Elastic Scattering of Protons from Mg^{24}

F. P. MOORING,* L. J. KOESTER, JR.,† E. GOLDBERG, D. SAXON, AND S. G. KAUFMANN*‡§
University of Wisconsin, Madison, Wisconsin
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The differential scattering cross section has been determined for protons scattered elastically from Mg^{24} at a laboratory angle of $164°\pm 5°$. The targets consisted of thin $Mg^{24}F_2$ films evaporated onto thick graphite. Protons scattered elastically from Mg^{24} were selected by a 90° magnetic analyzer and were counted by a proportional counter. At least nine anomalies occur in the cross section between 0.40 Mev and 3.95 Mev, indicating the excitation of nine levels of the compound nucleus, Al^{25}. At several of the resonances, competing reaction cross sections have been shown to be relatively small.

I. INTRODUCTION

THE nuclear spectroscopist has tended to neglect the elastic scattering of charged particles by atomic nuclei as a method for studying nuclear spectra. The complication of the experimental results by coulomb scattering is possibly the reason for this neglect, yet this complication by its very nature allows the nuclear physicist to obtain from scattering data information about the excited states of compound nuclei that other nuclear reactions cannot of themselves reveal. The recent experiments[1-8] at the University of Wisconsin on the elastic scattering of charged particles from nuclei have demonstrated clearly the power of this form of nuclear spectroscopy. The present report is concerned with the applications of such methods to the study of excited states of Al^{25} which are formed by protons incident on Mg^{24}.

The theory of elastic scattering of protons from nuclei with spin zero has been worked out in detail for the case of no competing reactions. (For discussions of the scattering equation see the references given in footnotes 7 and 8.) For such nuclei the theory allows one to make determinations of the angular momenta of the excited states of the compound nucleus and their parities relative to the ground state of the bombarded nucleus. One might expect the theory to be a good approximation for scattering resonances for which the elastic proton width is large compared to the sum of all other partial widths.

Mg^{24} has spin zero in the ground state and hence satisfies the first assumption of the theory. Protons with energies available from the Wisconsin electrostatic generator incident on Mg^{24} can initiate the following reactions:

$$p+Mg^{24}\rightarrow Al^{25*}\rightarrow Mg^{24}+p, \qquad (1)$$

$$p+Mg^{24}\rightarrow Al^{25*}\rightarrow Mg^{24*}+p'; \quad Mg^{24*}\rightarrow Mg^{24}+h\nu, \qquad (2)$$

$$p+Mg^{24}\rightarrow Al^{25*}\rightarrow Al^{25}+h\nu; \quad Al^{25}\rightarrow Mg^{25}+\beta^{+}. \qquad (3)$$

The cross section for reaction (3) should be relatively small compared with the elastic process. As for reaction (2), only direct measurements will allow one to make any statement about the relative values of the elastic and inelastic cross sections.

Previously, little information has been available concerning the excited states of Al^{25}. Curran and Strothers[9] bombarded thin targets of non-isotopic magnesium oxide with protons in the energy range from 0.150 Mev to 1.00 Mev and counted both gamma-rays and positrons. They found the half-life of the positron activity to be approximately 7 sec. Since Al^{26} was known to have approximately a 7-sec half-life and since Al^{27} was known to be the only stable aluminum isotope, they attributed the resonances which exhibited a positron activity to the reaction $Mg^{25}(p,\gamma)Al^{26}$ and those which did not they attributed to the reaction $Mg^{26}(p,\gamma)Al^{27}$. We now know that Al^{25} has a half-life of 6.3 sec;[10] hence, one might question the assignments of Curran and Strothers, especially since Mg^{24} is the principal isotope in ordinary magnesium.

Other workers[11,12] have since studied the (p,γ) reactions of the magnesium isotopes in a manner similar to Curran and Strothers. Tangen[12] knowing that both Al^{25} and Al^{26} have about the same half-lives, assigned from intensity considerations the (p,γ) resonances at 222 kev and 417 kev to the reaction, $Mg^{24}(p,\gamma)Al^{25}$. Using

* Now at Argonne National Laboratory, Chicago, Illinois.
† AEC Predoctoral Fellow. Now at University of Illinois, Urbana, Illinois.
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§ Work supported in part by the AEC and in part by the Wisconsin Alumni Research Foundation.
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TABLE I. Analysis of magnesium isotope.

