energy levels in Fe^{55} can be studied in the reactions $Mn^{55}(p,n)Fe^{55}$ and $Fe^{54}(d,p)Fe^{55}$ and from the β^+-decay of Co^{55}. For the former reaction, the neutron energies have been measured by Stelson and Preston[3] by means of photographic emulsions and by Elwyn *et al.*[4] using time-of-flight techniques. Slow neutron thresholds have been observed by Chapman and Slattery[5] for excitations above 900 kev and by Gossett and Butler[6] for excitations below 1.0 Mev. Both of these experiments used the counter ratio method[1,2] to detect the thresholds. The gamma rays following the $Mn^{55}(p,n)Fe^{55}$ reaction have also been studied by Lobkowicz *et al.*[7] using scintillation counter techniques. Although the results are generally consistent, there are still some differences between experiments. Sperduto and Buechner[8] have used magnetic analysis to study the proton groups from the $Fe^{54}(d,p)Fe^{55}$ reaction and report 33 levels in Fe^{55} below 4-Mev excitation. These include all levels observed in the (p,n) reaction studies plus many previously unobserved levels. Studies[9–11] of the β^+ decay of Co^{55} agree in part with the other studies of nuclear reactions, although several states are not populated in the β-decay interaction.

EXPERIMENTAL METHOD

The counter ratio method[1,2] of detecting slow neutron thresholds depends on the fact that a nearly bare BF_3 proportional counter is preferentially sensitive to neutrons of quite low energy. A rise in the ratio of counts in a bare BF_3 counter to counts in a counter whose efficiency is roughly the same for all neutron energies (e.g., a "long counter"[12]) may be observed in a neutron-producing reaction as the bombarding energy is increased. This rise in the ratio curve is attributed to the emergence of a new group of low-energy neutrons from the reaction, and therefore indicates the threshold for excitation of a particular state in the residual nucleus. The use of this ratio measurement greatly reduces, but does not completely eliminate, the effects of resonances in the yield from the neutron-producing reaction. Over these resonances the neutron spectrum and angular distribution, as well as the total neutron yield, may change sharply. Since the yield of a particular neutron group near its threshold may be much less than that of higher-energy groups, these resonance effects may introduce false rises in the ratio curve or mask the observation of true thresholds. Some of the difficulty can be eliminated by observing the behavior of the ratio curve for targets of various thicknesses[13] but this is not completely successful.

The present method makes use of a different type of energy-sensitive neutron detector. A diagram of the

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† A preliminary report describing this technique was given at the Thanksgiving Meeting of the American Physical Society, Chicago, 1956 [F. P. Mooring and L. L. Lee, Jr., Bull. Am. Phys. Soc. 1, 327 (1956)].
1 T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).
2 Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955).
3 P. H. Stelson and W. M. Preston, Phys. Rev. **82**, 655 (1951).
4 Elwyn, Landon, Oleksa, and Glasoe, Phys. Rev. **112**, 1200 (1958).
5 R. A. Chapman and J. C. Slattery, Phys. Rev. **105**, 633 (1957).
6 C. R. Gossett and J. W. Butler, Phys. Rev. **113**, 246 (1959).
7 Lobkowicz, Guhl, and Marmier, Helv. Phys. Acta **31**, 320 (1958).
8 A. Sperduto and W. W. Buechner, Bull. Am. Phys. Soc. **1**, 223 (1956). Also A. Sperduto (private communication).
9 M. Deutsch and A. Hedgran, Phys. Rev. **75**, 1443 (1949).
10 R. S. Caird and A. C. G. Mitchell, Phys. Rev. **94**, 412 (1954).
11 Mukerji, Dubey, and Malik, Phys. Rev. **111**, 1319 (1958).
12 A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
13 Butler, Dunning, and Bondelid, Phys. Rev. **106**, 1224 (1957).

