Inelastic Scattering in the 2s-1d Shell. I. Even-A Nuclei*

G. M. CRAWLEY† AND G. T. GARVEY
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
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The inelastic scattering of 17.5-MeV protons from a number of nuclei in the 2s-1d shell has been studied using lithium-drifted silicon detectors. Results for the even-A nuclei O^{16}, Mg^{24}, Mg^{26}, Si^{28}, and S^{32} are presented here. Angular distributions are obtained for up to twenty levels in each nucleus. While some of the angular distributions having the same l value are similar, there were a number of cases where angular distributions to states in the same nucleus with the same spin and parity have very different angular distributions. The differential cross sections for the most strongly excited levels are compared with a distorted-wave Born-approximation calculation using collective form factors. Reasonable fits to the differential cross sections were obtained for the $l=2$ transitions to the first excited states of Mg^{24}, Si^{28}, and S^{32} and for the $l=3$ transitions to the lowest-lying 3^- states of O^{16}, Mg^{24}, Si^{28}, and S^{32}. A previously unreported level in S^{32} at 6.76 MeV was observed.

I. INTRODUCTION

THE inelastic scattering of all projectiles, ranging from electrons to heavy ions, exhibits qualitative similarity in the relative intensity with which the states of the target nucleus are excited, provided the projectile energy is sufficiently high that the inelastic-scattering process may be considered as a "direct" interaction.[1–13] This similarity in relative intensities comes about because the incident projectile tends to preferentially excite the collective modes of the target nucleus. Therefore, the resulting energy spectrum of scattered particles is more characteristic of the target nucleus than the projectile type. In even-even nuclei the levels most readily excited are the lowest-lying states with spin parity 2^+ which show almost invariably strong collective behavior, and certain of the lowest-lying 3^- states.

The distorted-wave Born-approximation (DWBA) description of the inelastic-scattering process, in many cases, provides a satisfactory description for these strongly excited states.[14,15] When the magnitude of these cross sections are parameterized in the context of a collective model, the values obtained for the relevant parameters are in reasonable agreement with the values obtained from electromagnetic transition rates.

Because of the relatively better energy resolution available with semiconductor detectors many more levels than just the most strongly excited states can be resolved in inelastic-scattering experiments. For example, in this work some 30 peaks in the spectrum of protons scattered from Mg^{24} are observed with most of these peaks resulting from excitation of a single level. Recent microscopic descriptions of the inelastic-scattering process[16,17] could allow one to extract reliable nuclear-structure information from these more weakly excited levels if the reaction mechanism is sufficiently understood. Some theories of higher-order scattering processes have recently appeared,[18,19] but since they are spin-independent, their use for protons is questionable. A coupled-channel, spin-dependent treatment of the proton scattering is currently under consideration.[19] The body of data presented in this paper should serve as a good testing ground for new calculations of higher-order scattering processes.

The existing inelastic-scattering data at "direct

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† Present address: Physics Department, Australian National University, Camberra, Australia.

1 B. L. Cohen, Phys. Rev. **105**, 1549 (1957); B. L. Cohen and A. G. Ruben, *ibid.* **111**, 1568 (1958).

2 D. K. McDaniels, J. S. Blair, S. W. Chen, and G. W. Farwell, Nucl. Phys. **17**, 614 (1960); **17**, 641 (1960).

3 W. F. Hornyak and R. Sherr, Phys. Rev. **100**, 1409 (1955); P. C. Gugelot and M. Rickey, *ibid.* **101**, 1613 (1956); R. W. Peele, *ibid.* **105**, 1311 (1957).

4 M. Crut, D. R. Sweetman, and N. S. Wall, Nucl. Phys. **17**, 655 (1960).

5 H. W. Broek, T. H. Braid, J. L. Yntema, and B. Zeidman, Phys. Rev. **126**, 1514 (1962); J. Bellicard and P. Barreau, Nucl. Phys. **36**, 476 (1962).

6 G. Shrank, E. K. Warburton, and W. W. Daehnick, Phys. Rev. **127**, 2159 (1962).

7 A. Lieber and C. A. Whitten, Phys. Rev. **132**, 2582 (1963).

8 W. W. Daehnick and R. Sherr, Phys. Rev. **133**, B934 (1964).

9 W. W. Daehnick, Phys. Rev. **135**, B1168 (1964).

10 H. O. Funsten, N. R. Roberson, and E. Rost, Phys. Rev. **134**, B117 (1964).

11 T. Stovall and N. M. Hintz, Phys. Rev. **135**, B330 (1965).

12 G. T. Garvey, A. M. Smith, and J. C. Hiebert, Phys. Rev. **130**, 2397 (1963); J. C. Hiebert and G. T. Garvey, *ibid.* **135**, B346 (1964).

13 J. S. Blair, in *Proceedings of the International Conference on Nuclear Structure, Kingston, 1960*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 824; in *Proceedings of the International Conference on Direct Interactions, Padua, Italy, 1962*, edited by E. Clementel and C. Villi (Gordon and Breach Science Publishers, Inc., New York, 1963), pp. 669–692.

14 N. Austern, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1961), Vol. 2, Chap. 5.

15 R. H. Bassel, R. N. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240, 1962 (unpublished); R. H. Bassel, G. R. Satchler, R. M. Drisko, and E. Rost, Phys. Rev. **128**, 2693 (1962).

16 N. K. Glendenning and M. Veneroni, Phys. Rev. **144**, 839 (1966).

17 G. R. Satchler, Nucl. Phys. **77**, 481 (1966).

18 N. Austern and J. S. Blair, Ann. Phys. (N. Y.) **33**, 15 (1965).

19 T. Tamura, Rev. Mod. Phys. **37**, 679 (1965); T. Tamura (private communication).

interaction energies" which resolves any save the most strongly excited levels is still quite meager.

Ten nuclei, O^{16}, F^{19}, Na^{23}, Mg^{24}, Mg^{25}, Mg^{26}, Al^{27}, Si^{28}, P^{31}, and S^{32}, have been studied in this series of experiments performed at 17.5-MeV incident proton energy, which an over-all experimental energy resolution of about 50 keV. The advantage of investigating all these nuclei at the same lab and at nearly the same center-of-mass energy is that direct comparison of the absolute cross sections is greatly facilitated. This has been found to be particularly useful in comparing[20] the cross section between states in even-even and the adjacent odd-even or even-odd nuclei. In this paper the results of the scattering from the even-even nuclei are presented. The results for the odd-even nuclei will be presented in a forthcoming publication.[21]

Of the nuclei presented in this paper, O^{16}, Mg^{24}, and Mg^{26} had been previously studied by proton scattering at this laboratory[3,6,9]; however, with the better energy resolution available to this experiment, new results are obtained in these cases. Mg^{26} and Mg^{24} have been studied with (d,d') [22] and (α,α') [23] and the scattering from O^{16} has been studied with a variety of projectiles.

Much of the best inelastic-scattering data in the $2s$-$1d$ shell has been obtained with α-particle beams.[23–26] The α particle has zero spin and isospin while the proton has $\frac{1}{2}$ in both cases; therefore, inelastic proton scattering has accessible to it states forbidden in first order to inelastic α scattering (e.g., unnatural parity states).[27] All states differing in isospin by one unit from the target ground state which may be excited lie at an excitation energy so high that they are not unambiguously resolved in the nuclei involved in this study.

II. EXPERIMENTAL TECHNIQUES

The facility for charged-particle-reaction studies at Princeton has been described previously.[10] However, during 1963–1964 the beam intensity and duty cycle of the Princeton FM cyclotron were greatly improved. The increased intensity was brought about by changing to a hooded arc source with "feeler" extraction and by employing a quadrupole magnet in the beam transport system previous to magnetic analysis. With this arrangement a beam of 0.015 to 0.025 μA with an energy spread of 30 keV could routinely be put through the scattering chamber.

The duty cycle has been increased by employing an auxiliary rf system which increases the spill time of the accelerated protons.[28] The duty cycle can be increased by a factor of 20 with a corresponding loss of beam intensity. This diminished beam with increased duty cycle is most useful at forward angles where the large yield from the elastic scattering causes excessive pileup if the duty cycle is not increased beyond the normal 3%. At more backward angles where pileup was not a limiting factor, the time-spread beam was not used and the measurements were carried out at maximum beam current.

The detectors used in these experiments were the lithium-drifted silicon type, fabricated at this laboratory. In order to reduce the leakage current and decrease the charge collection time the detectors were cooled to approximately $-50°$C by circulating methanol (which has in thermal contact with a dry ice and methanol reservoir) through the detectors' mounts. An ORTEC type 203 preamplifier and amplifier operated in the double-delay-line mode. With a detector bias of 225 V this setup yielded an electronic noise level of about 12 keV. The double-delay-line mode of operation was chosen because it has the least timing uncertainty associated with its output pulses which were subsequently passed through a biased amplifier and routed into a multichannel analyzer.

Preliminary measurements with some detectors showed a definite "tail" in the low-energy side of all peaks. The effect was most noticeable on the elastic peak at forward angles where this tail extended, in some cases, 4 to 5 MeV below the elastic peak. In spite of this effect the full width at half-maximum of the elastic peak would appear acceptable, being only about 50 keV. It was clear that these "tails" resulted from these detectors having less than unit efficiency for the detection of protons at these energies because cross sections calculated using the number of counts in the peak would be as much as 30% below previous measurements. Inclusion of the counts in the "tail" into the cross-section calculation brought about agreement with previous results. Not all detectors showed this effect and only those that did not were used for the measurements presented in this paper. There was some indication that detectors with narrower depletion regions were the most susceptible to this effect although all detectors indicated a depletion depth of more than 2 mm and should have been adequate for 17-MeV protons. Figure 1 shows a comparison of our data for the elastic scattering from O^{16} to that of Daehnick,[9] which was obtained using scintillation counters. The agreement is excellent.

The experiment was carried out using four detectors which simultaneously viewed the scattered protons. A block diagram of this arrangement is shown in Fig. 2.