Isotope	Mass analysis Atom percent	Error	Spectroscopic analysis Element[a]	Percent
Mg^{24}	99.50	±0.02	Ag	<0.04
Mg^{25}	0.34	±0.01	Ca	<0.08
Mg^{26}	0.16	±0.01	Cu	<0.04
			Fe	<0.04
			Na	0.08
			Si	<0.05

[a] Impurities other than those listed were not detected.

isotopic targets Grotdal, *et al.*,[13] later confirmed the assignments of Tangen.

II. EXPERIMENTAL ARRANGEMENT

Monoenergetic protons produced by the Wisconsin electrostatic generator in conjunction with the 90° electrostatic analyzer, were used to bombard thin films of $Mg^{24}F_2$ evaporated onto spectroscopically pure graphite backings. Protons scattered elastically from Mg^{24} at a laboratory angle of 164°±5° were selected by a 90° magnetic analyzer[2] and were counted by a proportional counter and conventional counting circuits. The elastic scattering yield was observed as a function of incident proton energy over the energy range from approximately 0.40 Mev to 3.95 Mev. The experimental points were taken about 3 kev apart except at resonances where they were taken somewhat closer together. During the initial survey run the resolution of the 90° electrostatic analyzer was maintained at 1000. Later, for particular resonances, the resolution was raised to higher values.

The target chamber was insulated from the rest of the apparatus by Lucite spacers. Secondary electron currents were prevented from passing into or our of the target chamber by a suitably placed electron barrier maintained 300 volts negative with respect to the rest of the apparatus. A current integrator,[14] dependable to ±0.1 percent for ion beams of a few hundredths of a microampere or more, was used to determine the total proton charge incident on the target during a run.

TABLE II. Characteristics of targets.

Target No.[a]	Target material	Backing	Use	Target thickness for 1-Mev protons (kev)[b]
1	$Mg^{24}F_2$	graphite	Elastic scattering, better resolution data	1.4
3	$Mg^{24}F_2$	graphite	Elastic scattering, below 0.85 Mev	2.3
5	$Mg^{24}F_2$	graphite	Elastic scattering above 0.85 Mev	6.3
6	$Mg^{24}F_2$	1000A nickel	Inelastic scattering	10.1
7	non-isotopic magnesium	1000A nickel	Inelastic scattering	>60

[a] Targets were numbered according to position on target holder.
[b] Includes thickness of tantalum in target.

[13] Grotdal, Lönsjö, Tangen, and Bergström, Phys. Rev. **77**, 296 (1950).

[14] G. M. B. Bouricius and F. C. Shoemaker, Rev. Sci. Instr. **22**, 183 (1951).

III. TARGETS

In view of the large number of (p,γ) resonances previously seen with non-isotopic magnesium targets below 1 Mev,[9,11–13] of which only two have been identified as arising from the reaction[13] $Mg^{24}(p,\gamma)Al^{25}$, it was decided to use isotopic targets in the present experiment. The Mg^{24} isotope was obtained in the form of MgO from the Union Carbide and Carbon Corporation, Oak Ridge, Tennessee. An analysis furnished with the oxide is shown in Table I.

Because MgF_2 is easily evaporated to form uniform durable films, the MgO was converted to MgF_2. The chemistry was performed in connection with an earlier experiment.[5] The targets used during the elastic scattering runs consisted of thin $Mg^{24}F_2$ films evaporated onto thick spectroscopically pure graphite backings. Thin 1000A nickel-backed targets were used during investigations of low energy proton groups. Table II lists the characteristics of the targets used. The target material was evaporated from a tantalum boat. Hence, each target contained a small amount of tantalum which increased the absorption thickness of the targets but in no other way affected the results of the experiment.

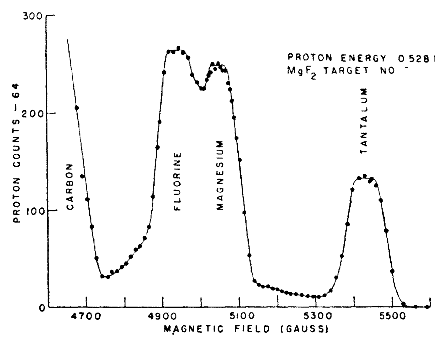

FIG. 1. Momentum analysis taken with the $Mg^{24}F_2$ target No. 3 at a proton bombarding energy of 0.528 Mev.

