TABLE IV. The columns labeled "E_{exc}" and "J^{π}" are the energies of excitation and the spins and parities, respectively, for the four lowest lying levels of N^{16}. The column labeled "configuration" gives the dominant shell-model configuration of these states predicted by Elliott and Flowers.[a]

E_{exc}(MeV)	J^{π}	Configuration
g.s.	2^-	$p_{1/2}^{-1}d_{5/2}$
0.120	0^-	$p_{1/2}^{-1}s_{1/2}$
0.295	3^-	$p_{1/2}^{-1}d_{5/2}$
0.392	1^-	$p_{1/2}^{-1}s_{1/2}$

[a] See Ref. 30.

of N^{16} are given in Table IV. Considering $N^{14}(t,p)N^{16}$ as a stripping reaction, the two neutrons which are stripped from the triton must be uncoupled,[27] with one filling the (neutron) $1p$ shell, and the other starting the $2s$-$1d$ shell. It is of interest to see whether such a reaction is inhibited. The results listed in Table I show that although these cross sections are not particularly large, they do not seem to be very highly inhibited compared to the other reactions.

It should be noted that the ground-state and second-excited-state reactions may proceed with angular momentum transfers of $L=3$, while the first and the third excited states require $L=1$. The p_0 and p_2 angular distributions do, indeed, have generally similar shapes, as do the p_1 and p_3 distributions (Fig. 11).

V. CONCLUSIONS

It seems clear that the reactions described here proceed primarily by a direct interaction mechanism, even at energies as low as 1.2 MeV.

Qualitatively, the predictions of the cluster model seem to be borne out by both the shape and magnitude of the (t,d_0) angular distributions.

A PWBA fit to the (t,d_0) data is reasonably satisfactory, in view of the known shortcomings of plane-wave theories. The failure of the DWBA in the case of the (t,d_0) reaction suggests that inclusion of exchange stripping is necessary. The DWBA with the zero-range approximation gives quite a reasonable fit to the 1.95 MeV (t,α_0) angular distribution, although it fails to predict the proper magnitude of the cross sections. This may indicate that the formulation of the theory used for the present calculations gives the proper mechanism of the interaction but fails to take into account properly the structure of the nuclei.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Dr. G. R. Satchler for performing the DWBA calculations, as well as for many helpful discussions. We are also indebted to Dr. S. Meshkov for several interesting discussions. We wish to thank Dr. L. Cohen for his assistance during the course of the experiment, and V. W. Slivinsky for his help in taking the elastic-scattering data.

PHYSICAL REVIEW VOLUME 134, NUMBER 3B 11 MAY 1964

Differential Cross Sections for the Reaction $Li^7(Li^7,\alpha)Be^{10}$†

T. G. DZUBAY AND J. M. BLAIR
School of Physics, University of Minnesota, Minneapolis, Minnesota
(Received 2 December 1963)

Absolute differential cross sections are presented for the reaction $Li^7(Li^7,\alpha)Be^{10}$, where the Be^{10} is left in its ground state, first excited state, and combined second, third, and fourth excited states, for laboratory energies from 2.30 to 3.77 MeV. The total cross sections exhibit the rapid rise with increasing energy usually shown by heavy-ion reactions at low energies. The ratios of the coefficients of the Legendre polynomials which describe the angular distributions show structure in the neighborhood of 3.2-MeV bombarding energy. This is thought to be indicative of a compound-nucleus contribution.

INTRODUCTION

As a part of our program of investigation of reactions produced by lithium ions, we have previously[1–3] studied the angular distributions of alpha particles from C^{12} and Be^9 targets. In the present work we have extended these studies to the reaction $Li^7(Li^7,\alpha)Be^{10}$, where the residual Be^{10} nucleus was left in the ground and first four excited states. The alpha-particle groups leaving Be^{10} in its second, third, and fourth excited states could not be resolved, but were counted together. Lower energy groups of alpha particles could not be separated from a continuum, so no attempt was made to measure yield. The techniques described in the previous papers were used in this work, except that the target situation was more complicated, since self-supporting lithium foils could not be constructed.

