# Scattering of 10-Mev Protons on Carbon and Magnesium*

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(Received June 21, 1954)

In order to study the mechanism of excitation of nuclear levels by inelastic scattering, a scattering chamber of 36-inch diameter was constructed. The deflected beam of the Berkeley 60-inch cyclotron was brought out of the shielding by means of strong focusing magnets. Particles from the nuclear reactions were detected by either of two systems, a quadruple proportional-counter telescope, or a coincidence crystal spectrometer. Energy resolution was of the order of 2.5 percent. The angular distribution of protons from the reactions $C^{12}(p,p')C^{12*}$, $Q=-4.43$ Mev, and $Mg^{24}(p,p')Mg^{24*}$, $Q=-1.38$ Mev, were found to be peaked in the forward direction. Since the compound nucleus is excited to about 13 Mev, where the level density is expected to be high and the statistical theory of the nucleus should hold, it is proposed that two processes of excitation occur. One, the formation of the compound nucleus and its subsequent decay—symmetrically about 90°; two, direct collision of the incident proton with a nucleon on the surface shell of the nucleus. The elastic scattering of protons on the above nuclei was also studied and interference maxima were found. Three new levels are believed to have been confirmed in magnesium.

## I. INTRODUCTION

THE inelastic scattering of particles on nuclei has been used by a large number of investigators as a way of exciting nuclear energy levels. The actual mechanism of the transfer of energy and angular momentum, however, has not been quite clear. Rhoderick[1] was the first to be concerned with this problem, for he found that the angular distribution of the inelastically scattered protons from the 1.38-Mev level in magnesium-24 was peaked in the forward direction. He was unable to reconcile this result with the idea that the excitation proceeded through compound nuclear formation. Other investigators,[2–6] working with bombarding energies of 7.3, 9.5, and 32 Mev, have also found anisotropies in the angular distribution of inelastically scattered protons. Wolfenstein[7] showed that the angular distribution arising from the decay of the compound nucleus need not be isotropic, but that if the excitation be high enough so that the density of compound nuclear states is high and the states overlap, the distribution should at least be symmetric about 90°. This follows from the assumption that interference terms between outgoing waves of different parity cancel out. Two processes that have nothing to do with the compound nucleus suggest themselves to explain the observed anisotropies. They are: either electric charge excitation,[8] or a direct collision of the incident proton with a nucleon on the surface shell of the nucleus. Electric excitation is tentatively ruled out by the large size of the observed cross section. Recently Gugelot[9] and Eisberg[10] have suggested the direct collision idea in connection with level-density determinations by inelastic scattering.

For the direct collision theory, we will follow an analysis given by Austern, Butler, and McManus[11] for $X(n,p)Y$ reactions which should be equally applicable to $(n,n')$, $(p,n)$, and $(p,p')$ reactions. These authors suggest that the direct collision process can compete with compound nuclear formation because the struck particle receives nearly all the energy and consequently may get over the barrier more readily than a low-energy evaporation particle. The energy region in which this type of reaction may be found is between 10 and 30 Mev. The lower limit is set by the barrier, the upper by nuclear transparency. The anticipated cross section for the emission of a high-energy proton group may be several millibarns. They arrive at this figure by correcting the total free $n$-$p$ scattering cross section for the time that the initial and final particles spend outside the nucleus.

Using the impulse approximation, they calculate the angular distribution of the emitted particle to have sharp forward maxima, similar to Butler stripping distributions, depending on the allowed values of orbital-angular-momentum transfer. If the struck particle can be assumed to be in a single-particle state, they show that the angular distribution becomes especially simple. It is the purpose of this paper to show that the observed angular distribution of inelastically scattered protons on magnesium can be in part accounted for in this way.