IV. MAGNETIC ANALYZER

A 90° magnetic analyzer[2] was used to select the proton groups scattered from the various elements in the target. Figure 1 shows a momentum analysis taken with target No. 3 at an incident proton energy of 0.528 Mev. During the elastic scattering yield measurements the field of the magnetic analyzer was adjusted to count only the protons scattered elastically from Mg^{24}. Frequent momentum analyses similar to that shown in Fig. 1 were taken throughout the experiment to insure that the field was being properly adjusted to count elastic protons from Mg^{24}.

The magnetic field was measured with a proton resonance detection unit of the type described by Knoebel

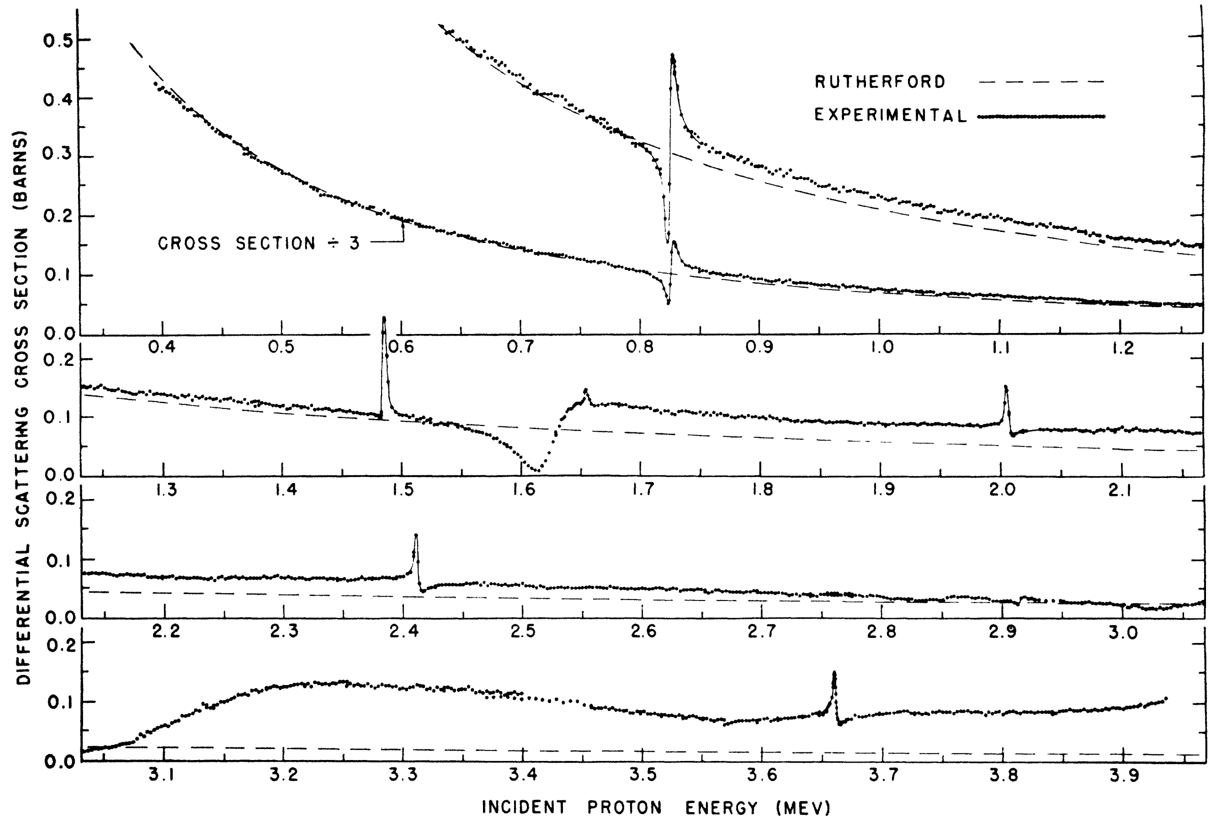

FIG. 2. Differential scattering cross section in barns per steradian for protons scattered elastically from Mg^{24} at a laboratory angle of $164°\pm5°$ as a function of incident proton energy.

and Hahn.[15] The resonant frequency of the proton resonance detector was measured with a war surplus Army Signal Corps frequency meter, BC-221-AF, the calibration of which was checked periodically against a standard 1000 kilocycle crystal. Field measurements were easily reproducible to within the 0.1 percent needed in the present experiment.