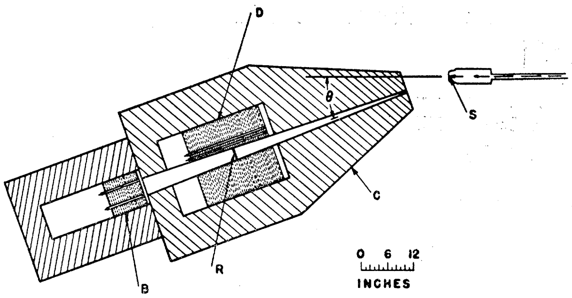

FIG. 1. Experimental arrangement. Neutrons from target *S* are collimated by collimator and shield *C*. The lithium scatterer is placed at *R* and is surrounded by a ring of BF_3 counters *D* embedded in paraffin. Neutrons not scattered by *R* are detected in *B*, another array of BF_3 counters in paraffin.

experimental arrangement is shown in Fig. 1. Monoenergetic protons from the Van de Graaff generator induce a (p,n) reaction in a thin target at *S* and thereby give rise to monoenergetic neutron groups. As the proton energy is increased the energy of each neutron group increases by a corresponding amount. Neutrons from *S* are collimated into a beam by collimator *C* and are allowed to strike a resonant scatterer *R*. Neutrons scattered from *R* are detected by a ring of counters *D* while neutrons transmitted through *R* are detected by neutron counter *B*.

Ideally for this method, the scatterer *R* should be a material whose neutron cross section consists of a single sharp resonance (at a neutron energy of several hundred kev) superimposed upon a small potential-scattering cross section which is almost independent of neutron energy. When none of the neutron groups from the target have the resonant energy, the ratio of scattered neutron flux (counts in *D*) to transmitted neutron flux (counts in *B*) will remain constant, independent of resonances in the reaction producing the neutrons. However, as the energy of a particular neutron group passes through the resonant energy for neutron scattering in *R* there will be an increase in the measured ratio because of the increased scattering and decreased transmission of the particular neutron group. The magnitude of this fluctuation in the ratio will depend on the strength of the neutron group relative to other groups from the target as well as the thickness of the resonant scatterer. Knowing the resonant neutron energy and the bombarding proton energy, one can easily calculate the *Q*-value for the reaction producing the particular neutron group.

In practice no material has the ideal neutron cross section described above. However, the cross section of lithium comes very close to satisfying these requirements. The neutron cross section of lithium has a single scattering resonance with a width of about 25 kev at a neutron energy of about 257 kev.[14] The cross section at resonance is $\sim$12 barns while the nonresonant cross section increases gradually from about 1 barn at low neutron energies to about 2 barns at 3 Mev. No other materials come as close to satisfying the resonance requirements, so lithium was used as the resonant scatterer in the present experiment.

Collimating the neutrons from the reaction allows one to count only neutrons leaving the target at a particular angle to the incident proton beam. Because of the motion of the center of mass of the reacting system, the energy of the emergent neutrons varies appreciably with angle when energetic protons interact with nuclei of low or medium atomic weight. This variation of neutron energy with angle can be used to eliminate false rises in the ratio which may be due to resonances in the total neutron yield from the reaction rather than to the emergence of a new neutron group of the proper energy. If observations are made at two widely separated angles, a change in the counting ratio corresponding to a true neutron group will be observed at a lower bombarding energy in the forward direction than at larger angles. On the other hand, the effects of resonances in the neutron-producing reaction will be observed at the same bombarding energy for all angles of observation. It is then quite easy to compare ratio curves taken at two angles and determine which effects are due to true neutron groups and which are due to resonances in the yield of the (p,n) reaction.