A by-product of this investigation was the measurement of the elastic scattering of 10-Mev protons on magnesium and carbon. Renewed interest in this type of scattering has been expressed recently by Cohen,[12]

* The work was performed under the auspices of the U. S. Atomic Energy Commission.
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1 E. H. Rhoderick, Proc. Roy. Soc. (London) **201**, 348 (1950).
2 H. E. Gove and H. F. Stoddart, Phys. Rev. **86**, 572 (1952).
3 Burcham, Gibson, and Rotblat, Phys. Rev. **92**, 1266 (1953).
4 Baker, Dodd, and Simmons, Phys. Rev. **85**, 1051 (1952).
5 R. Britten, Phys. Rev. **88**, 283 (1952).
6 R. M. Eisberg and G. Igo, Phys. Rev. **93**, 1039 (1954).
7 L. Wolfenstein, Phys. Rev. **82**, 690 (1951).
8 R. Huby and H. C. Newns, Proc. Phys. Soc. (London) **A64**, 619 (1951).
9 P. C. Gugelot, Phys. Rev. **93**, 425 (1954).
10 R. Eisberg, Phys. Rev. **94**, 739 (1954).
11 Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).
12 B. L. Cohen and R. V. Neidigh, Phys. Rev. **93**, 282 (1954).

who finds a remarkable number of diffraction maxima and minima.

## II. EXPERIMENTAL METHOD[13]

The arrangement of the experimental apparatus is shown schematically in Fig. 1. The deflected molecular hydrogen beam may be traced from the deflector through a $\frac{1}{4}$-inch collimating slit to the target port and into the iron snouts. Shielded from the fringing magnetic field of the machine by the iron, it passes into a long brass pipe to the 36-inch scattering chamber and subsequently to the Faraday cup for integration.

Focusing is achieved by two magnetic quadrupole lenses.[14] These lenses, whose design and action is illustrated in Fig. 2, increase the beam intensity through an eighth-inch-square collimating hole by a factor of 400 over the intensity obtainable without the lenses. Maximum beam current is $0.8\times10^{-6}$ amp. Accurate positioning screws are provided on the mount to permit movement of the beam to the desired location. A set of three collimators defines the beam axis in the chamber.

The required motions of targets and counters in the scattering chamber are carried out by remote control.

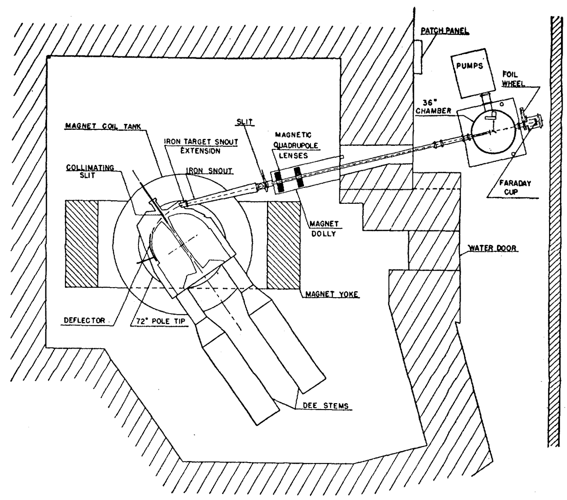


FIG. 1. Schematic diagram of the emergent beam apparatus at the 60-inch Berkeley cyclotron.

An average time of 15 minutes was consumed in reaching an operating pressure of $3\times10^{-5}$ mm Hg. A 100 percent feedback electrometer was used to measure the charge collected by the Faraday cup and the