For fields above 13,000 gauss, field inhomogeneities apparently prevented a proton resonance signal large enough to be detected. Above 13,000 gauss a flip coil and fluxmeter was used to measure the magnetic field. Fortunately, the differential cross section for protons scattered elastically from Mg^{24} greatly exceeds that for protons scattered elastically from F^{19} at incident proton energies above 3.1 Mev. (Figure 2 shows a large rise in the Mg^{24} cross section at these energies.) Thus, the number of protons scattered at 164° from Mg^{24} greatly exceeded the number scattered from F^{19}. If the magnetic field became either too high or too low to count the protons scattered from Mg^{24}, a lower counting rate would occur. Hence, above a bombarding energy of 3.1 Mev, the proton counting rate could be used to indicate whether or not the magnetic field was properly adjusted.

[15] H. W. Knoebel and E. L. Hahn, *A Transition Nuclear Magnetic Resonance Detector*, Preliminary Report, University of Illinois.

V. COUNTING ARRANGEMENT

A proportional counter was used to count the charged particles. The counter consisted of a 2-in. brass cylinder with an insulated 0.005-in. molybdenum wire anode. The counter gas was a mixture of argon and 2 percent carbon dioxide.

Alpha-particles arising from the reaction $F^{19}(p,\alpha)O^{16}$ formed a background for the elastically scattered protons over much of the energy range covered. By properly adjusting the counter voltage and gas pressure a large differentiation in pulse sizes was obtained. Two similar scalers were used to record these pulses. One was biased to count all the particle pulses, while the other was biased to count only the alpha-pulses. The proton yield measurements represent the differences between the readings obtained with the two scalers.

VI. DISCUSSION OF RESULTS

(A) Cross-Section Determination

Figure 2 shows, as a function of incident proton energy, the differential scattering cross section in barns per steradian for protons scattered elastically from Mg^{24} at a laboratory angle of $164°\pm5°$. The differential cross-section values were determined by assuming that the scattering was Rutherford below 0.8 Mev. The fact

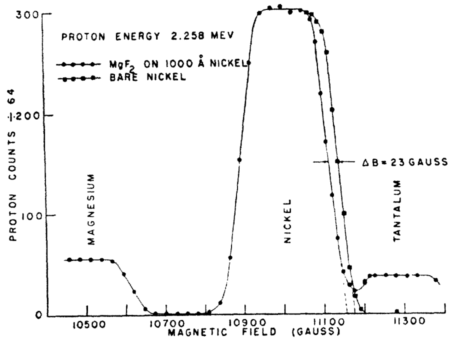

FIG. 3. Momentum analyses showing shift in the nickel group. The circles represent data taken with a thin $Mg^{24}F_2$ film evaporated onto a 1000A nickel foil; the squares, data taken with a blank 1000A nickel foil. The shift of 23 gauss corresponds to an absorption thickness of 10 kev for 1-Mev protons.

that the scattering yield follows a one over energy squared law for the lower proton energies is evidence for this assumption. Estimates based on scattering theory indicate that at an incident proton energy of 0.5 Mev the differential scattering cross section should deviate from the Rutherford value by no more than 2 percent unless the interaction radius is more than five times the usually accepted one.

Target thickness determinations indicate that the cross-section assignments are not far in error. Figure 3 shows two momentum analyses taken at an incident proton energy of 2.258 Mev. The circles represent data taken with a thin $Mg^{24}F_2$ target evaporated onto a 1000A nickel foil; the squares, data taken with a blank 1000A nickel foil. The shift of the high energy edge of the nickel group corresponds to the energy lost by a proton in passing twice through the $Mg^{24}F_2$ film. This shift at half-maximum is 23 ± 5 gauss, which corresponds to an absorption thickness for the $Mg^{24}F_2$ film (including the tantalum impurity) of 10.1 ± 2.2 kev for 1-Mev protons. From this one calculates for the differential scattering cross section at 1 Mev a value of 0.23 ± 0.06 barn per steradian, whereas one gets from the assumption of Rutherford scattering at low energies a value of 0.233 ± 0.008 barn per steradian for the cross section at 1 Mev.