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[20] G. M. Crawley and G. T. Garvey, Phys. Letters **19**, 228 (1965).
[21] G. M. Crawley and G. T. Garvey (to be published).
[22] A. G. Blair and E. W. Hamburger, Phys. Rev. **122**, 566 (1961).
[23] I. M. Naqib, Ph.D. thesis, University of Washington, 1962 (unpublished).
[24] A. Springer, University of California Radiation Laboratory Report No. UCRL-11681 (unpublished).
[25] J. Kokame, K. Fukunaga, and H. Nakamura, Phys. Letters **20**, 672 (1966).
[26] F. W. Bingham, Phys. Rev. **145**, 901 (1966).
[27] W. W. Eidson and J. G. Cramer, Phys. Rev. Letters **9**, 497 (1962).
[28] H. O. Funsten, A. Lieber, R. Roberson, and R. Sherr, Rev. Sci. Instr. **35**, 1653 (1964).

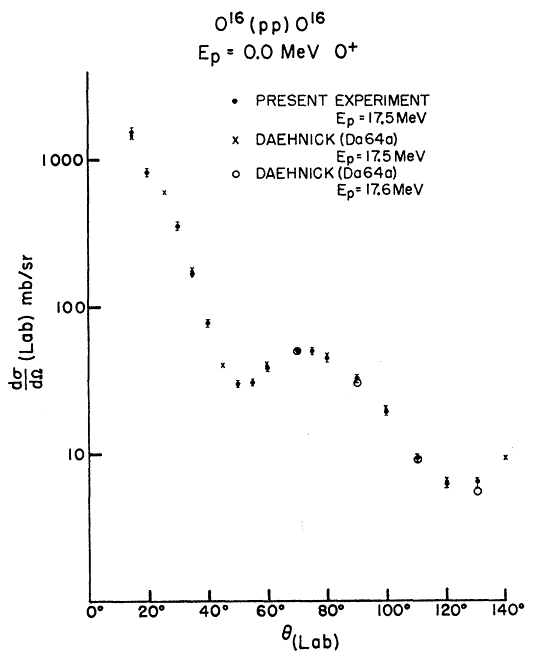

FIG. 1. Comparison of $O^{16}(p,p)O^{16}$ at $E_p = 17.5$ MeV taken with CsI counters and with Si(Li) detectors.

All detectors were tied in common through a single preamplifier. The routing signal associated with each detector was picked off with a small transformer (UTC-H45), amplified, and fed into the master routing circuit. The linear signals from the ORTEC 203 post-amplifier were attenuated and presented to a Nuclear Data 4096-channel analyzer to be routed into the subgroup of 1024 channels appropriate to that detector. If two routing signals occurred within 1.5 μsec, no pulse was stored. Dead-time corrections were made by additionally routing the signals from the detector with the lowest counting rate into another smaller analyzer in parallel with the 4096 and comparing the number of counts in the elastic peak from both analyzers. A correction based on this difference was then applied to all spectra in that run. In the worst cases the dead-time correction was 30% and was more typically 3 to 5%.

For reasons given above the linear amplification system was operated in a double-delay-line mode. In this mode the noise level is strongly dependent on the capacity at the preamplifier input. Care must be taken to keep this capacity at a minimum by the use of unshielded wire rather than cable for interconnecting the detectors and selecting pickup transformers for the routing signals with the smallest possible capacity. The resulting four-detector setup has a capacity of 20 pF as measured at the preamplifier input and so its effect on the noise level is negligible. The leakage current on each detector is below 0.1 μA so that connecting all four in common does not materially affect the noise due to detector current leakage.

To correct for possible drifts in the beam current integrator and/or target nonuniformity, a monitor counter permanently mounted at 90° was used.

Figure 3 shows a typical energy spectrum. With 50-keV resolution many states are clearly resolved in the target nucleus. The analysis of this type of data, involving some 15 to 20 levels per target taken at 20 different angles for 9 targets, requires the use of a computer. The data-analysis program assigns energies to each peak, compares this energy with that expected for the possible reactions, totals the number of counts in a peak, and if possible separates levels appearing in a single peak, and finally determines the center-of-mass cross section. The energy calibration is specified for each spectrum by indicating certain levels as known and specifying the incident energy. The computer then uses these levels to fix an energy scale for the spectrum. Energy determinations are made with a standard deviation often as small as 4 or 5 keV; however, to allow for any systematic errors which might be present, a 15-keV error is assigned to levels below 5-MeV excitation and a 25-keV error is assigned for the levels above.

III. TARGETS AND ABSOLUTE CROSS-SECTION DETERMINATION

Two of the targets used (viz., Mylar and aluminum) were available as thin foils of about 1 mg/cm² thickness. Four of these foils were cut using a machined block of known area as a check on the uniformity of the foils. For the absolute measurements of cross section, foils of a few mg/cm² thickness were used to reduce the error in the weighing, although there was good agreement between the thick- and the thin-foil measurements.

Mg^{24} and Mg^{26} were available as isotopically enriched foils but were heavily contaminated with oxygen and carbon. In addition, the Mg^{26} foil was quite nonuniform, which led to an increase of the total energy resolution of the detected protons to 70 keV. The Mg^{26} cross section was normalized to a previous measurement[6] at a lab angle of 60° where the elastic cross section is not

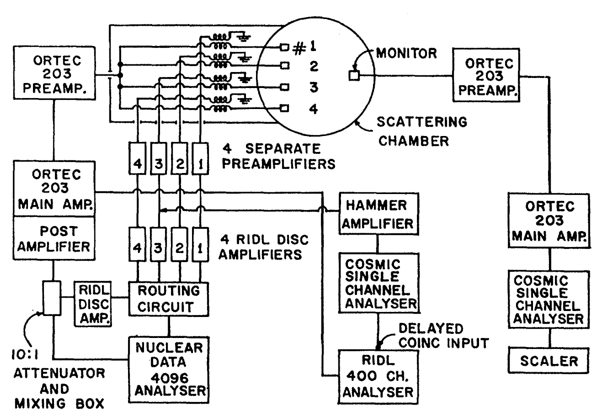

FIG. 2. The electronic block diagram of the system utilizing 4 detectors.

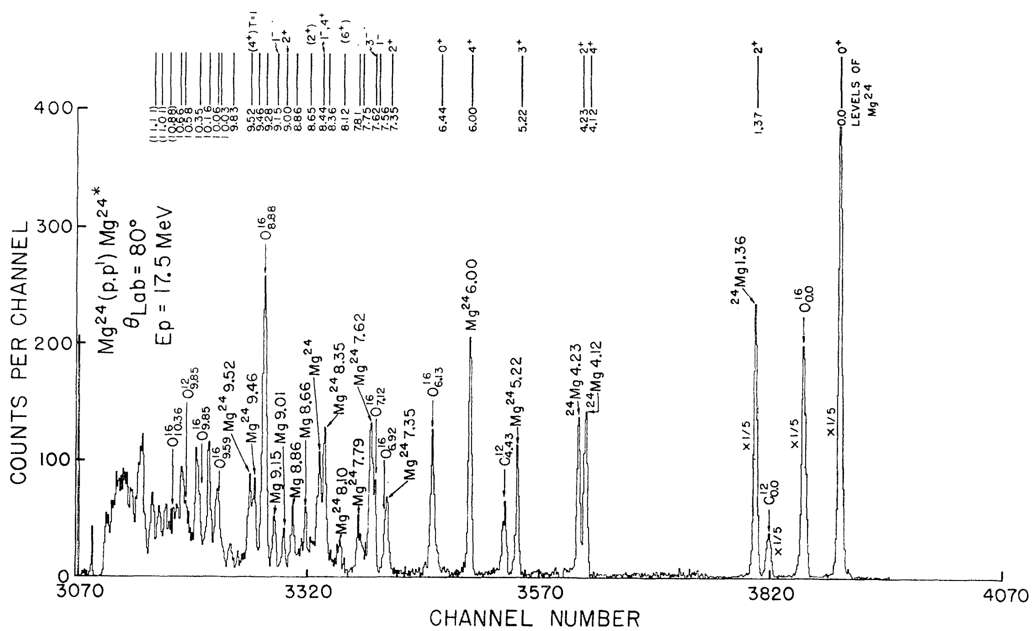

FIG. 3. Spectrum of inelastic protons from Mg^{24} at an incident proton energy of 17.5 MeV. The known energy levels of Mg^{24} up to 10.66 MeV are included. Above 10.66 MeV the energies shown in parentheses are those from the present experiments. The energies affixed to the spectrum are those determined from this experiment (see Sec. II of the text).

strongly angle-dependent. The Mg^{24} cross section was normalized using a thick foil of natural magnesium.

The silicon target was prepared by breaking a large, thin-wall quartz bubble and selecting a flat, uniform piece of sufficient size. The absolute cross sections were normalized using the known O^{16} elastic cross section and taking account of the isotopic abundance (92.21%) of Si^{28} in natural silicon.

Sulfur targets were prepared by condensing sulfur vapor on the surface of cold water where it formed an elastic film.[29] These films were backed by 20 μg/cm^2 of Formvar for support. The absolute cross section was measured in two different ways which agreed to 6%. First, a thick sulfur film obtained by the above technique was weighed after a low beam current run to obtain the absolute cross section. Next, CS_2 liquid was placed in the bottom of a gas cell with $\frac{1}{2}$ mil Havar windows. The vapor pressure of CS_2 at room temperature is approximately $\frac{1}{2}$ atm so the vapor makes a good gas target. The S^{32} cross section was obtained by normalizing to the known C^{12} cross section,[8] taking account of the isotopic abundance (95.0%) of S^{32} in natural sulfur.

IV. EXPERIMENTAL RESULTS

A. Inelastic Scattering from O^{16}

The spectrum of protons scattered by a Mylar $(C_{10}H_8O_4)_n$ target is shown in Fig. 4 along with an energy-level diagram[30] and angular distributions for the first six states in O^{16} are given in Fig. 5.[31] It is clear that the first excited 0^+ state at 6.05 MeV has been resolved from the strong 3^- state at 6.13 MeV. The angular distribution of this 0^+ state is the most weakly forward peaked of all the 0^+ states observed in this series of experiments. The cross section decreases rapidly beyond 90° and can no longer be separated from the 3^- state. The states at 6.92 MeV (2^+) and 7.12 MeV (1^-) are clearly separated. Both cross sections show quite strong forward peaking and have pronounced minima in their angular distributions at 80° and 120°, respectively.