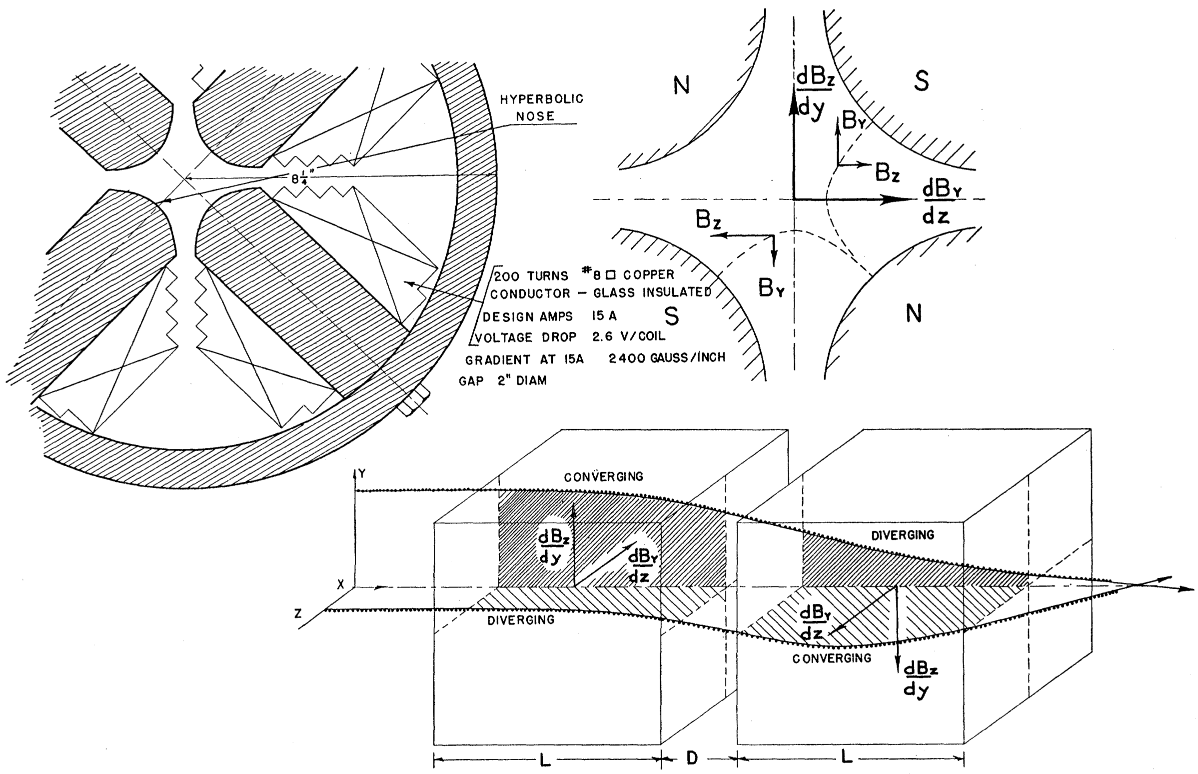


FIG. 2. Design parameters and illustration of the double-focussing properties of a magnetic lens system. $1/F=K^2L^2\{\frac{2}{3}L+D\}$, $K=(1/BR)(dB_y/dz)$. (Illustration after Courant, Livingston and Snyder.) See reference 14.

[13] A detailed account of the experimental technique employed may be found in University of California Radiation Laboratory Report UCRL-2546 (unpublished).

[14] Courant, Livingston, and Snyder, Phys. Rev. **88**, 1190 (1952).

beam's energy was determined by range in aluminum. The spread in the beam energy was 1 percent (full width at half-maximum).

Unsupported targets of gold and silicon monoxide were prepared by evaporation. The acetate backings were dissolved away. Thin carbon targets were made by spraying aquadag onto a clean sheet of Teflon and peeling off the dry deposit. For aluminum and magnesium, rolled foils were employed.

Scattered particles are detected in a telescope of four proportional counters. The range, hence the energy of the particle, is determined by how much aluminum absorber must be interposed in the particle's path to require it to traverse the first two counters and stop in the third. Cross sections were measured with this counter relative to Rutherford scattering from gold. A typical setting of the range bite was 0.57 mg/cm$^2$ aluminum equivalent. Over-all energy resolution, largely dependent on the range straggling of the particles in the aluminum absorbers and the spread in the beam itself, was about 2.5 percent (full width at half-maximum).

Another mode of particle detection was the use of a sodium iodide crystal spectrometer in coincidence with a thin proportional counter. The thin counter identified the particle by its $dE/dx$. Pulse heights were measured by a fast pulse-height analyzer built after a design by Fairstein and Porter.[15] Energy resolution was 2.5 percent for 10-Mev protons. Energy calibration was achieved by identifying the observed inelastic proton groups with known levels in aluminum,[16] silicon,[17] and oxygen. Fifteen groups in all were used. Energies can be estimated to $\pm 0.1$ Mev. Angular resolution was one degree.