† Supported in part by the U. S. Office of Naval Research.
[1] J. J. Leigh and J. M. Blair, Phys. Rev. **121**, 246 (1961).
[2] R. K. Hobbie, C. W. Lewis, and J. M. Blair, Phys. Rev. **124**, 506 (1961).
[3] R. K. Hobbie and F. F. Forbes, Phys. Rev. **126**, 2137 (1962).

APPARATUS

The accelerator, target chamber, detectors, and electronic equipment used in the present work were the same as those described previously.[3,4]

The targets consisted of thin layers of LiF evaporated onto nickel foils a few microinches thick.[5] LiF was selected because of its chemical stability and fairly high (870°C) melting point. Lower melting-point lithium compounds were subject to excessive evaporation at the spot on the target receiving the greatest ion-beam intensity. Nickel foils were used rather than SiO target backings because the latter tended to split after a short period of ion bombardment. The LiF was prepared starting with 99.994% pure Li^7 purchased from Oak Ridge National Laboratory. The metal was dissolved in water and then HF was added until the pH was about 3. The LiF precipitate was dried and later evaporated onto nickel backing from a tantalum boat. The target thickness measurement using Coulomb scattering showed that this target fabrication procedure did not introduce any gross impurities. No groups of scattered ions were observed which could not be accounted for by known target components except for small amounts of carbon, presumably from pump oil condensed on the target.

PROCEDURE

The yield of alpha particles was observed at laboratory angles from 10 to 160° in 10° increments at bombarding energies of 2.45, 2.90, 3.30, 3.50, 3.70, and 3.90 MeV. The effective average energies in the LiF layer were 2.30, 2.75, 3.16, 3.36, 3.57, and 3.77 MeV. During all of the alpha-particle observations, the targets were oriented so that the incoming ion beam struck the LiF layer before passing through the nickel supporting foil.

To avoid evaporation of LiF from the spot being bombarded, it was found necessary to limit the ion beam to 0.075 μA spread uniformally over a 3-mm diam spot.

In addition to alpha particles from the reaction of interest, small numbers of alpha particles were observed from the reactions $C^{12}(Li^7,\alpha)N^{15}$ and $H^1(Li^7,\alpha)He^4$ due to target contamination from pump oil. At some angles of observation the most energetic alpha particles from these reactions appeared in the alpha-particle spectrum between the α_0 and α_1 groups from the Li^7+Li^7 reaction. Since the angular distributions of the alpha particles from the reactions of Li^7 on C^{12} and H^1 are known,[3,6] it was possible to estimate the contamination at other angles and hence make the appropriate corrections. The correction was less than 5% for the α_1 data, but was larger for the α_0 data and necessitated rejecting the α_0 data for angles from 10 to 30°.

No alpha particles which could be attributed to the $F^{19}(Li^7,\alpha)Ne^{22}$ reaction were observed. This is not surprising, since the larger nuclear charge of F^{19} inhibits this reaction compared with the one of interest.

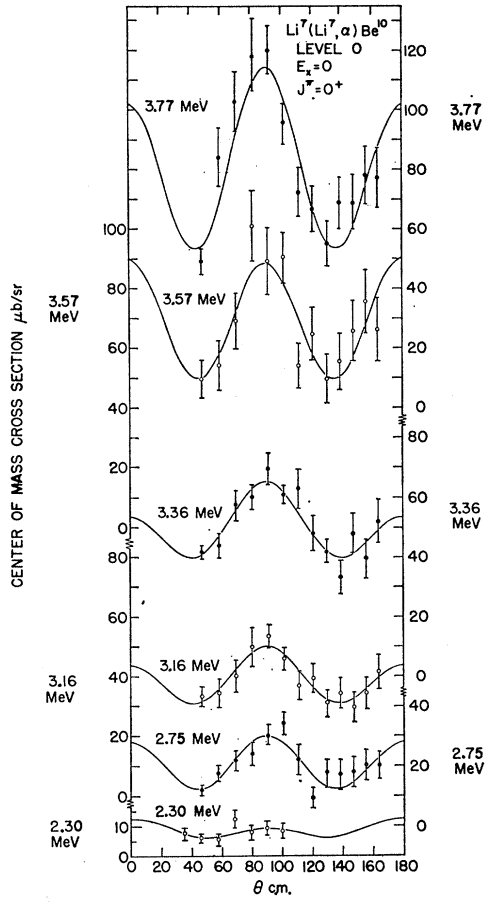

FIG. 1. Center-of-mass cross sections as a function of center-of-mass angle for $Li^7(Li^7,\alpha)Be^{10}$ for various Li^7 energies when Be^{10} is left in its ground state.