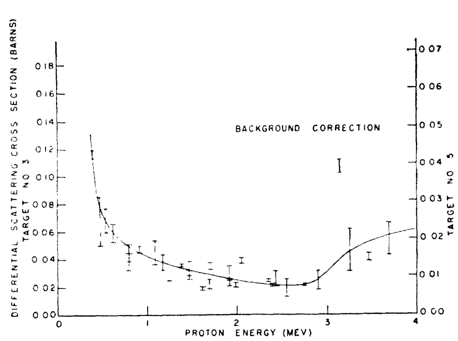

FIG. 4. Background correction curves for targets No. 3 and No. 5. The data are a compilation of background measurements made with three different graphite backings.

(B) Background Corrections

The targets used to obtain the data in Fig. 2 were backed with thick graphite. Although a spectroscopic analysis revealed only slight traces of impurities in the graphite, a large background scattering arose from these impurities. Figure 4 shows the background curve that was used to correct the experimental data. The curve is a compilation of background measurements made with three different targets, No. 1, No. 3, No. 5. These data indicate that the background is very nearly independent of target thickness, but arises primarily from impurities in the thick graphite used as target backings.

The data for the correction curve were taken from the momentum analyses, which for the most part exhibit a high energy tail on the magnesium peaks. Figure 1 shows such a momentum analysis. One might expect that the background scattering continues to rise under the magnesium peak. However, measurements made in an earlier experiment with blank graphite targets from the same lot[1] indicate that the background scattering does level off at a magnetic field corresponding to the magnesium peak.

The length of the vertical line at each experimental point on the correction curve represents an estimate of a maximum and a minimum value of the background scattering. These estimates exceed, except at one point, the uncertainties due to statistical fluctuations. A smooth curve was drawn through the points and the scattering yield measurements were corrected accordingly.

(C) Discussion of Curve

The differential scattering cross section curve (Fig. 2) shows several interesting features. At least nine different scattering anomalies occur in the cross section between 0.40 Mev and 3.95 Mev corresponding to excited states of Al^{25}. The fluctuation in the experimental points at 2.91 Mev was repeated several times and appears to be real. Above 3.7 Mev the cross section rises, probably because of the presence of a broad resonance somewhere above 3.95 Mev.

The resonance reported by Grotdal, *et al.*,[13] for an incident proton energy of 0.417 Mev was not observed in the present experiment, although the differential scattering cross-section measurements extended down to a bombarding energy of 0.396 Mev. A resonance which is markedly asymmetric, i.e., has a dip of small area compared to its rise, will usually cause an observable anomaly even though the resonance width is small compared to the spread in proton energies, whereas a narrow resonance symmetric about the Rutherford level might have been missed because of inadequate resolution. On the other hand, the resonance may occur below a bombarding energy of 0.396 Mev.

For comparison, the theoretical Rutherford cross section is shown in Fig. 2 over the entire range of bombarding energies. On the low energy side of the 0.83-Mev resonance the observed cross-section values follow closely the expected coulomb scattering, whereas on the high energy side it is about 10 percent higher. Since the data below 0.85 Mev were taken with target No. 3 and the data above with target No. 5, there may be some question concerning the reality of this deviation. However, the available evidence indicates that the deviation is real.

Data taken with both target No. 3 and target No. 5 near the 0.83-Mev and the 1.49-Mev resonances give the same normalization factor between the two targets and lead to the cross-section values shown in Fig. 2. Also, a series of momentum analyses taken with target No. 1 on both sides of the 0.83-Mev resonance appears to confirm the observed deviation from Rutherford scattering.

The experimental points fall somewhat below the theoretical Rutherford cross section for the lowest bombarding energies. This small deviation, which becomes more pronounced with decreasing energy, is believed to be due to target thickness effects. The energy lost by a proton in the target increases with decreasing proton energy. Hence, the spread in momenta of the scattered protons increases with decreasing energy, and as a consequence the image formed by the magnetic analyzer becomes wider. For sufficiently low bombarding energies the image becomes wider than the exit slits and some of the scattered protons that enter the magnetic analyzer chamber will be intercepted by the exit slits. These considerations are believed to account for the deviation of the experimental points from the Rutherford values below 0.45 Mev.

(D) The Effect of Mg^{25} and Mg^{26}

The magnesium fluoride used in this experiment contained 99.5 percent Mg^{24}, 0.34 percent Mg^{25}, and 0.16 percent Mg^{26} (see Table I). The contaminating magnesium isotopes are believed to have had a negligible effect on the results of the present experiment. In order that the elastic scattering yield of Mg^{25} be as much as 5 percent of the yield from Mg^{24}, the differential scattering cross section of Mg^{25} must be 14.6 times that of Mg^{24}. Except possibly at resonances, it is unlikely, in view of scattering theory, that the cross section of Mg^{25} so greatly exceed that of Mg^{24}. A similar argument also holds for the effect of Mg^{26}.