## III. RESULTS AND CONCLUSIONS

### A. Particle Groups from Magnesium and Carbon

Figure 3 shows a partial spectrum of protons resulting from the bombardment of naturally occurring magnesium with 10-Mev protons. Easily identified are the elastic and first inelastic levels of magnesium-24. It is evident that in measuring the yield from the 1.38-Mev level, the small satellite arising from Mg$^{26}$, whose abundance is 11.3 percent, must be subtracted. The other satellite is a contribution from the 0.46-Mev level in Mg$^{26}$. Other particle groups were observed with both counters corresponding to the 4.13–4.24-Mev doublet in Mg$^{24}$ (not resolved), to the 1.89- and 2.84-Mev levels in Mg$^{26}$, and to 0.6- and 3.4-Mev levels in Mg$^{25}$. Three further groups were clearly seen with the crystal counter, corresponding to $Q$ values of $6.3\pm 0.1$, $5.9\pm 0.1$, and $5.1\pm 0.1$ if calculated for Mg$^{24}$. These have in part been reported also by Hausman *et al.*,[18] Gove and

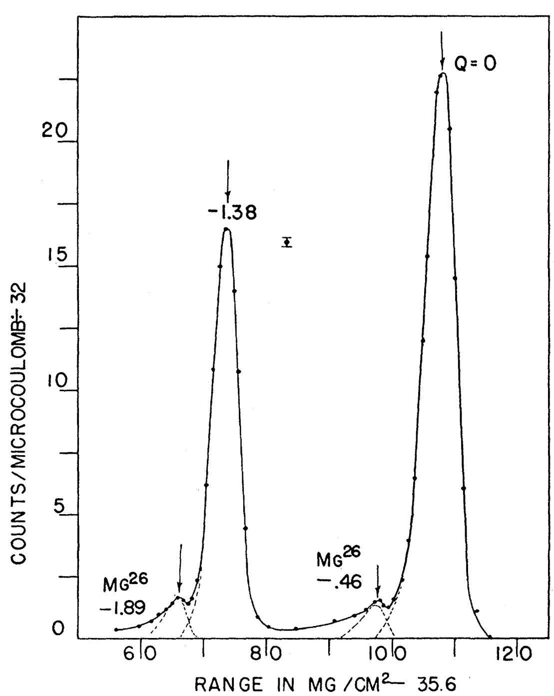


FIG. 3. Partial spectrum of protons from the reaction Mg$(p,p')$Mg* at 90° and 10 Mev (Range interval = 0.57 mg/cm$^2$.)

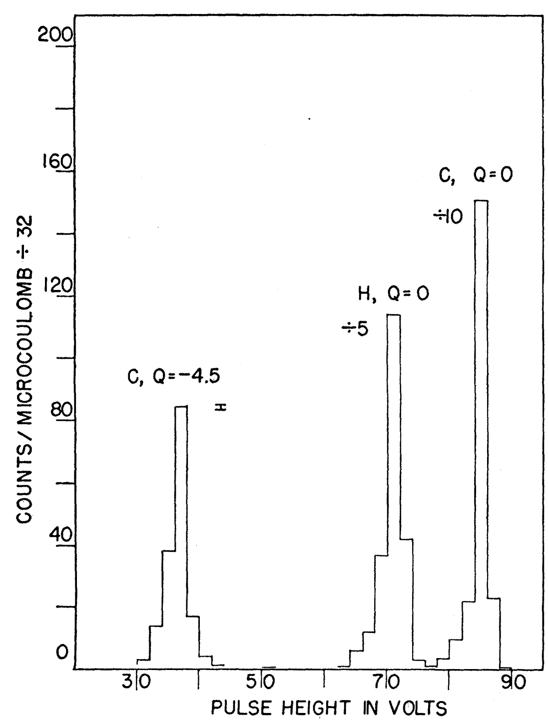


FIG. 4. Spectrum of protons from (CH)$_n$ target bombarded with 9.94-Mev protons, $\theta = 24°$ (lab). (2-volt window).

[15] E. Fairstein and F. M. Porter, Rev. Sci. Instr. 23, 650 (1952).

[16] Reilley, Allen, Arthur, Bender, Ely, and Hausman, Phys. Rev. 86, 857 (1952).

[17] D. E. Alburger and E. M. Hafner, Revs. Modern Phys. 22, 376, 343 (1950).

[18] Hausman, Allen, Arthur, Bender, and McDole, Phys. Rev. 88, 1296 (1952).