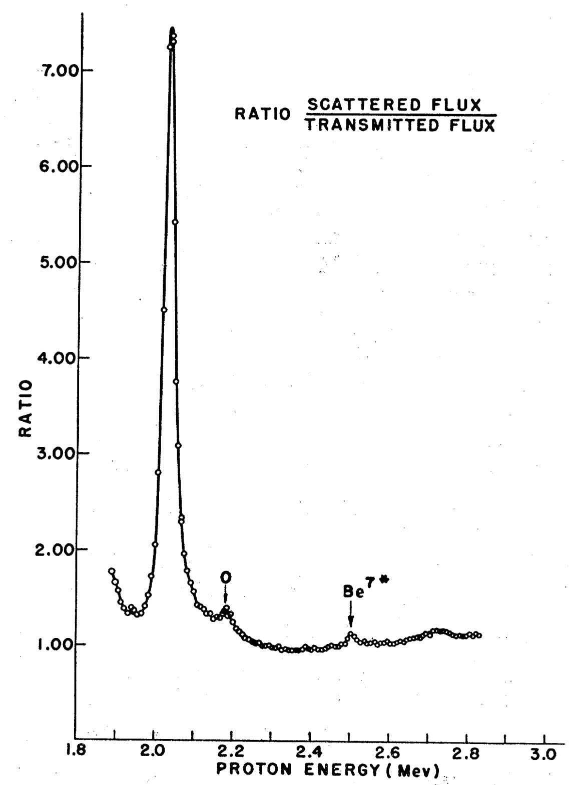

FIG. 2. Ratio of scattered to transmitted neutron flux as a function of proton energy for a $Li^7(p,n)Be^7$ neutron source. The detector was set at 0° relative to the incident proton beam and the target was about 5 kev thick for 2.0-Mev protons.

[14] C. T. Hibdon (private communication).

The measurements to be described here were made with the large shielded neutron detector which has been used for some time at Argonne for the measurement of neutron transmission cross sections.[15] As shown in Fig. 1, neutrons from the target were scattered by a lithium slab into a shielded ring of BF_3 proportional counters embedded in paraffin, while neutrons transmitted through the lithium were counted by another shielded cluster of BF_3 counters in paraffin. The resonant scatterer was a slab of lithium $2\frac{7}{8}\times7\frac{1}{4}\times\frac{1}{2}$ in. thick having a transmission of approximately 50% at resonance. This lithium was greased with vaseline and wrapped with thin Mylar tape to prevent oxidation of the lithium.

RESULTS

In order to test the method, the $Li^7(p,n)Be^7$ reaction was first used as the source of neutrons. This reaction produces a strong group of neutrons associated with production of Be^7 in its ground state and a much weaker group associated with its 430-kev excited state. Figure 2 shows a plot of the ratio of scattered neutron flux to transmitted flux at 0° for the $Li^7(p,n)$ neutron source. The strong peak at a proton energy of 2.030 Mev is due to neutron emission which leads to the ground state of Be^7 and corresponds, after correction for target thickness, to a neutron energy of 257 kev, the energy of the scattering resonance in Li. The peak at a proton energy of 2.502 Mev is attributed to the second neutron group from the $Li^7(p,n)Be^{7*}$ reaction, and yields a value of 432 ± 5 kev for the excitation energy in Be^7, in good agreement with other measurements.[16] Extrapolation of Batchelor's[17] measurements on the relative intensities of the two neutron groups indicates that at this bombarding energy the low-energy neutron group should be about 2% as intense as the ground-state group. The 10% rise in the ratio gives an indication of the possible sensitivity of the method. The peak in the ratio at a proton energy of 2.18 Mev corresponds to a neutron energy of 431 kev for the ground-state neutron group. The total neutron cross section for oxygen shows a strong resonance at this energy so this small peak in the ratio curve is attributed to resonance scattering in the vaseline and Mylar covering the lithium and in the oxidized surface of the lithium scatterer.

The $Mn^{55}(p,n)Fe^{55}$ reaction was then studied with a target consisting of a thin manganese layer evaporated on a tantalum backing. The target used in most of the work had a thickness of about 40 kev for 2.2-Mev protons. A 15-μa resolved proton beam from the Argonne Van de Graaff generator was used to bombard the target, which was mounted in a rotating assembly to prevent excessive heating and consequent deterioration of the target.