(E) Evidence for Scattering from Magnesium

Early in the experiment, in order to see if the resonances being observed were caused by scattering from Mg^{24}, short yield curves of protons scattered elastically from non-isotopic magnesium, Mg^{24}, and F^{19} were taken for incident proton energies near 2.00 Mev. The results are shown in Fig. 5. A scattering resonance was observed with an ordinary magnesium metal target. With the $Mg^{24}F_2$ target, when the magnetic field was adjusted to count protons scattered elastically from Mg^{24}, a resonance was observed at the same energy and with a similar shape; but, when the field was adjusted for protons scattered from fluorine, no anomalous scattering was observed. This is good evidence that the results obtained in the present experiment are due to the elastic scattering of protons from Mg^{24}.

VII. HIGHER RESOLUTION DATA

In analyzing elastic scattering data it is important to know the shapes of the scattering anomalies, since detailed information on the shape of a scattering anomaly permits, in most cases, an unambiguous determination of the angular momentum and relative parity of the corresponding excited state of the compound nucleus. In the present experiment, the shapes of the broad resonances near 1.6 Mev and 3.1 Mev (Fig. 2)

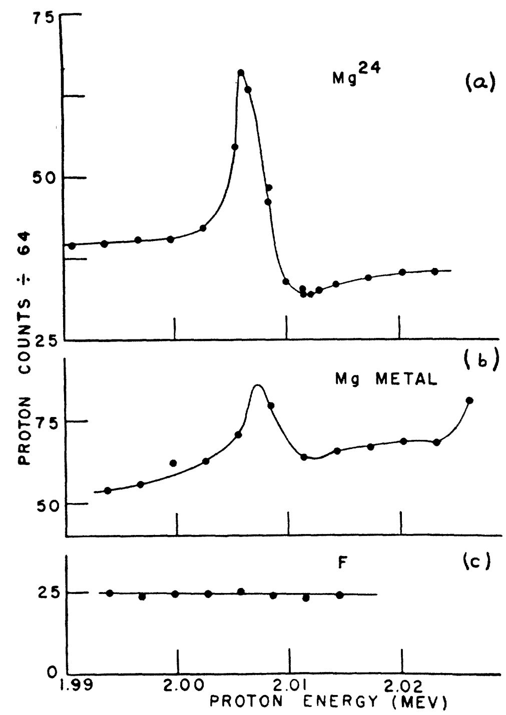

FIG. 5. Elastically scattered proton yields from (a) Mg^{24}, (b) non-isotopic magnesium metal, and (c) F^{19}, for bombarding energies near 2.000 Mev.

are though to have been little affected by target thickness and energy resolution. Except for the 3.66 Mev resonance, better resolution data were taken for all the narrow resonances. Target No. 1 was used for all of these measurements, the results of which are shown in Fig. 6. Repeated data near 2.91 Mev merely served to confirm the existence of a level in this region, and the results are not shown. Attempts to reach again energies above 3.5 Mev failed, and a pressing time schedule prevented further investigation of the 3.66-Mev level.

In each of the curves of Fig. 6 a triangle is used to represent the energy distribution in the incident proton beam. The cited proton energy spread is the ratio, in percent, of the width of the triangular distribution at half-maximum to the incident proton energy. A rec-