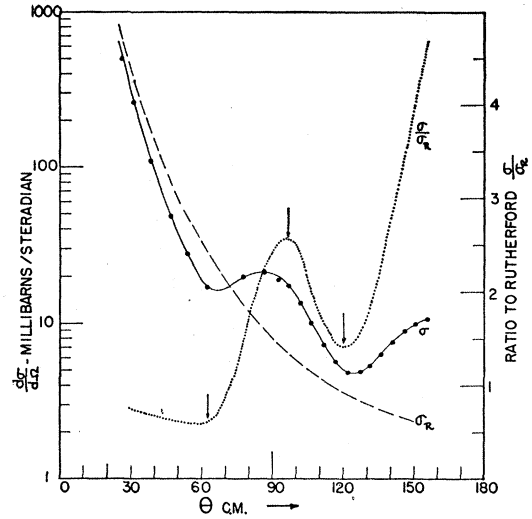


FIG. 5. The angular distribution of elastically scattered protons from Mg at 10 Mev.

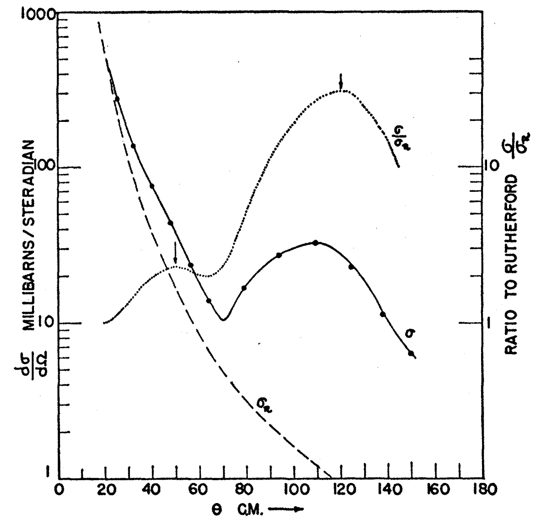


FIG. 6. The angular distribution of elastically scattered protons from carbon at 10 Mev.

Stoddart,[19] and Baker, Dodd, and Simmons.[4] The 6.3-Mev level has previously been assigned to $Mg^{24}$.[20] Figure 4 shows the spectrum of protons from a polystyrene $(CH)_n$ target bombarded with 9.94-Mev protons. The center group is from the hydrogen.

### B. Differential *p-p* Scattering Cross Section

The differential *p-p* scattering cross section was found to be 54.6 mb/steradian at 48° in the center-of-mass system. This figure is believed to be accurate within the statistical error of 3 percent and compares well with those published by Allred *et al.*,[21] and recently by Cork at 9.6 Mev.[22] Agreement with two independent observers using different detection equipment indicates that there are no large errors in our technique.

### C. Angular Distributions of Elastic Events

The angular distribution of elastic scattering of 9.94-Mev protons on magnesium and carbon (reduced to center-of-mass system) are shown in Figs. 5 and 6. The general character of these curves and the absolute cross sections agree well with those published by Baker, Dodd, and Simmons[4] and Burcham, Gibson, and Rotblat.[3] The energies used by these investigators was 9.6 and 9.5 Mev, respectively. The magnesium curve shown in the present data is extended to further backward angles and shows a rise in the cross section leading to a second maximum. Since these data were taken at the same time as the hydrogen cross section was measured, it is felt that the absolute cross sections are accurate to within ±3 percent. The angular measurement is good to $\frac{1}{2}$°. Relative cross sections are known to 2.5 percent. Unfortunately there are not enough data to fix the interference angles with greater accuracy.

### D. Angular Distributions of Inelastic Events

Figures 7 and 8 show the angular distributions of protons inelastically scattered from the 1.38-Mev and 4.43-Mev levels in magnesium and carbon (corrected to the center-of-mass system). The magnesium curve shows little or no resemblance to Baker's, possibly because of the different bombarding energy. The value of the cross section at 30° is well below those at 45° and 60°. Possibly the discrepancy between these results and those of Baker lies in the fact that Baker does not resolve the 1.89-Mev $Mg^{26}$ level which appears as a satellite. The magnesium curve was taken with both counters and findings for angular dependance checked with each other to 3 percent. There was, however, a 5 percent difference in the absolute cross section between the two methods. This can be blamed on a faulty calibration of the range interval of the range counter. It is clearly seen that the curve is not symmetric about 90°.