Since several targets were used during the course of the work, it was necessary to normalize the data taken from each. This was accomplished by measuring the yield at 40° at each of the energies with a single target. The observed yields were converted to absolute cross sections by comparison with the yields for Coulomb scattering of the Li^7 ions by the Li and F in the target. For this measurement, the proportional counter was removed from the particle identification system, and the scattered Li^7 ions were detected by the surface-barrier detector alone.

In this experiment, the Coulomb scattering measurements were more complicated than in previous work[2] because of the presence of several elements in the target. In addition to Li^7 scattered by Li^7, there was Li^7 scattered from F and Ni in the target and from a C contaminant on the surface of the target, as well as recoil nuclei of each of these elements. It was found that the spectrum peak due to Li^7-Li^7 scattering could best be

[4] J. M. Blair and R. K. Hobbie, Phys. Rev. **128**, 2282 (1962).
[5] Chromium Corporation of America, Waterbury, Connecticut.
[6] N. P. Heydenburg, C. M. Hudson, D. R. Inglis, and W. D. Whitehead, Jr., Phys. Rev. **74**, 405 (1948).

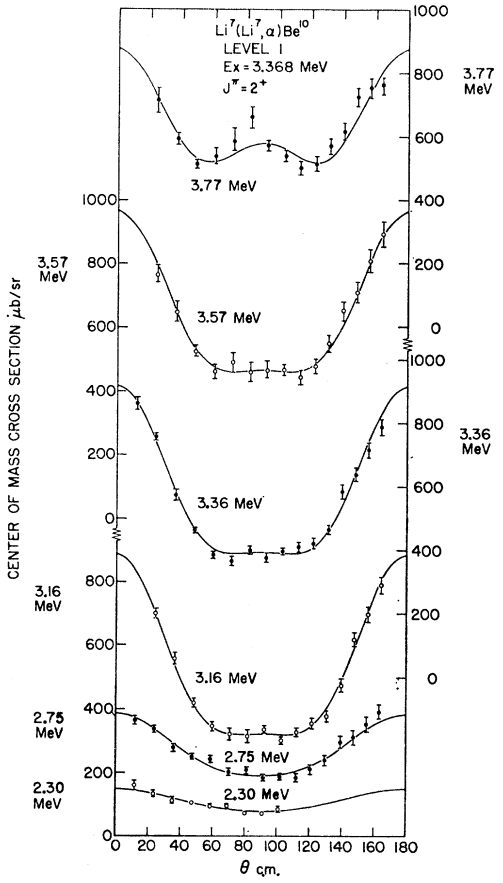

FIG. 2. Center-of-mass cross sections as a function of center-of-mass angle for $Li^7(Li^7,\alpha)Be^{10}$ for various Li^7 energies when Be^{10} is left in its first excited state.

resolved at a detector angle of 40°, but even at this angle there was a serious background under the Li^7 peak due to adjacent peaks. Much better resolution was obtained by observing Li^7 scattered from F at 70°. Calculations based on these scattering measurements suggested that there was 0.85 ± 0.09 as much Li as F in the target, in contrast to the anticipated ratio of 1.00. This discrepancy was attributed to the uncertain background under the Li^7-Li^7 scattering peak. The absolute cross section calculations were based on a ratio of Li to F of 1.00 with a 15% error included because of this discrepancy.

Although the energy lost by the Li^7 ions in the LiF layer did not enter directly into the absolute cross section determination, this information was needed to determine the average energy of the beam in the target. The method of obtaining the energy lost by the lithium ions in the LiF layer was to use the results of the elastic-scattering measurement to obtain the number of atoms per unit area and then convert published information[7] on rate of energy loss of protons to the rate for lithium ions. This conversion used the relation that the stopping cross section for ions of a given velocity is proportional to the mean-square charge of the ions. Of course, the evaluation of the scattering data depended upon knowing the average energy of the ions in the target, but consistent results for the calculation were easily obtained since the energy loss in the target was small compared with the total energy of the incident ions. The mean square of the ionic charge was evaluated from data previously obtained in this laboratory.[8] Typical values of atomic stopping cross sections obtained by this method are 103×10^{-15} eV-cm²/molecule and 136×10^{-15} eV-cm²/atom for 3.5-MeV Li^7 ions in LiF and Ni, respectively. The latter quantity is in 2% agreement with recent measurements by Teplova *et al.*[9]

The LiF layer on a typical target used in this experiment produced an energy loss of 275 ± 50 keV for 3.50-MeV Li^7 ions.