The unnatural parity state at 8.88 MeV (2^-) has a flat angular distribution which decreases slightly at forward angles and is quite strongly excited. The strong excitation of this state has been noted previously[3,9] but is still somewhat surprising as the excitation of this state requires either a spin-flip reaction, a second-order scattering process, or a compound-nucleus contribution. In (α,α') experiments[32,33] this state is also strongly excited but in both proton[9] and α[33] scattering the cross section shows considerable energy dependence. The

[29] E. Nielsen and A. Weinstein, Rev. Sci. Instr. **24**, 1146 (1963).

[30] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1962).

[31] Tabulations of many of the cross sections presented in this paper are available in Princeton University Technical Report No. PUC-937-1965-164 (unpublished).

[32] B. G. Harvey, E. J-M Revit, A. Springer, J. R. Meriweather, W. B. Jones, J. H. Elliott, and P. Darriulat, Nucl. Phys. **52**, 465 (1964).

[33] University of Washington Cyclotron report, 1965 (unpublished).

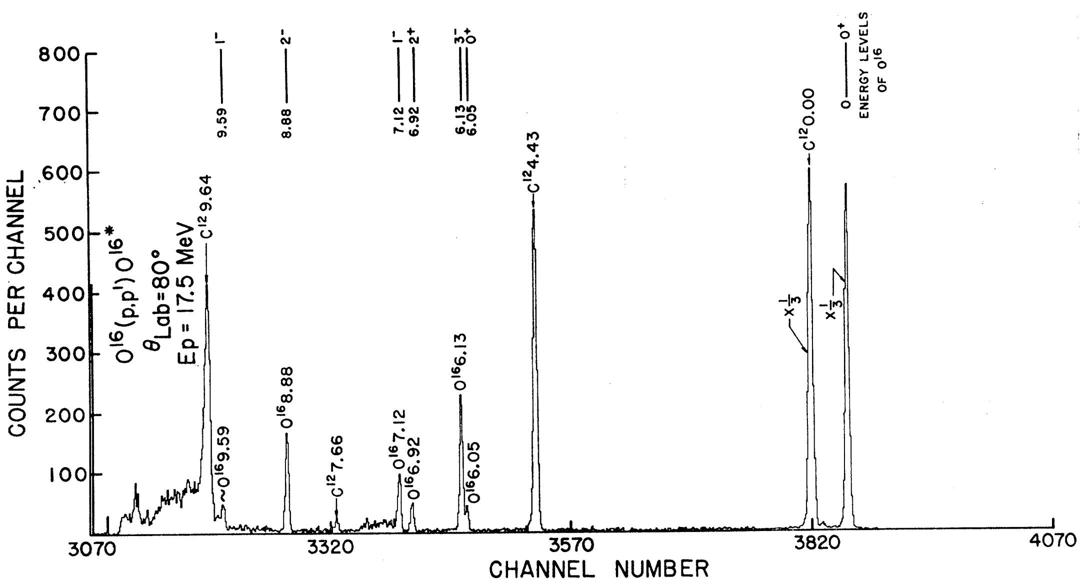

FIG. 4. Spectrum of inelastic protons from a Mylar target at an incident proton energy of 17.5 MeV. The known energy levels are also shown. See the caption to Fig. 3.

9.59- (1^-) and 9.85-MeV (2^+) states have been observed to be very weakly excited, having a cross section of less than 1 mb for all angles at which they were observed. The small cross section for the 9.85-MeV level is consistent with its small electromagnetic decay rate[34] to the ground state.

The inelastic scattering of 14–18-MeV protons from O^{16} has also been studied by Daehnick[9] with a resolution of about 180 keV compared with the 50-keV resolution in the present experiment. There is excellent agreement between the elastic cross sections from these two experiments. Daehnick was not able to separate either the 6.05- and 6.13-, or the 6.92- and 7.12-MeV doublets. Thus the cross section for the 6.13-MeV state in the present experiment is lower, particularly at forward angles, where the 0^+ state contributes about 10% of the total cross section of the doublet. Because of the different resolution, comparison with higher states is difficult, but the agreement of the summed cross sections of the 6.92- and the 7.12-MeV states is reasonable.

B. Inelastic Scattering from Mg^{24}

A spectrum of protons scattered from Mg^{24} at 80° is shown in Fig. 3. The known energy levels[35,36] up to 10.66 MeV are included in this figure. Above 10.66 MeV, the energies are those of the present experiment and are shown in parentheses. Angular distributions for a number of levels in Mg^{24} are shown in Figs. 6 and 7. One striking feature of these angular distributions now observed, because the states at 4.12 and 4.23 MeV are resolved, is the marked difference between the distributions for the first 2^+ state at 1.37 MeV and the 2^+ state at 4.23 MeV. Similarly, the 4^+ states at 4.12 and 6.00 MeV have very different angular distributions and magnitudes. These low-lying levels in Mg^{24} have been interpreted as the members of $K=0$ and $K=2$ bands built on the ground state and the 4.23-MeV (2^+) state, respectively. In the absence of a direct $l=4$ multipole transition between the Mg^{24} ground state and the 4.12-MeV state, this 4^+ ($K=0$) state would have to be excited by a higher-order process. It is interesting to note that the cross section of this state is four or five times smaller than the corresponding cross section of the first 4^+ states in Ne^{20} (Ref. 6) or Si^{28}. In Ne^{20} the first 4^+ state is also believed to be a member of the ground-state band while in Si^{28} the role of this state is not clear. In Si^{28} the angular distribution for the 4^+ state is more similar to the 4^+ state in Ne^{20}, and certainly different than in Mg^{24}. Thus there appears to be a marked difference in the matrix elements connecting the ground states and the first 4^+ states in these apparently similar nuclei.

The unnatural-parity 3^+ state in Mg^{24} at 5.22 MeV has a flat differential cross section and yields a much larger relative cross section in this (p,p') experiment than in (α,α') scattering.[23,27] The implication is that the spin-flip contributions are significant in inelastic scattering by 17.5-MeV protons. The cross section for the 0^+ state at 6.44 MeV shows the steep rise in the forward direction which seems to be characteristic of 0^+ states observed in this experiment.

The strongest states in the spectra above 7 MeV are levels at 7.35 (2^+), 7.62 (3^-), 8.36, 8.44, and 9.32 MeV.

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[34] R. E. Meads and J. E. G. McIldowie, Proc. Phys. Soc. (London) **A75**, 257 (1960).

[35] P. N. Endt and C. Van der Leun, Nucl. Phys. **34**, 1 (1962).

[36] R. W. Ollerhead, J. A. Kuehner, R. J. A. Levesque, and E. W. Blackmore, Bull. Am. Phys. Soc. **11**, 64 (1966).

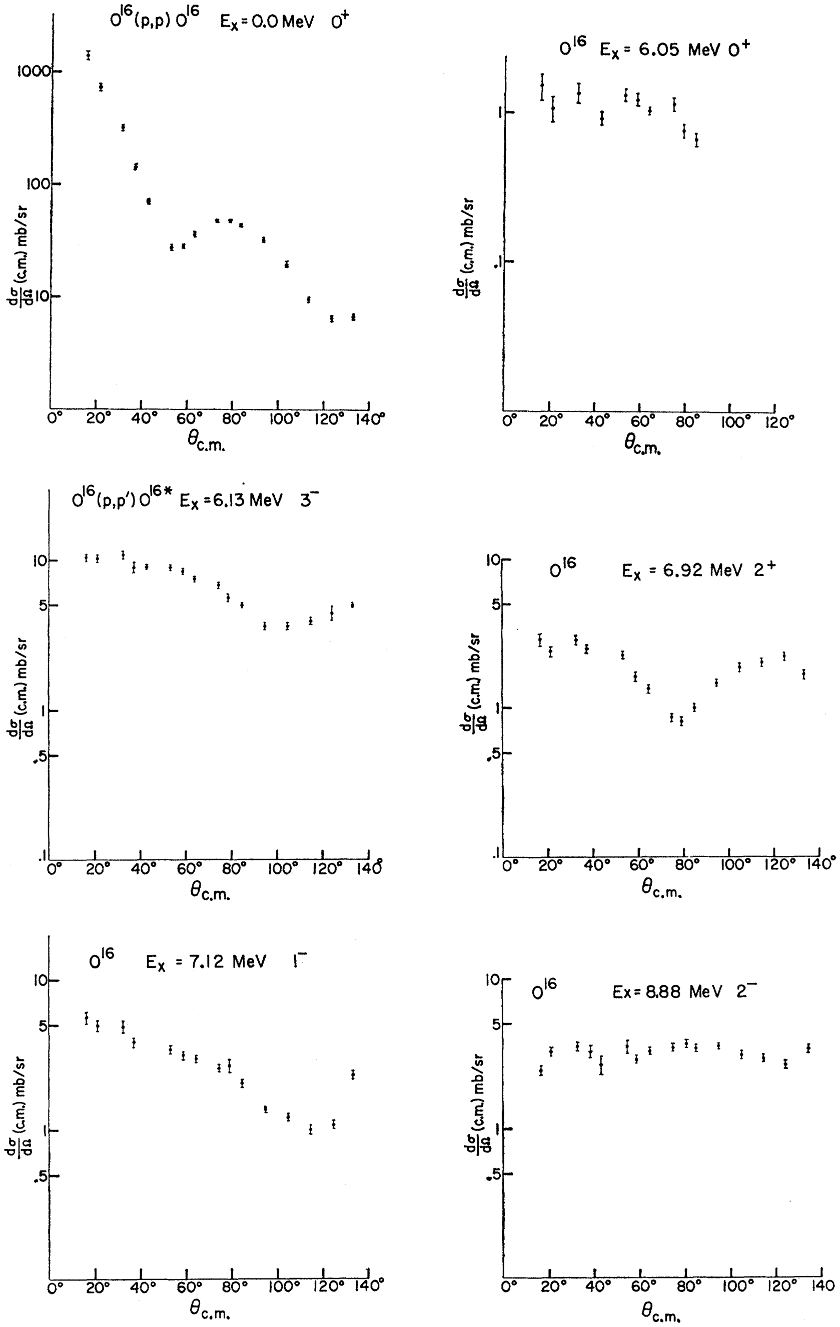

FIG. 5. Angular distributions for states in O^{16} excited by inelastic proton scattering. The errors shown do not contain the uncertainty in the absolute normalization (~10%).