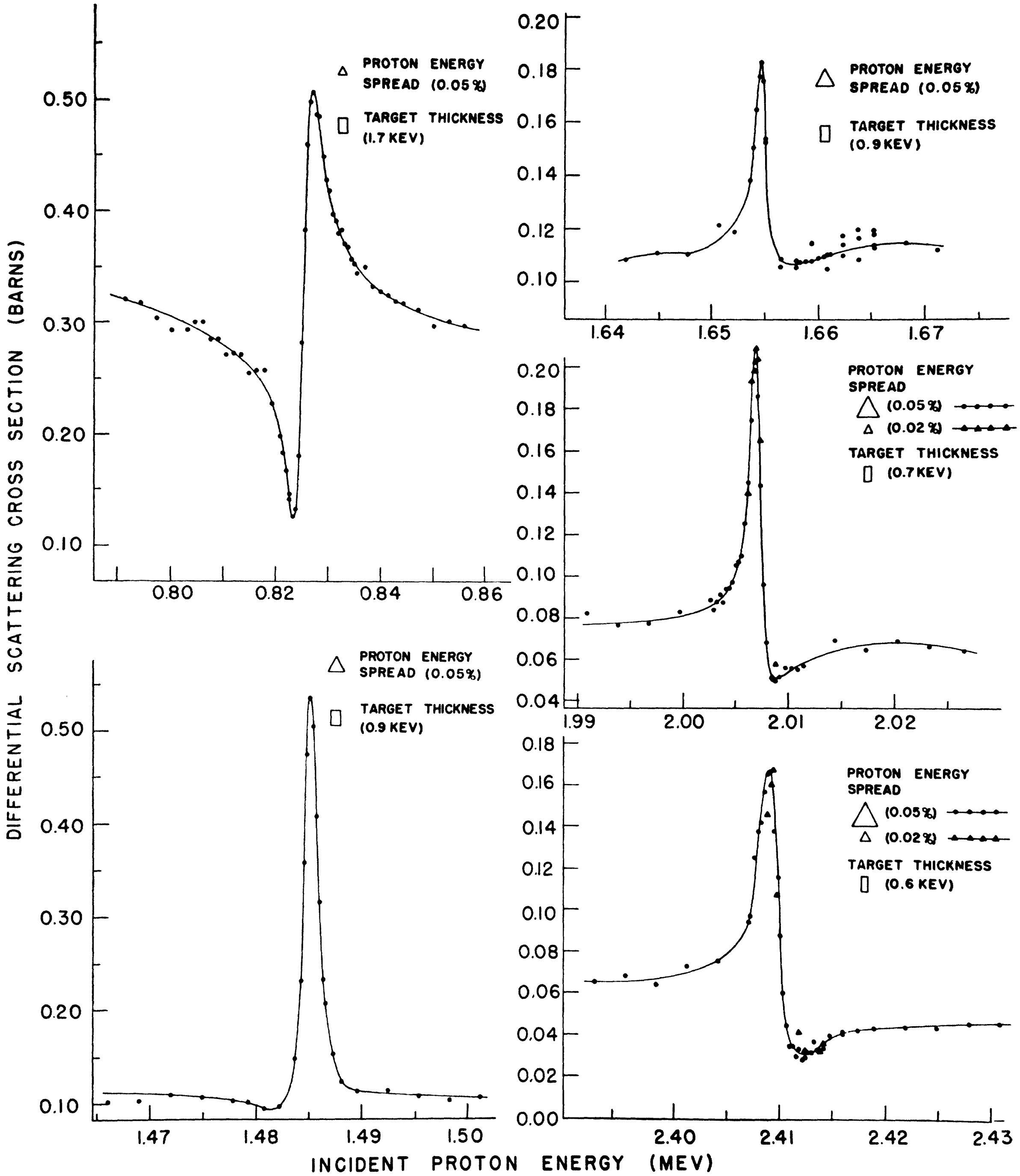

FIG. 6. A compilation of the better resolution data taken with target No. 1 over narrow resonances.

tangle is used to represent the target thickness at the resonance energy. A visual comparison of the energy spread and target thickness with the widths of the peaks and dips in the cross section at resonance gives some indication of how well the shapes of these resonances have been determined. In no case can it be said that target thickness and energy spread do not have an appreciable influence upon the observed shapes of the narrow resonances. No satisfactory method of correcting elastic scattering data for target thickness and energy spread is known to the authors.

VIII. COMPETING REACTIONS

In the simple form of scattering theory one assumes that there are no reactions other than elastic scattering and that the bombarded nucleus has zero spin in the ground state. The second of these assumptions is automatically satisfied by the choice of Mg^{24} as a target nucleus. In order to get an estimate of the relative value of the inelastic scattering cross section, momentum analyses were taken at several of the higher energy resonances. A non-isotopic magnesium metal target evaporated onto a 1000A nickel foil (target No. 7) was used in most of these measurements. For certain small regions target No. 6, a $Mg^{24}F_2$ nickel-backed target, was used.