As a check on this method of determining target thickness, the energy loss in a bare nickel backing foil, calculated in this way, was compared with the spread

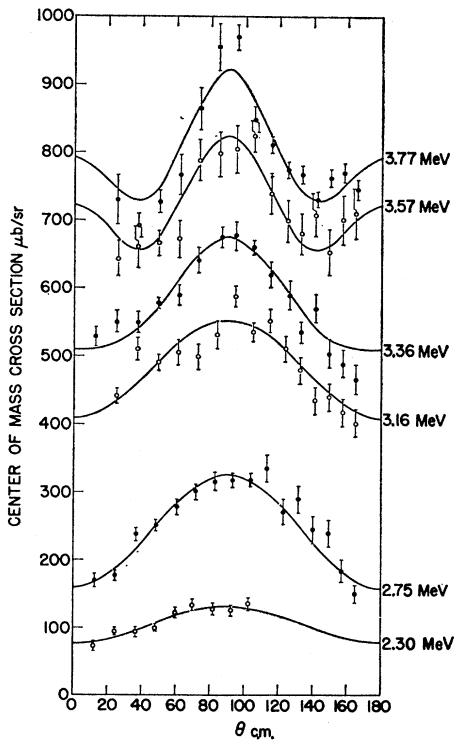

FIG. 3. Center-of-mass cross sections as a function of center-of-mass angle for $Li^7(Li^7,\alpha)Be^{10}$ for various Li^7 energies when Be^{10} is left in its second, third, or fourth excited state.

[7] Ward Whaling, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 193.

[8] L. L. Pinsonneault, M.S. thesis, University of Minnesota, 1961 (unpublished). Also reported briefly in *Reactions Between Complex Nuclei*, edited by A. Zucker, F. Howard, and E. Halbert (John Wiley & Sons, Inc., New York, 1960), p. 138.

[9] Ya. Teplova, I. S. Dmitriev, V. S. Nikolaev, and L. N. Fateeva, Zh. Eksperim. i Teor. Fiz. **42**, 44 (1962) [English transl.: Soviet Phys.—JETP **15**, 31 (1962)].

in energy of the Li^7 ions resulting from their being scattered in the foil at 90°. The nickel foil was oriented at 45° with respect to the ion beam so that some ions were scattered at 90° with no energy loss in the nickel, whereas other ions passed through $2\sqrt{2}$ times the normal thickness of the nickel. From the previously determined relationship between pulse height from the surface-barrier detector and Li-ion energy, the spread in pulse height was converted to energy loss in the nickel foil. A typical nickel foil measured with 3.50-MeV incident Li^7 ions gave an energy loss of 389±23 keV from the Coulomb scattering data and 348±6 keV from the direct measurement of energy loss by the detector. A further check on this foil was made by weighing a measured area. Again converting Whaling's information on energy loss by protons to that by Li^7 ions, this method gave an energy loss of 345±70 keV.

The cross-section calculations for $Li^7(Li^7,\alpha)Be^{10}$ are quite insensitive to errors in the LiF thickness. An error of 50 keV would cause only a 1.5% error in the Coulomb scattering cross section. The average charge brought by each ion to the current collector is rather slowly energy-dependent, so a 50 keV uncertainty in target thickness would produce an uncertainty of no more than 1% to 2.5% in the reaction cross section.