Previous α-scattering data[23,25] suggest that the 8.36-MeV state has spin and parity 3^- while experiments studying γ decays[36] in Mg^{24} imply that there is a doublet (4^+ and 1^-) at 8.44 MeV which is not resolved in our experiment. It is not clear in the inelastic α-scattering experiments that there are not contributions from the doublet at 8.44 MeV to the peak observed at 8.36 MeV. A similar situation exists at around 9.5 MeV. The (p,p') spectra show levels at 9.44 and 9.52 MeV, the β^+ decay of Al^{24} [37] suggests a 4^+ level at 9.52 MeV, while γ-decay measurements[38] imply that the 9.52-MeV level has spin parity 6^+ ($K=2$). The most strongly excited level at high excitation has an energy of 9.320 ± 0.025 MeV which indicates that energy assigned in the literature[35] may be too low.

[37] M. Rickey, E. Kashy, and D. Knudsen, Bull. Am. Phys. Soc. **10**, 550 (1965).

[38] J. A. Kuehner and E. Almqvist, Bull. Am. Phys. Soc. **10**, 37 (1965).

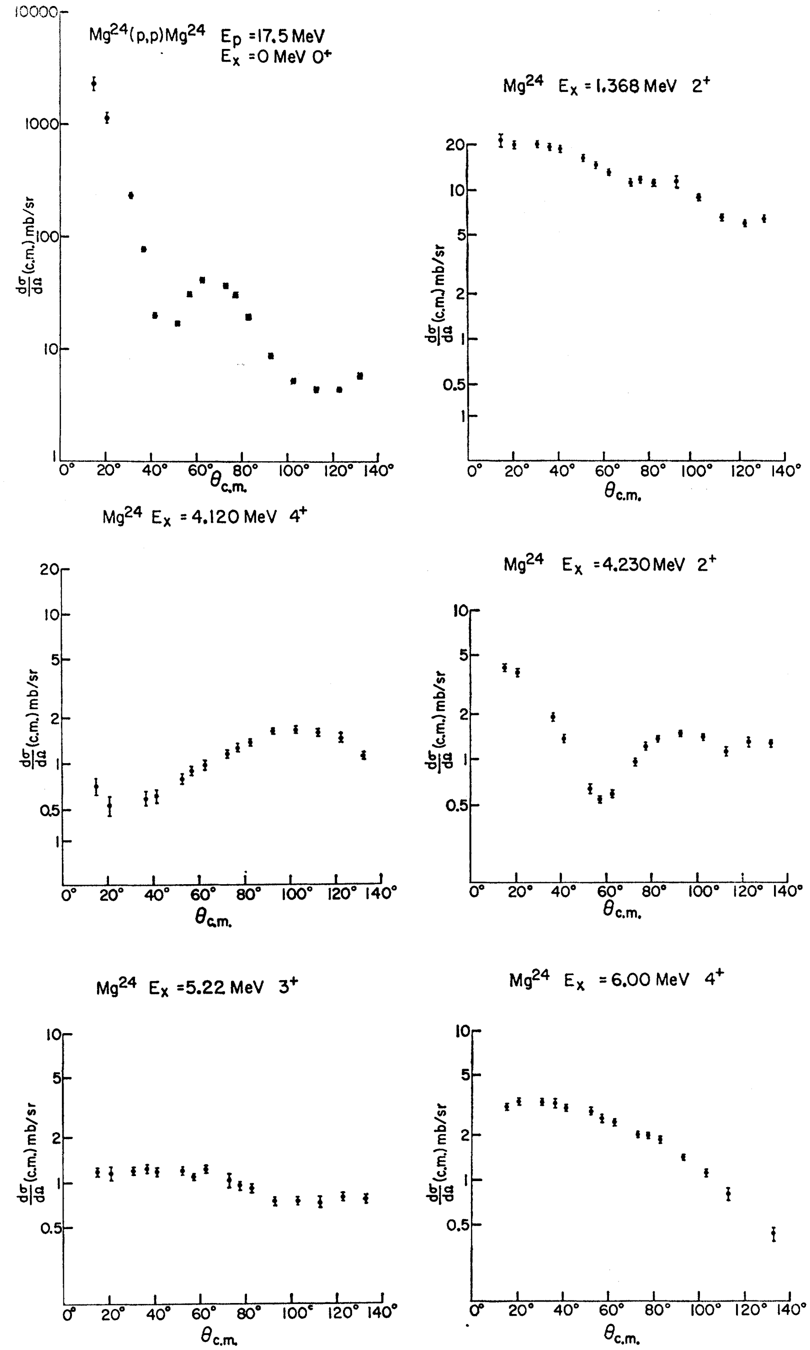

FIG. 6. Angular distributions for states up to 6.0 MeV in Mg^{24} excited by inelastic proton scattering. The errors shown do not contain the uncertainty in the absolute cross section (~10%).

C. Inelastic Scattering from Mg^{26}

A spectrum of inelastic protons scattered at 80° in the laboratory system is shown in Fig. 8. The known energy levels[35] up to 6.12 MeV are shown beside the spectrum. Above 6.12 MeV the computed values of the energies of peaks are given in parentheses. Angular distributions from a number of levels are shown in Fig. 9.

The groups of closely spaced levels known around 4.3 and 4.9 MeV are not resolved in this experiment, but the energies assigned to the corresponding peaks in the spectrum were 4.33±0.02 and 4.90±0.02 MeV. An examination of the proton spectrum indicates the 4.83- and 4.97-MeV states have cross sections at least three times smaller than that for the 4.90-MeV level.

The first 2^+ state at 1.81 MeV is again the most

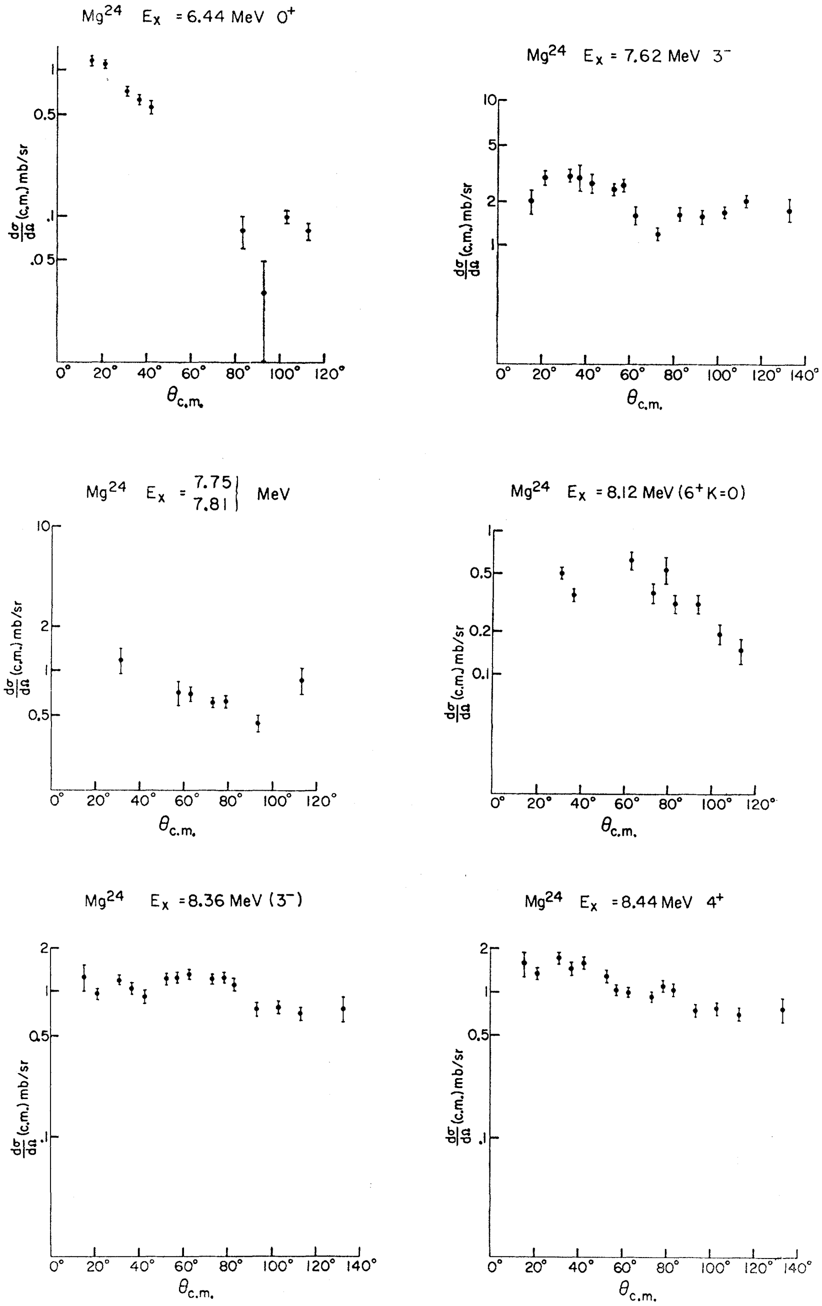

FIG. 7. Angular distributions for states from 6.44 to 8.44 MeV in Mg^{24} excited by inelastic proton scattering. The errors shown do not contain the uncertainty in the absolute cross section ($\sim$10%).

strongly excited but its cross section is not as large as the first 2^+ state of Mg^{24}. The second excited state at 2.94 MeV is also a 2^+ state and its angular distribution has the same slope as that of the 1.81-MeV state out to 70°. Beyond 70° the cross section for the 2.94-MeV state decreases more rapidly than the 1.81-MeV cross section. The angular distribution for the state at 4.90 MeV is very similar to that for the 1.81-MeV state back to 130° which suggests that its spin also is 2^+. However, none of these angular distributions resemble the angular distribution for either the first 2^+ (1.37-MeV) or the second 2^+ (4.23-MeV) states in Mg^{24}. In fact, these Mg^{26} distributions are rather similar to the Mg^{25} differential cross sections for the members of the ground-state rotational band, which are presumably also excited via a quadrupole mechanism.