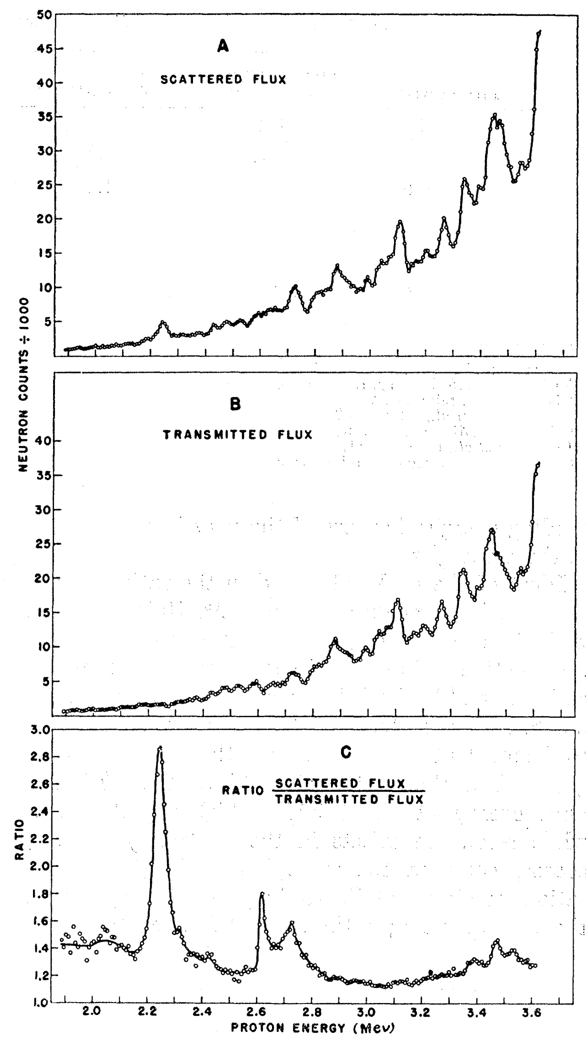

FIG. 3. Results for 0° observation with the $Mn^{55}(p,n)Fe^{55}$ neutron source. Curves *A* and *B* indicate the scattered and transmitted neutron flux, respectively, as a function of proton energy. Curve *C* shows the ratio of scattered to transmitted flux, also as a function of proton energy. The target used for these measurements was about 45 kev thick for 2.0-Mev protons.

Results for observation at 0° relative to the incident proton beam are shown in Fig. 3. The upper two curves show the scattered and transmitted neutron flux as a function of the energy of the incident protons. It is evident the neutron yield shows pronounced resonances which can distort threshold determinations. The lower curve shows the ratio of scattered to transmitted flux, again as a function of bombarding energy. Peaks in this ratio should occur at proton energies for which neutron groups leave the target with an energy of 257 kev, the resonant energy for neutron scattering from lithium. These neutron groups correspond to various excited states in the residual nucleus Fe^{55} above about 700-kev excitation. It was not possible to use the ratio technique with the present equipment at lower bom-

[15] Hibdon, Langsdorf, and Holland, Phys. Rev. **85**, 595 (1952).
[16] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[17] R. Batchelor, Proc. Phys. Soc. (London) **A68**, 452 (1955).

TABLE I. Energy levels in Fe^{55} as measured in various reactions; excitation in Fe^{55} in kev.

Present work	$Mn^{55}(p,n)Fe^{55}$ Counter ratio	Time-of-flight[c]	$Mn^{55}(p,n\gamma)Fe^{55}$ [d]	$Co^{55}(\beta^+)Fe^{55}$	$Fe^{54}(d,p)Fe^{55}$ [g]
437±20	414±3[a]	399	410	420[e,f]	413
936± 8	931±2[a]	901	930	937[e,f]	933
1315±10	1327[b]	2701	1320		1322
1414± 6		1358	1405	1410[e,f]	1413
				1657[e]	
				1840[f]	
					1925
			2070		2060
2156± 6	2170[b]			2170[f]	2150
	2554[b]		2520		

[a] Gossett and Butler, reference 6.
[b] Chapman and Slattery, reference 5.
[c] Elwyn *et al.*, reference 4.
[d] Lobkowicz *et al.*, reference 7.
[e] Caird and Mitchell, reference 10.
[f] Mukerji *et al.*, reference 11.
[g] Sperduto and Buechner, reference 8.

barding energies because of the very low neutron yield at those energies.