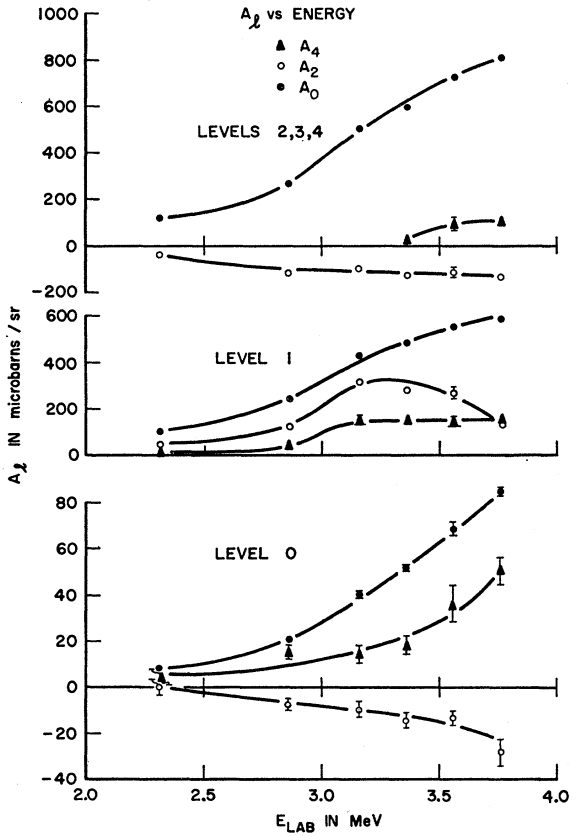

FIG. 4. Coefficients A_0, A_2, and A_4 of the Legendre polynomials used to fit the differential-cross-section curves in Figs. 1–3.

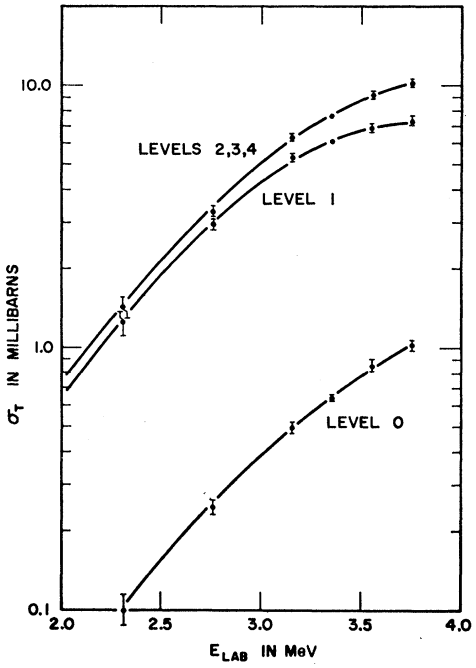

FIG. 5. Total cross sections for the reaction $Li^7(Li^7,\alpha)Be^{10}$ as a function of Li^7 energy when Be^{10} is left in its ground state, first excited state, and combined second, third, and fourth excited states.

RESULTS

The cross sections for the $Li^7(Li^7,\alpha)Be^{10}$ reaction leaving Be^{10} in the ground state, first excited state, and combined second, third, and fourth excited states are shown in Figs. 1–3. The energies indicated on the curves are the average laboratory energies of the Li ions in the LiF layer on the target. The angles and cross sections have been converted to the center-of-mass coordinate system. The error bars on these curves indicate the standard deviations for counting statistics at each point. They do not include the uncertainties in target normalization. The smooth curves are the results of fitting the function $\sigma(\theta)=\sum_{l=0}^{N} A_l P_l(\cos\theta)$ to the data points by a least-squares procedure. Only even-order Legendre polynomials were considered because the identity of beam and target nuclei requires symmetry about 90° in the center-of-mass system. The values of A_l are plotted in Fig. 4. The error bars shown reflect both the statistical uncertainty in the original data and the value of χ^2 obtained for the fit. The total cross sections as functions of energy are shown in Fig. 5. The error bars on these curves represent the statistical standard deviation resulting from the normalization of the yield curves at various energies to the 3.36-MeV point where the comparison with Coulomb scattering was made. In addition, there is an over-all uncertainty of ±18%, due mainly to the uncertainty in the lithium-fluorine ratio in the targets. If this ratio were truly 1.00, the over-all uncertainty in total cross sections would be reduced to ±10%.