The Mg^{26} state at 3.58 MeV, probably a 0^+ state, is only weakly excited, but does show the characteristic forward peaking observed for other 0^+ states in this region. The unnatural parity state at 3.94 MeV (3^+) has more structure in the angular distributions than other unnatural parity states in this region and is also

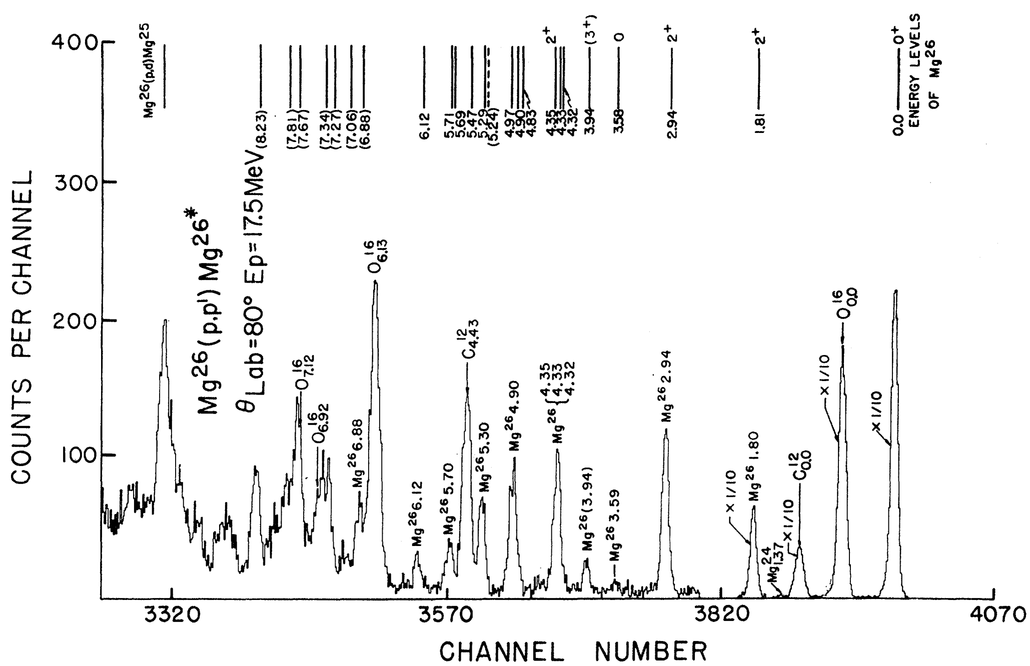

FIG. 8. Spectrum of protons scattered from a Mg^{26} target. See the caption to Fig. 3.

observed to have the smallest cross section. The cross section for this state decreases sharply in the forward direction. The angular distribution for the group of states at 4.3 MeV is rather flat and is similar to the distribution from the 3.94-MeV state, except at forward angles where the 4.33-MeV cross section increases. Of the group of states near 4.90 MeV only the 4.90-MeV state is observed to be strongly excited, in apparent disagreement with some inelastic α-scattering results.[39]

The results for the low-lying levels agree with the previous 18.1-MeV (p,p') data of Schrank *et al.*[6]

D. Inelastic Scattering from Si^{28}

A proton spectrum taken at 55° with an SiO_2 target is shown in Fig. 10. The known energy levels of Si^{28} [35] up to 8.3 MeV are also shown with a 3^- assignment shown for the 6.88-MeV state as a result of recent measurements.[40,41] Angular distributions for a number of levels in Si^{28} are shown in Fig. 11.

The 4^+ state at 4.61 MeV has a large cross section as is the case[6] in Ne^{20}. The angular distributions for the 4.61-MeV (4^+) state and the first 2^+ state at 1.77 MeV in Si^{28} are very similar out to 140°. The evidence from γ-γ correlation measurements by Broude and Gove,[42] however, confirms that the spin of the 4.61-MeV state in Si^{28} is indeed 4^+. This adds to the evidence found for the low-lying states of Mg^{24} that the shape of the angular distributions for inelastic proton scattering from these medium-light nuclei at this energy does not depend simply on the transferred angular momentum as seems to be the case for inelastic α scattering at 40 MeV.

The large yield observed corresponding to the excitation energy of 6.88 MeV is certainly due to the 3^- member of the doublet[41] at this energy; however, its somewhat irregular shape of the angular distribution indicates some contribution from the other state. The level shows enhanced electric octupole decay to the ground state[41] and thus should be strongly excited in inelastic scattering. The strong excitation of this level has been recently noted[25,26] in inelastic α scattering over a range of energies. It is interesting to note that the collective nature of this level along with the correct spin assignment had been made much earlier[43] but for some reason was overlooked. The shape of the angular distribution for the 6.88-MeV level is consistent with the shape expected for an $l=3$ transition.

The unnatural parity state at 6.27 MeV is observed to have a flat angular distribution with a magnitude of about 1 mb/sr. In this respect it is very similar to the 3^+ state at 5.22 MeV in Mg^{24}. However, it is not clear with which states its intensity should be meaningfully compared as it is in Mg^{24}. The excitation of this 6.27-MeV state is no larger than that observed[26] for inelastic α scattering at comparable energies.

[39] J. S. Blair, Argonne National Laboratory Report No. ANL-6878, especially pp. 148–150 (unpublished).

[40] R. Nordhagen, M. Hoffman, F. Ingebretsen, and A. Tveter, Phys. Letters **16**, 163 (1965).

[41] A. E. Litherland, T. K. Alexander, and P. J. M. Smulders, Bull. Am. Phys. Soc. **11**, 65 (1966).

[42] C. Broude and H. E. Gove, Ann. Phys. (N. Y.) **23**, 71 (1963).

[43] W. J. Hornyak, J. C. Jacmort, M. Riore, J. P. Garron, C. H. Ruhla, and M. Liu, J. Phys. Radium **24**, 1052 (1963).

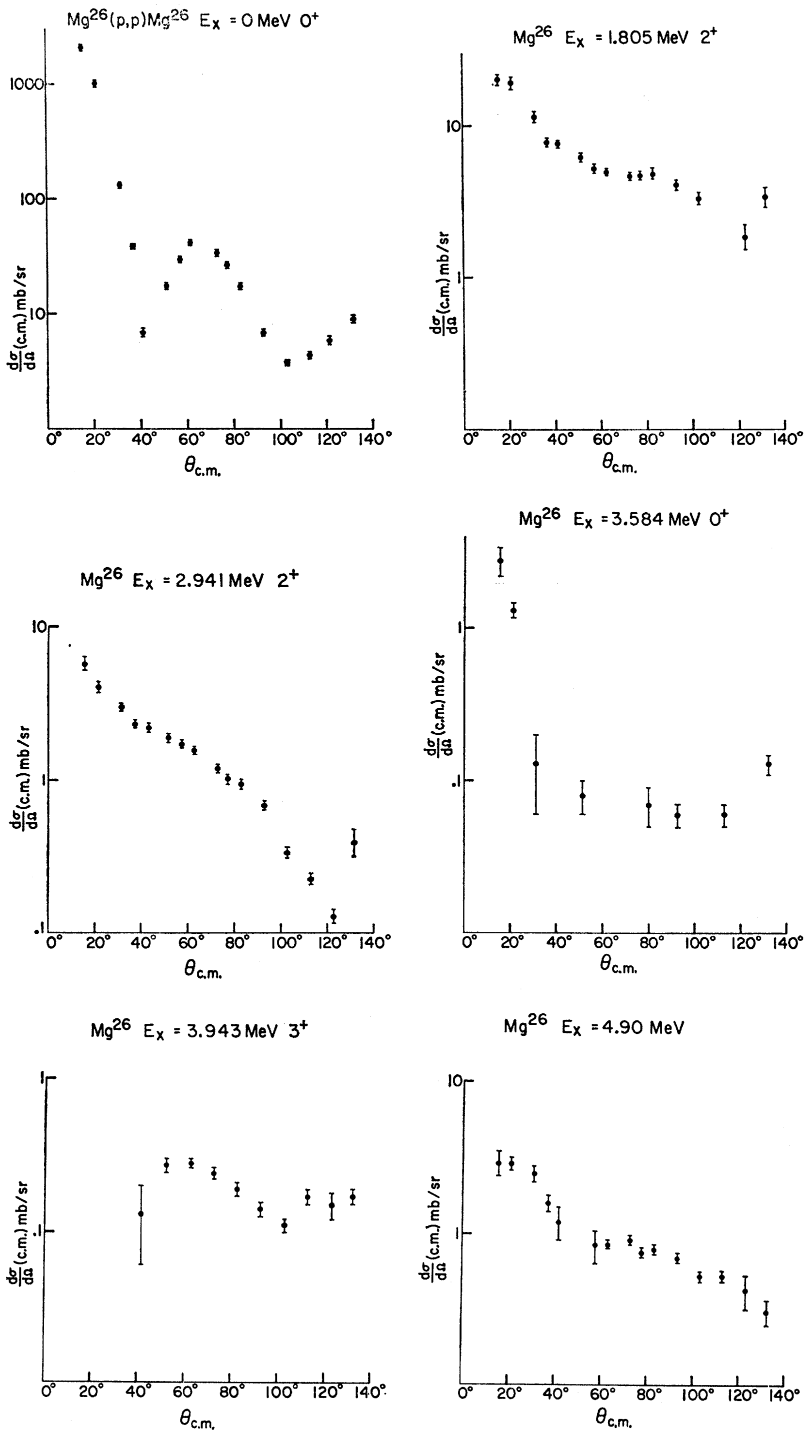

FIG. 9. Angular distributions for states in Mg^{26}. The errors shown do not contain the uncertainty in the absolute cross section (~10%).

E. Inelastic Scattering from S^{32}

A spectrum of protons from natural sulfur on a Formvar backing is shown in Fig. 12. The level in brackets and the level starred at 6.76 MeV have not been reported previously. A 20-keV uncertainty is placed on the energy of this level. Above 7 MeV the energies assigned to the resolvable peaks which show up at a number of angles are shown in parentheses. The spin assignments shown in Fig. 12 are taken from Ref. 35 and recent work of Poletti and Grace.[44]

[44] A. R. Poletti and M. A. Grace, Nucl. Phys. 78, 319 (1966).