Most of the peaks observed in the ratio correspond quite well to known states in Fe^{55}. Unfortunately, as with the ordinary counter ratio method, resonances in the reaction yield can cause spurious indications in the ratio curve. To check for this possibility, the measurements were repeated with the resonant detector at 60° to the incident proton beam. For this angle true neutron groups from the reaction should have the 257-kev resonant energy at about 20-kev higher proton energy, while resonance effects in the neutron yield will, of course, come at the same bombarding energy. The ratio curve taken at 60° to the proton beam, along with the corresponding ratio curve taken at 0° with the same target, is shown in Fig. 4. The peaks labeled 2 through 5 shift in energy by the expected amount and hence can be said to correspond to true excited states in Fe^{55}. The peak A is attributed to scattering of neutrons corresponding to peak 2 by oxygen contaminant in the lithium resonant scatterer, as was also observed for the $Li^7(p,n)$ neutron source. The other peaks in the two curves are not observed to shift by the proper amount and are therefore attributed to effects of resonances in the neutron-producing reaction.

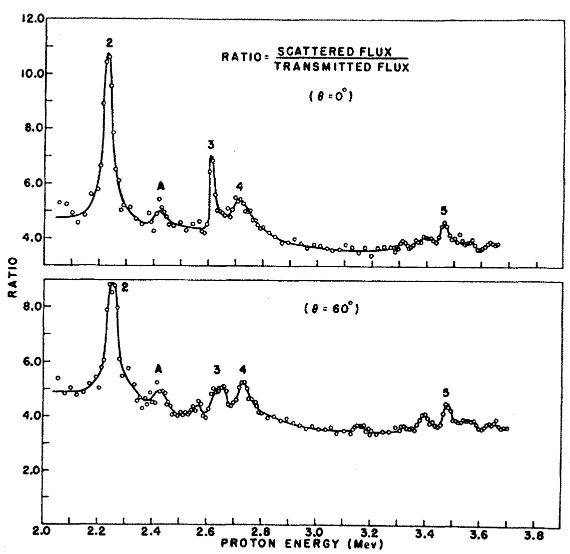

FIG. 4. Comparison of ratio curves taken at 0° and 60° to the proton beam for the $Mn^{55}(p,n)Fe^{55}$ reaction. The peaks numbered 2–5 shift the expected amount on changing the angle of observation. Peak A is attributed to neutron scattering from oxygen contaminant in the lithium. The Mn target was about 40 kev thick to 2.0-Mev protons.

In order to investigate states of lower excitation in Fe^{55}, the transmission of lithium was measured for neutrons from the $Mn^{55}(p,n)Fe^{55}$ reaction for proton energies below those used in the ratio measurements. The transmission of the lithium should show a resonant dip for neutrons with an energy of 257 kev. The results of these measurements, for neutrons at 60° to the incident proton beam, are shown in Fig. 5. The dip at a proton energy of 1.310 Mev corresponds to neutrons leaving Fe^{55} in its ground state. After correction for

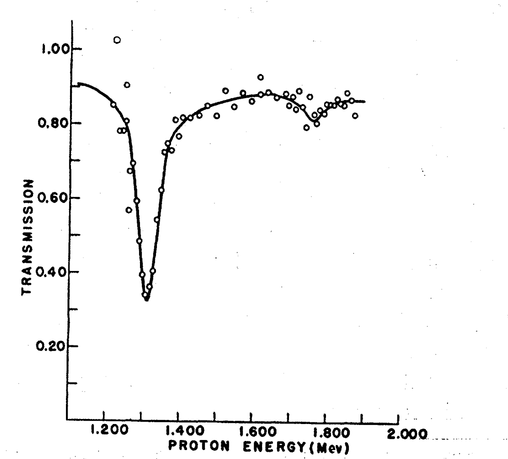

FIG. 5. Transmission of lithium for $Mn^{55}(p,n)$-Fe^{55} neutrons as a function of proton energy for 60° observation. The target was the same as that used for the observations in Fig. 4.

target thickness this yields a ground-state Q-value of $-(1.011\pm0.005)$ Mev in good agreement with recent threshold measurements.[6] The very weak dip at a proton energy of about 1.75 Mev corresponds to a known state in Fe^{55} at about 420-kev excitation which evidently is populated very weakly by the (p,n) reaction at this bombarding energy.