There is no essential disagreement with Burcham's curve on carbon. The absolute cross sections obtained here are lower, but the shape of the curve is the same. I disagree with their conclusion that the curve is symmetric about 90° because the points of these data, although not as many in number, have better statistics (1.5 percent). They fall within their quoted statistical error. An examination was made to see whether the

[19] H. E. Gove and H. F. Stoddart, Massachusetts Institute of Technology Progress Report, February, 1952 (unpublished), p. 67.
[20] K. Boyer, Massachusetts Institute of Technology, Laboratory of Nuclear Science and Engineering Progress Report, July, 1950 (unpublished), p. 174.
[21] Allred, Armstrong, Bondelid, and Rosen, Phys. Rev. 88, 433 (1952).
[22] B. Cork, University of California Radiation Laboratory Report UCRL-2373 (unpublished).

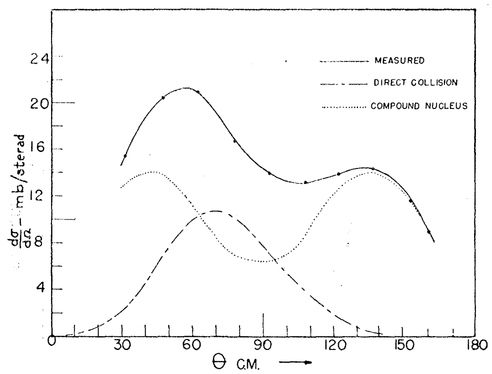


FIG. 7. The angular distribution of protons from the reaction $Mg^{24}(p,p')Mg^{24*}$, $Q=-1.38$. (For detail see text.)

counter efficiency varied with energy, hence with angle, of the incoming particle. Possible asymmetries in target alignment were checked. The conclusion was that errors from these sources were 3 percent at the very most. No data exist for 45°, for at this angle the hydrogen elastic peak overlaps the inelastic peak and a subtraction of the hydrogen cross section cannot be made accurately.

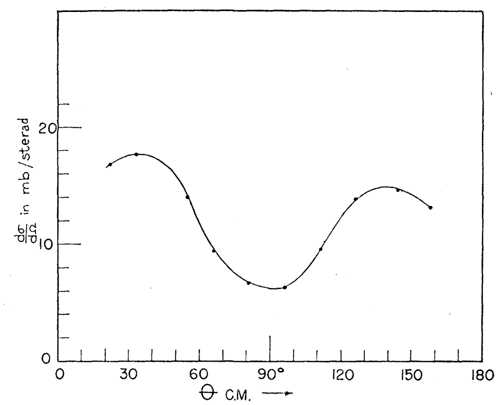


FIG. 8. The angular distribution of protons from the reaction $C^{12}(p,p')C^{12*}$, $Q=-4.4$.

## IV. DISCUSSION

The dashed curve presented in Fig. 7 was calculated from the simplest case in the direct collision theory of Austern, Butler, and McManus. Only two parameters were required in the calculation to satisfy the condition that when the curve was subtracted, the remaining contribution—that due to compound nuclear formation —be symmetric about 90°. These parameters, the amount of the direct process and the nuclear radius, are quite unique, for the calculation is very sensitive to them. The cross section does indeed turn out in millibarns and the nuclear radius used was $1.6\times10^{-13}A^{\frac{1}{3}}$ cm. It is not surprising that this radius should be a little large, for the scattering is assumed to take place at the very edge of the nucleus. (Neutron scattering leads to $1.57\times10^{-13}A^{\frac{1}{3}}$ cm: Feshbach.)[23] Whether the simplest case of the direct collision theory may be applied to magnesium (an even-even nucleus), and whether a statistical theory may be applied to the compound nuclear part (only 10 levels enter at this excitation) is not certain, but the results indicate that this is a start on the problem.

As for the elastic data, it is interesting to note that the angles at which diffraction effects are found in carbon and magnesium at 10 Mev are all proportional to those found by Cohen at 20 Mev by the same factor, namely, 1.39. If diffraction effects should indeed be proportional to λ, the wavelength of the incident proton in the center-of-mass system, the factor should be 1.48.

The author wishes to express his sincere gratitude to Professor A. C. Helmholz for his valuable guidance and support in all phases of the work. The ample assistance of Mr. Robert Ellis and Mr. F. Vaughan is gratefully acknowledged. The author is also indebted to Dr. Warren Heckrotte for several discussions on the analysis of the inelastic data and to all the members of the 60-inch cyclotron crew and staff who made this investigation possible.

[23] H. Feshbach and V. F. Weisskopf, Phys. Rev. **76**, 1550 (1949).