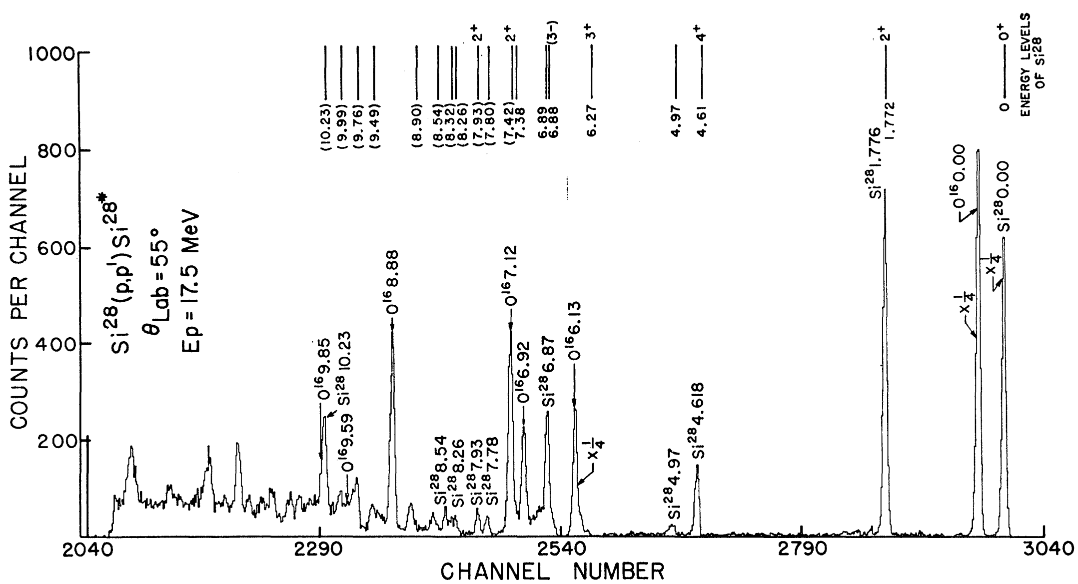

FIG. 10. Spectrum of protons scattered from SiO_2. See the caption to Fig. 3.

Angular distributions for a number of levels are shown in Fig. 13. The states at 2.24 (2^+), 4.29 (2^+), 4.46, and 5.01 MeV (3^-) are the most strongly excited.

The level at 5.01 MeV was previously assigned angular momentum 3 with no parity assignment, however, the large cross section observed for this level makes it definitely 3^-. The collective octupole nature of this level has been observed in inelastic electron scattering[45] and as will be shown later the angular distribution shown in Fig. 13 is consistent with $l=3$. The yield from inelastic electron scattering experiments[45] gives a peak at 4.36 MeV which reflects contributions from both the 4.28- and 4.46-MeV levels. The relatively large yield observed at higher momentum transfer shows one of these levels (4.28 or 4.46 MeV), to have $J>2$. The level at 4.28 MeV is known to have spin parity 2^+[44] and the large cross section shown in Fig. 13 for the 4.46-MeV level with angular distribution inconsistent with $l=3$, shows the most likely spin-parity assignment to the 4.46-MeV level to be 4^+. This would then be another example of very similar $l=2$ and 4 distributions as is observed in Si^{28}.

The level at 3.78 MeV shows the strong forward-peaking characteristic of the inelastic scattering to 0^+ states.

V. DISTORTED-WAVE BORN-APPROXIMATION CALCULATIONS

A. Introduction

In previous investigations[10,46] of the inelastic scattering of 17.5-MeV protons from somewhat heavier nuclei, the observed angular distributions seemed only to depend on the l value involved in the excitation. These results could be well fit with the predictions of a distorted-wave Born approximation. In spite of the irregular behavior observed in our results, we still felt that is was significant to see if a DWBA calculation could reproduce some of the effects observed, particularly for the "collective" transitions.

The distorted-wave theory has been discussed in detail elsewhere.[14,15] Suffice it to say that the method employed used the Oak Ridge National Laboratory code SALLY with the spin-orbit potential included and renamed JULIE.

In this theory the expression for the differential cross section for inelastic scattering is given by

$$\frac{d\sigma}{d\Omega}=\left(\frac{M}{2\pi\hbar^2}\right)^2\frac{k_f}{k_i}\frac{2J_f+1}{2J_i+1}\sum_{l,m}\frac{|B_{lm}|^2}{2l+1},$$

where k_i, k_f refer to the relative momenta of the system in the initial and final states, M is the reduced mass of the system, and B_{lm} is given by the expression

$$B_{lm}=\int dr_0 X_f^{(-)}(k_f r_0)F_l(r_0)Y_l^{m*}(\hat{r}_0)X_i^{(+)}(k_i r_0).$$

The distorted waves $X^{(\pm)}$ are obtained from solving the Schrödinger equation with an optical potential which reproduces the elastic scattering. The form factor used here, assuming collective coordinates for the even-even nuclei, is

$$F_l(r)=\frac{1}{(2l+1)^{1/2}}\beta_l R_0\frac{dU}{dr},$$

where U is the real part of the optical potential and $R_0=r_0A^{1/3}$ is obtained from the radius of the real part

45 R. Lombard, P. Kossanyi-Demay, and G. R. Bishop, Nucl. Phys. 59, 398 (1964).

46 A. L. McCarthy and G. M. Crawley, Phys. Rev. 150, 935 (1966).

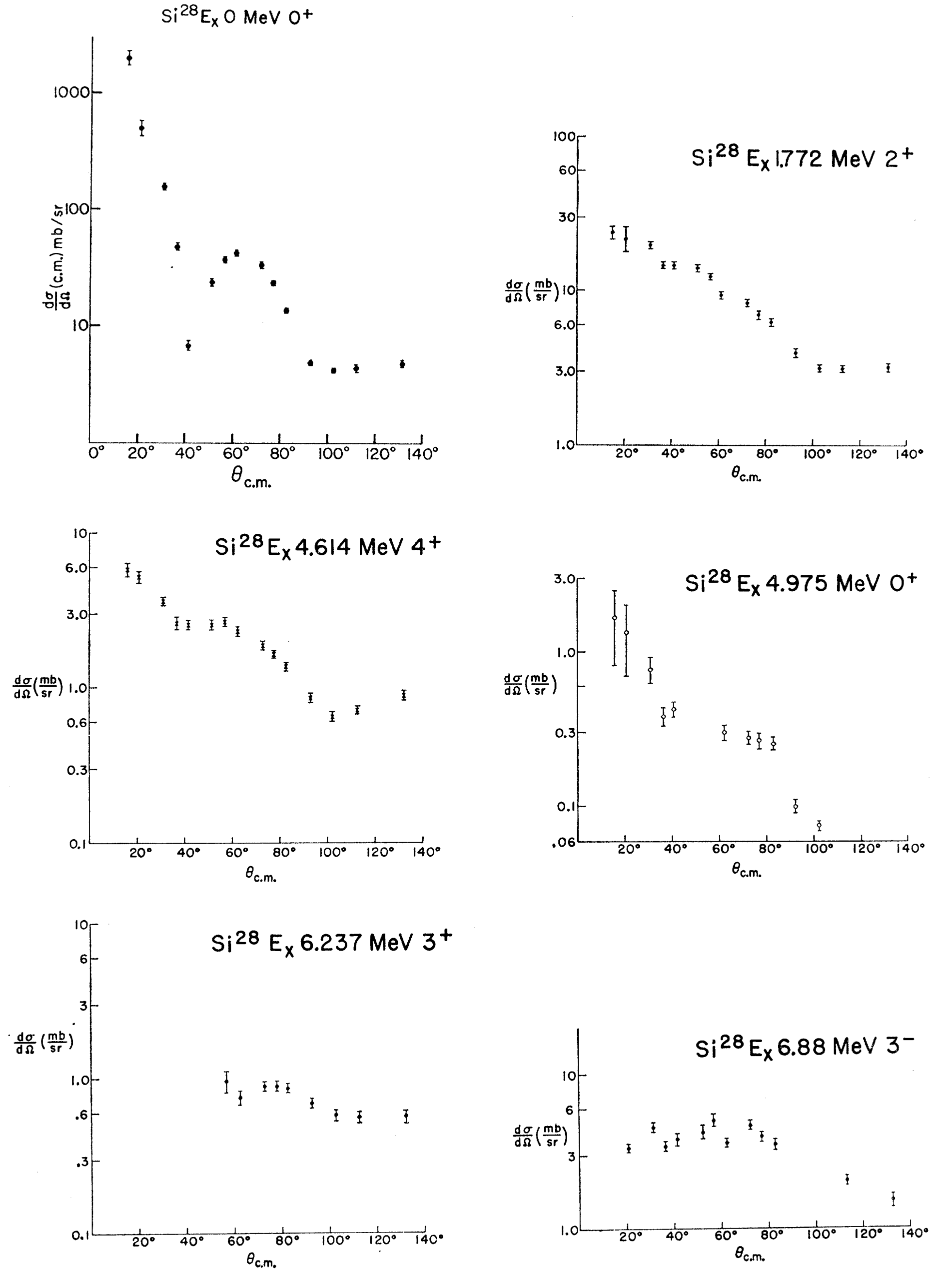

FIG. 11. Angular distribution for states in Si^{28}. The error shown does not contain the uncertainty in the absolute cross section (~10%).

of the optical potential. Once the optical parameters have been obtained, the cross section for inelastic scattering in this approximation is uniquely determined apart from a normalization factor β_l, which is determined by normalizing to the experimental data.

The reduced electromagnetic transition probability $B(El)$ is expressed in terms of the deformation parameter β_l of the rotational model by

$$B(El)_{l>0}=\frac{9}{16\pi^2}\frac{Z^2e^2R_e^{2l}\beta_l^2}{2l+1},$$

assuming a uniform spheroidal charge distribution of average radius R_e.