DISCUSSION

A summary of the excitation energies obtained for states in Fe^{55} is shown in Table I, along with some of the values obtained by other experimenters. There is evident agreement between the experiments for most of the low-lying states. The level at 1.42 Mev, not observed by the counter ratio method, is clearly evident in the present work. The fact that several levels observed in the (d,p) reaction have not been observed in the present work or in any other study of the (p,n) reaction probably indicates that they are not populated in the (p,n) process. The β^+ decay of Co^{55} also leads to two levels which are not observed in any of the other studies of the Fe^{55} nucleus.

The efficiency of the method used in the present experiment can be improved greatly over that indicated here without sacrificing any of the advantages of the method. The existing equipment used subtended a much smaller solid angle than is desirable and its background counting rates were much higher than necessary. The use of shielding and counters especially designed for this use can make it a very sensitive and effective method of measuring neutron energy groups from reactions induced by beams from electrostatic accelerators.

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Elastic Nucleon-Deuteron Scattering in a Soluble Model as a Test of the Impulse Approximation

THOMAS FULTON,* *The Johns Hopkins University, Baltimore, Maryland*

AND

PHILIP SCHWED, *RIAS, Baltimore, Maryland*

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A comparison of the results of the Born and impulse approximations for a well-defined situation is made by calculating the nucleon-deuteron differential elastic cross sections in both approximations at incident nucleon laboratory energies of 32, 94, and 146 Mev. In order to carry out the impulse approximation computation in complete detail, including, in particular, contributions from off-energy-shell two-particle matrix elements, the assumption is made that the two-particle scattering is completely described by effective range theory. This assumption, though incorrect, nevertheless retains some of the features of the actual physical situation and provides a means of comparing the results of calculations using the impulse approximation and the Born approximation as well as a way of studying the effect of including two-particle matrix elements off the energy shell. Exact solutions to the two-particle model are written down with the aid of the Gel'fand-Levitan theory and are used in a precise numerical evaluation of the impulse approximation expressions. The results of the Born and impulse approximations differ considerably. Also, indications are that, as expected, the pickup term (which dominates at large angles) is not adequately treated by either of the above approximations. When this term is not considered, a study of the remaining expressions shows that off-energy-shell effects are significant for the deuteron wave functions employed. In view of the rather restrictive assumptions made on the two-particle data, a detailed comparison of the results with experiment is not possible. Nevertheless there is a suggestion that the impulse approximation, including off-energy-shell effects, describes the experimental results best.

1. INTRODUCTION

THE problem of nucleon-deuteron scattering has received almost as much attention in recent years as that of nucleon-nucleon scattering. Although nucleon-deuteron scattering presents us with the added complications of a three-body problem, it is the only means available so far for studying the neutron-neutron interaction in the laboratory. In addition, it can in principle provide us with further information about the other nucleon-nucleon interactions, since intrinsic three-body forces are probably not too important in as loose a structure as the deuteron.

Low-energy (0–25 Mev) nucleon-deuteron scattering has been extensively treated.[1] Our own concern will be with the intermediate energy range (25–250 Mev). Calculations have also been carried out at high energies.[2] As can be expected, the nature of the approximations involved is different in the different energy ranges.

In the intermediate energy range of interest here, there are two methods presently available for approximating the scattering, assuming that the relevant potentials are known. The first of these, the Born approximation, has been employed extensively for the case of incident nucleons with energies of approximately

* Consultant at RIAS, Baltimore, Maryland.

[1] For a review of this work, as well as a rather extensive list of references, see H. S. W. Massey, *Progress in Nuclear Physics* (Butterworth-Springer, London, 1953), Vol. 3, p. 235.

[2] R. J. Glauber, Phys. Rev. **100**, 242 (1955).