Only at the 2.41-Mev resonance (Fig. 2) was a low energy proton group found that could be definitely attributed to the inelastic scattering of protons from Mg^{24}. At a bombarding energy of 2.416 Mev a low energy proton group was found with the magnesium metal target No. 7 at a magnetic field corresponding to the excitation of the well-known 1.38 Mev level[16] in Mg^{24}. This group persisted when the $Mg^{24}F_2$ target No. 6 was used. Short excitation curves taken for both the elastic and inelastic groups showed a resonance at the same incident proton energy. These data indicate that the low energy group is due to the inelastic scattering of protons from Mg^{24}, leaving it in the 1.38-Mev excited state. Estimates based on relative target thicknesses and observed yields indicate that at the 2.42-Mev resonance the differential inelastic scattering cross section is about 10 percent to 15 percent of the off-resonance elastic value.

Momentum analyses were also taken at the 2.01-Mev, 2.92-Mev, and the 3.1-Mev resonances. At each resonance a weak proton group was found that may be due to the inelastic scattering of protons from Mg^{24}. However, the evidence is anything but conclusive. Assuming that the observed low energy groups are inelastic proton groups from Mg^{24}, one finds that at the 2.01-Mev resonance the inelastic cross section is less than one percent of the off-resonance elastic value; at the 2.92-Mev resonance the inelastic value is about 10 percent of the off-resonance elastic value; and at the 3.1-Mev resonance the inelastic value is less than 2 percent of the elastic value at 3.25 Mev.

The level in Mg^{24} responsible for the observed low energy groups at the 2.92-Mev and the 3.1-Mev resonances, if they are indeed due to Mg^{24}, is the 1.38-Mev level. At the 2.01-Mev resonance a low energy proton group occurs at a magnetic field corresponding to the excitation of a level in magnesium 0.78 Mev above the ground state. The only reported level in any of the magnesium isotopes that can account for this level is the 0.83-Mev level in Mg^{24} observed by Mandeville.[17] The agreement is within experimental uncertainties. However, since a non-isotopic target was used for the momentum analysis at the 2.01-Mev resonance, the observed weak proton group may arise from some unknown level in either Mg^{25} or Mg^{26}.

No further investigations of the occurrence of inelastic scattering at any of the other resonances were made. Except possibly at the 2.41-Mev resonance, it is unlikely that competing processes have effects on the narrow resonances comparable to the large distortions introduced by target thickness and the spread in proton energies. For this reason, extensive measurements of the cross sections of the competing reactions did not appear profitable.

IX. CONCLUSIONS

Analyses of other elastic scattering data have recently been completed at the University of Wisconsin. By applying scattering theory to the observed differential cross section for protons scattered elastically from O^{16}, Laubenstein and Laubenstein[7] were able to infer values for the angular momenta and relative parities of several excited states of F^{17}. By analyzing the data of Goldhaber and Williamson[3] on the scattering of protons from C^{12}, Jackson and Galonsky[8] found that the angular momenta and relative parities of excited states of N^{13} appear to be uniquely determined by the shapes of the elastic scattering resonances.

The interpretation of the data in the oxygen and carbon work was greatly hampered by large uncertainties in the cross-section values introduced by experimental difficulties. The widths of the resonances were for the most part relatively large; consequently, target thickness and proton energy spread had little effect on the observed shapes. In the present experiments, it is thought that the cross-section values are known to within 10 percent over most of the energy range covered. Except for the wide resonances near 1.6 Mev and 3.1 Mev, the observed shapes of the resonances were considerably affected by target thickness and proton energy spread. For these resonances the determination of the angular momenta of the compound states may be difficult. In several cases, however, it may be possible to eliminate for a resonance all but a few possible J-values by comparing the observed shape with predicted shapes.

At the higher energies the cross section rises, indicating the presence of a wide level above 3.95 Mev that reaches down to affect the scattering at lower energies. Such a resonance will introduce interference effects that will complicate the analysis of the 3.66-Mev resonance and possibly the 3.1-Mev resonance.

No attempt has been made in this report to state accurate resonance energies since they can be determined for a scattering resonance only by a theoretical analysis of the data. The numbers cited are used merely to identify particular resonances and are not intended to indicate true resonance energies. Attempts are at present being made to interpret the data in terms of dispersion theory.

The authors would like to express their appreciation to Professor R. G. Herb for his constant interest and encouragement throughout the experiment.

[16] D. E. Alburger and E. M. Hafner, Revs. Modern Phys. **22** 406 (1950).
[17] C. E. Mandeville, Phys. Rev. **76**, 436 (1949).