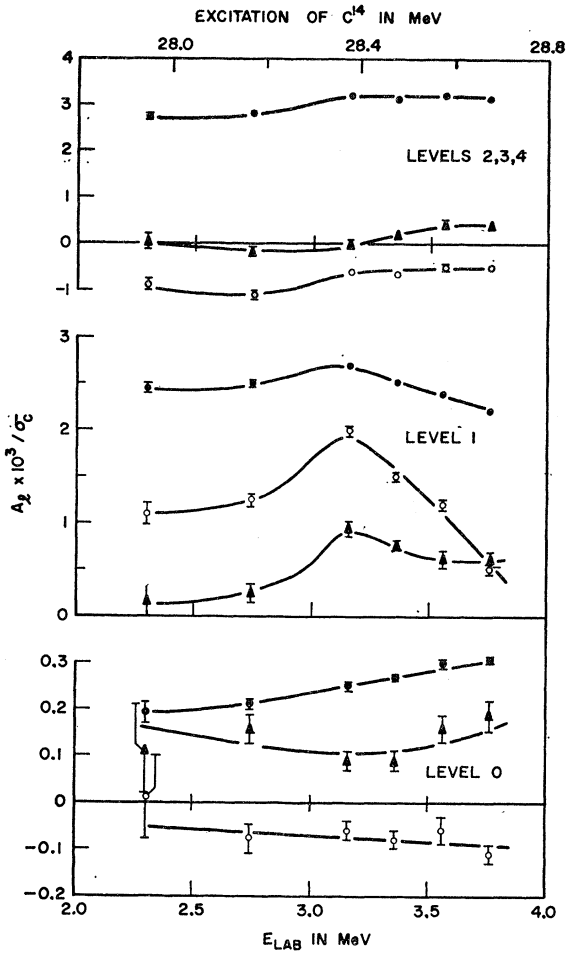

FIG. 6. Ratios of A_l to cross sections for compound-nucleus formation as a function of incident-ion energy for the $Li^7(Li^7,\alpha)Be^{10}$ reaction. The order of A_l is identified by ●$-l=0$; ○$-l=2$; ▲$-l=4$.

DISCUSSION

Work reported from Chicago[10] on this reaction at 2.1 MeV gives an angular distribution for the α_1 group which resembles our curve for α_1 at 2.30 MeV, except that their yield at 90° is lower with respect to the yield at 0° than is ours. This appears to be an extension of the trend shown by the curves in Fig. 2 in which the rise at 90°, present in the highest energy curve, gradually decreases as the energy is reduced. The Chicago work did not result in an angular distribution for the α_0 group because the yield at 2.1 MeV was too low.

The total cross section curve for the α_1 group shown in Fig. 5, when extrapolated to 2.1 MeV, gives a value of 0.8 mb, which is only 28% of the result reported from Chicago for this energy. The source of this discrepancy, which is several times the sum of the errors estimated for the two measurements, is not at all clear since quite different methods of obtaining absolute values were used. The procedure used in the present work is essentially a comparison of counting rates, since it is independent of detector solid angle and current-integrator calibration and only slightly dependent upon target-thickness determinations.

In some previous work[1–3] with lithium-produced reactions, the angular distributions of the charged particles produced have exhibited strong forward to backward asymmetries when plotted as a function of the center-of-mass angle. In the present work, this cannot occur because of the identity of the target and beam nuclei. The relative simplicity of the angular distribution is shown by the fact that the observations can be described satisfactorily by the first three even Legendre polynomials.

The Legendre polynomial coefficients shown in Fig. 4 are influenced by the rapid increase in cross section with energy. The effect of the Coulomb barrier penetration can be eliminated by calculating A_l/σ_c, where σ_c is the cross section for compound-nucleus formation calculated in the manner described by Blatt and Weisskopf.[11] A channel radius $R=5.69\ F$ was used. The results of these calculations, plotted in Fig. 6, show structure in level 1 and in levels 2–4 at an excitation energy of 28.4 MeV in the compound nucleus. The fact that this structure is absent in the ground-state data is consistent with spin-selection rules.

ACKNOWLEDGMENTS

We wish to express our appreciation to Professor R. K. Hobbie for his work in writing the computer programs used and for many helpful discussions. Dr. Elliot H. Auerbach provided the subroutines for generating Coulomb wave functions. We are grateful to F. F. Forbes for aid with the electronic equipment and to the other members of the Van de Graaff group for their help in operating the accelerator and taking data.

[10] M. N. Huberman, M. Kamegai, and G. C. Morrison, Phys. Rev. **129**, 791 (1963).

[11] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 354.