B. Optical Parameters

Perey[47] has made a systematic study of the optical parameters for elastic proton scattering, although he has in the main considered nuclei above $A=40$. As a first attempt, the values obtained, using Perey's prescription for the potential, were used to fit the elastic

[47] F. G. Perey, Phys. Rev. **131**, 745 (1963).

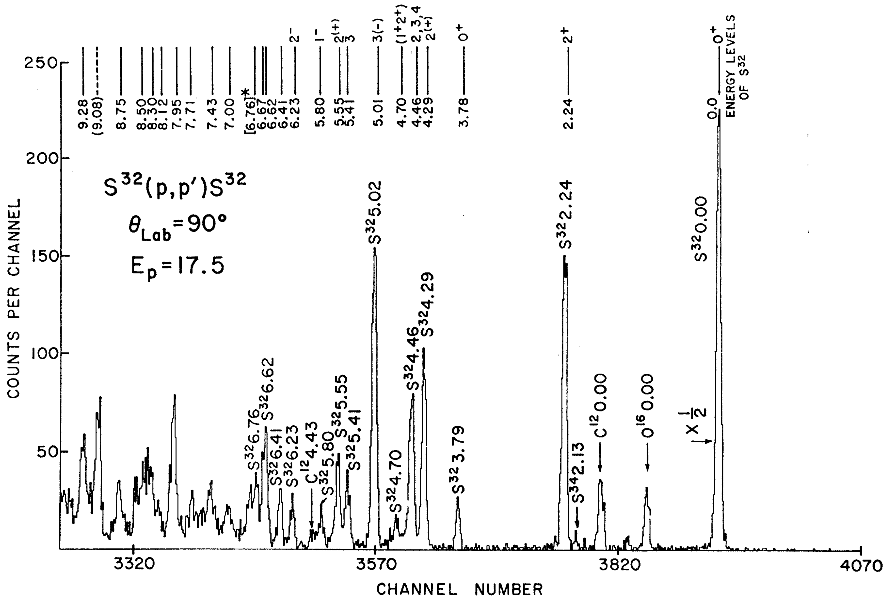

FIG. 12. Spectrum of protons scattered from natural sulfur on a Formvar backing. See the caption of Fig. 3.

scattering. For Mg^{24} the fit to the elastic scattering was quite good, but for the other nuclei there was only qualitative agreement with the data. Therefore, a search of the optical parameters was made within reasonable constraints. Naturally, the fits were improved and, in all cases, excellent agreement even for O^{16} was obtained without radical changes from the parameters suggested by Perey.

One feature of the elastic-scattering data deserves comment. The value of the cross section at the second maximum in the angular distribution around 70° was 44 ± 4 mb/sr for all the nuclei from F^{19} through Si^{28}. However, for P^{31} and S^{32}, the value at this maximum in the angular distribution was about 75 mb/sr, with the peak in the angular distribution being much sharper for these two nuclei. It is interesting to note that this is the region where the nuclear quadrupole moment changes from plus to minus.[48] The fits to the elastic-scattering distribution for P^{31} and S^{32}, although not unique, did indicate that a smaller value of the diffuseness parameter than is conventionally used gave better agreement with the data.

C. Comparison of the DWBA Fits with the Data

It is clear from the angular distributions shown in Fig. 14 that there is no simple l dependence in the angular distributions. Many states in the lighter nuclei with the same spin, in the same even-even nucleus, have very different angular distributions. The most strongly excited states, namely the first 2^+ levels, are considered first since their angular distributions are most alike.

Figure 15 shows the angular distributions for the first excited states (2^+) in Mg^{24}, Mg^{26}, Si^{28}, and S^{32}, together with the angular distributions predicted by the DWBA theory, using the values of the optical parameters suggested by Perey. The agreement between the experimental points and the theoretical prediction is reasonable for Mg^{24} and Si^{28}, but the theoretical curves do not reproduce the strong forward peaking observed in Mg^{26} or S^{32}.

The various sets of optical parameters which gave reasonable fits to the elastic-scattering data were also used in the DWBA program to try to obtain better fits for these 2^+ states. The results of the best fits obtained from these optical parameters are shown in Fig. 16. The optical parameters used are shown in Table I. The agreement of the DWBA prediction with the experimental points for the Mg^{24} 2^+ state at 1.37 MeV is excellent and the fit to the Si^{28} 1.77-MeV 2^+ state is satisfactory. However, one important point to note is that even using the fairly wide variation in

TABLE I. Optical-model parameters yielding the best fit for the $l=2$ or 3 transitions shown in Figs. 16 and 17. All potential-well depths are given in MeV, V_R is the depth of the central real potential, V_{SO} is the depth of the spin-orbit potential, and W_R and V_I are the central, imaginary, volume, and surface potentials, respectively. All lengths are in units of 10^{-13} cm. The radius and diffusness parameter for the Woods-Saxon shape of the real well are r_0 and a, while those for the imaginary surface potential are r_I and a_I. The radius for the charge distribution is taken as $r_cA^{1/3}$.

Nucleus	V_R (MeV)	W_R (MeV)	r_0 (F)	r_c (F)	a (F)	V_{SO} (MeV)	r_I (F)	a_I (F)	V_I (MeV)
Mg^{24}	47.3	0	1.20	1.20	0.64	7.65	1.20	0.50	22.9
Mg^{26}	46.9	0	1.25	1.25	0.65	7.5	1.25	0.47	44.0
Si^{28}	42.8	0	1.30	1.30	0.62	7.5	1.25	0.44	45.4
S^{32}	42.4	0	1.30	1.30	0.62	7.5	1.30	0.44	34.5
O^{16}	44.9	0	1.25	1.25	0.65	8.5	1.25	0.47	30.2

[48] H. E. Goue, in *Proceedings of the International Conference on Nuclear Structure, Kingston, 1960*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 441.

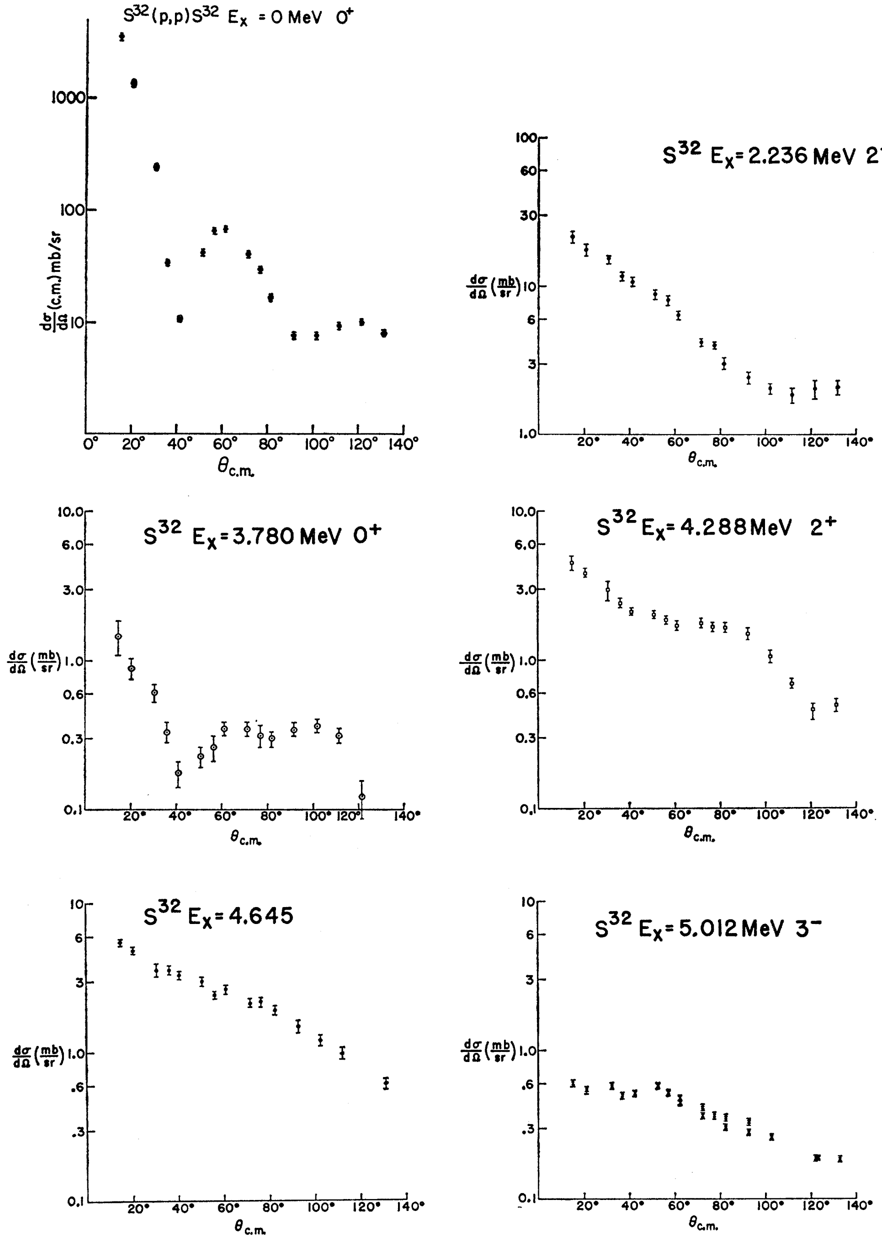

FIG. 13. Angular distribution for states in S^{32}. The error shown does not contain the uncertainty in the absolute cross section (∼10%).

optical parameters which gave satisfactory fits to the elastic-scattering data, the DWBA program could not reproduce the forward peaking in the angular distributions for the 2^+ states in Mg^{26} and only gave fair agreement for the first 2^+ state in S^{32}.

In cases where the DWBA angular distribution was in reasonable agreement with the observed angular distributions (for example, the Mg^{24}, Si^{28}, and S^{32} results shown in Fig. 16), a value for the parameter β_l was obtained by comparing the integrated predicted cross section from 15° to 90° to the experimental cross section integrated over the same angular range. The values of β_l obtained in this manner are shown in Table II, together with values obtained from electromagnetic measurements.

As a measure of the dependence of the β_2 values on the fitting parameters, the angular distribution for the 1.37-MeV $l=2$ transition in Mg^{24} obtained using the Perey parameters shown in Fig. 15 was used to extract a β_2. The value was found to be 0.65 (Perey) compared with $\beta_2=0.52$ from the parameters which gave a better fit to the angular distribution. Within this 15 to 20% accuracy the agreement between the β_2's obtained from the present inelastic proton-scattering measurements

TABLE II. The multipole transition strengths between the ground and designated excited state as extracted from this experiment compared to the strengths obtained from electromagnetic interactions. The comparison is made through the value extracted for β_l, the "effective deformation" parameter of the collective model.

Nuclide	Energy level (MeV)	l^π	β_l (from present pp' expt.)	Electromagnetic measurements β_l^{EM} [a]
O^{16}	6.13	3^-	0.79	0.73[b]
	6.92	2^+	0.28	0.26
Mg^{24}	1.37	2^+	0.52	0.65[c]
	7.35	2^+	0.15	>0.09[d]
	7.62	3^-	0.29	0.28[d]
	8.36	(3^-)	0.21	
Si^{28}	1.77	2^+	0.57	0.40[c]
	6.88	3^-	0.46	0.45[d]
S^{32}	2.24	2^+	0.37	0.37[c]
	4.29	(2^+)	0.20	
	5.01	(3^-)	0.41	0.33[e]
	5.80	(2^+)	0.12	
	6.23	(2^+)	0.14	

[a] The β_l^{EM} values are extracted from the literature using the relationship β_l^{EM} (single-particle value) $=2[(2l+1)\pi]^{1/2}/(l+3)Z$.
[b] I. Alexander, Can. J. Phys. 43, 1563 (1965).
[c] Reference 49.
[d] T. K. Alexander, C. Broude, A. J. Ferguson, J. A. Kuehner, A. E. Litherland, R. W. Ollerhead, and P. J. M. Smulders, Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee, 1966 (unpublished).
[e] Reference 45.

and electromagnetic measurements[49] is generally quite good except for the case of Si^{28}.

The value obtained for β_2 in Si^{28} from electromagnetic measurements is 0.40, which is appreciably smaller than the value obtained here (0.57). Using $\beta_2=0.40$ reduces the predicted DWBA cross section to half its observed value. In a very careful study[50] of the excitation of this state with 30.3-MeV protons the values obtained for β_2 were 0.48 using a DWBA fitting approach similar to the one used here, 0.43 using a distorted-wave calculation with a deformed imaginary potential, and 0.41 using a coupled-channel approach. Clearly the coupled-channel approach is more correct in this case because of the large value of β_2. In a recent letter[25] a significantly lower value of $\beta_2=0.29$ was extracted from inelastic α-particle scattering at 28.4 MeV, but the work of Bingham[26] shows there is appreciable energy dependence in these cross sections.

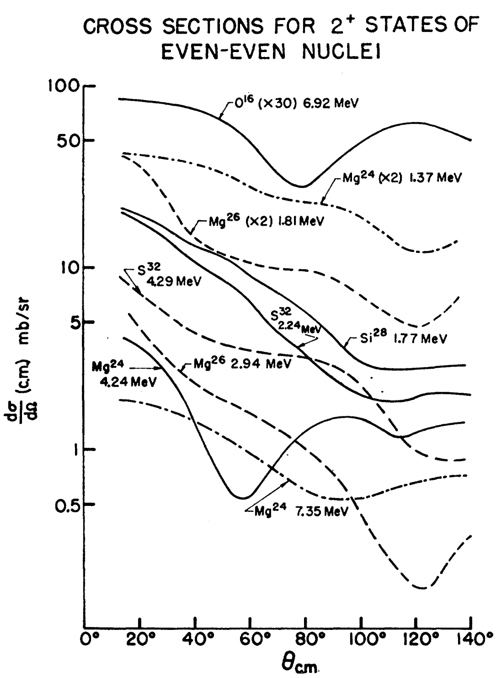

FIG. 14. Angular distributions of 2^+ states excited by inelastic proton scattering.

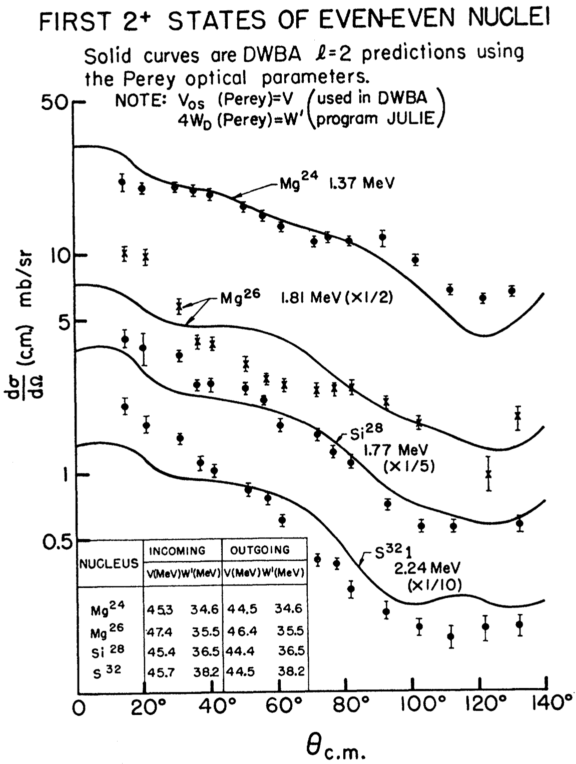

FIG. 15. DWBA fits for the largest $l=2$ cross sections using the Perey parameters.

Unfortunately there are only a few $l=3$ transitions known in these nuclei and these are usually to states at higher excitation energy where the optical parameters in the outgoing channel may be quite different from those in the incident channel. Four examples of $l=3$ transitions are shown in Fig. 17. The fits to these admittedly featureless distributions are better than those obtained for the $l=2$ cases. The optical parameters used are the same as those used to obtain the best $l=2$ fits, except for O^{16}, where the best fit for the 3^- state that still allowed a reasonable fit to the elastic scattering data was used. All parameters are shown in Table I.

[49] P. H. Stelson and L. Grodzins, Nucl. Data 1, 21 (1965).

[50] R. K. Cole, C. N. Waddell, R. R. Dittman, and H. S. Sandhu, Nucl. Phys. 75, 241 (1966).

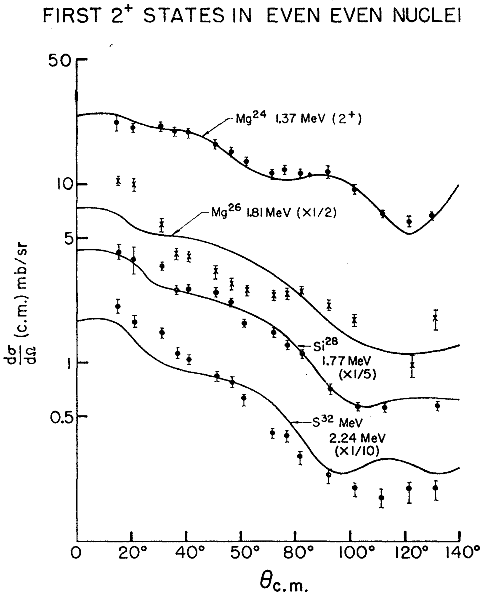

FIG. 16. DWBA fits for the largest $l=2$ cross sections using the "best-fit" parameters given in Table I.

The values obtained for the effective transition probability, parameterized in terms of β_3, are shown in Table II. These values agree excellently with the value of β_3 extracted from electromagnetic processes.

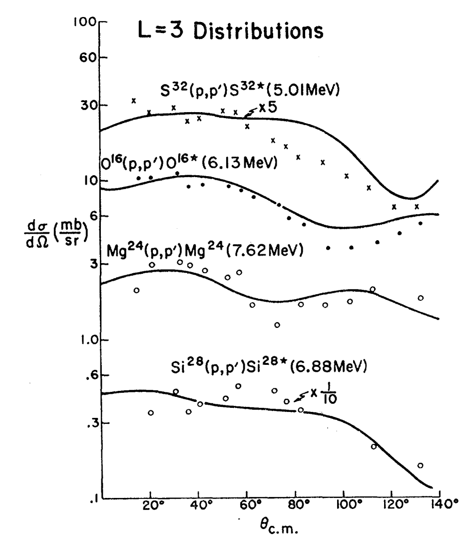

FIG. 17. DWBA fits for $l=3$ differential cross sections using the "best-fit" parameters given in Table I.

It should also be pointed out that the relative cross sections observed in this body of data agrees very well with the relative cross sections observed in the (α,α') scattering for the levels most strongly excited in the α experiments. However, the fact that proton scattering tends to have more available final states and that the proton angular distributions do not exhibit strong oscillations make the identification of high-lying collective states less simple than in the case of (α,α') scattering.

VI. CONCLUSION

In addition to the discussion of the individual levels observed in this experiment and the parameters extracted from the DWBA calculations, a few general comments seem in order.

The irregular behavior of elastic- and inelastic-scattering cross sections as a function of energy for intermediate-energy protons (15–40 MeV) and α particles (30–60 MeV) is a bothersome feature, as it casts doubt in the meaningfulness of the extracted nuclear-structure parameters. In particular, at the proton energies employed here, the differential cross sections do not show a sufficiently unique shape for each l value to allow the assignment of l values. In spite of these objections the values obtained for β_l agree excellently with those obtained from electromagnetic transition rates. The difference in shape of a differential cross section for that predicted from using simple collective form factors may be exploited (e.g., Mg^{26} lowest-lying 2^+ states) to gain better understanding of these wave functions.

Though unnatural parity states are observed to have relatively larger cross sections (compared to adjacent levels) than are observed in inelastic α-particle scattering, they are still relatively small. Thus it seems that caution must be applied in discussing the degree of inhibition present in (α,α') experiments exciting these levels, as they seem to be weakly excited even when the spin-flip mechanism is allowed. The same cross-section ratios between strongly excited states observed in (α,α') are also found in our experiment. However, high-lying collective states [e.g., 8.36-MeV (3^-) Mg^{24}] are not as prominent in the inelastic proton spectrum because the neighboring levels are more strongly excited presumably because of the less selective nature of inelastic proton scattering and the fact that there are fewer open channels for protons at 17.5 MeV.