The Fermi-Kurie plot is shown in Fig. 2. Each of these graphs contains data accumulated from the runs on different sources. The counting intervals for each point were from four to twenty minutes. The statistical accuracy of most of the points is about one percent.

In taking the data, emphasis was placed on the high energy group because of the interest in its shape. The end-point energy of this group is found to be 2.838 ± 0.005 MeV. In addition, the electron spectrum was resolved into four groups. The highest energy group at 2.838 MeV was found to have an intensity of 47% ($\log ft = 7.1$). The intensity of the next group at 1.028 MeV is 34% ($\log ft = 5.3$). The third group at 0.718 MeV makes up 18% of the decays ($\log ft = 5.5$). The intensity of the fourth group at 0.30 MeV was taken as 1% as determined by gamma-ray measurements. It was felt that the thickness of the source used in these experiments would have introduced appreciable distortion in the low-energy region occupied by the last group.

A shape factor plot is shown in Fig. 3 for the highest energy group. The beginning of the next group is marked at 1.028 MeV. An allowed shape factor, $S=1$, is shown along with an empirical shape factor,[7] $1+0.3/W$ (where W is the total β energy in mc^2 units), which has been found to fit all well-measured beta spectra. The experimentally observed spectrum is consistent with either of these shape factors.

5. CONCLUSION

The shape of the beta spectrum involved in the decay of Mn^{56} to the first excited state of Fe^{56} has been measured. No evidence for a deviation from the allowed shape was observed. However, measurements are also consistent with a shape factor of the form $1+0.3/W$. There is no evidence of a contribution from twice forbidden matrix elements.

ACKNOWLEDGMENTS

The authors wish to thank the Indiana University Cyclotron Group for making the bombardments. J. DiSalvo is thanked for helping with the chemical separation.

PHYSICAL REVIEW VOLUME 128, NUMBER 6 DECEMBER 15, 1962

Nuclear Excitation by 180° Electron Scattering*

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(Received July 23, 1962)

We have studied magnetic multipole transitions in Be^9, B^{10}, B^{11}, C^{12}, N^{14}, O^{16}, and Si^{28} by measuring the energy spectra resulting from the scattering of 41.5-MeV primary electrons through an angle of 180°. At this angle of scattering, electric multipole transitions were greatly suppressed, and in addition, the background radiation tail accompanying the elastic peak was minimized. Inelastic electron scattering cross sections were obtained by comparing the inelastic peaks to the electron-proton elastic scattering peak and radiation widths were deduced by using virtual photon theory. Inelastic scattering peaks corresponding to excitation energies of 2.4 and 14.7 MeV were measured for Be^9; 7.9, 11.8, and 14.0 MeV for B^{10}; 2.1, 4.4, 4.9, 7.3, 9.1, 10.4, and 12.9 MeV for B^{11}; 15.1 MeV for C^{12}; 9.2 and 10.5 MeV for N^{14}; and 11.6 MeV for Si^{28}. No excitations were observed for O^{16} below 15 MeV, and no excitations were observed in Ca^{40} below the giant resonance for 160° electron scattering.

I. INTRODUCTION

IN nuclear excitation by electron scattering, in contrast to photon absorption, it is possible to uncouple the momentum and energy transfer so that a given type of multipole transition is enhanced by a proper choice of scattering kinematics. By observing electrons of energies of the order of 200 MeV, scattered through intermediate angles, Fregeau,[1] Helm,[2] and others[3] have studied electric multipole transitions. By observing 40-MeV electrons scattered through angles of 132° and 160°, Barber *et al.*[4] have studied magnetic dipole transitions. According to Schiff,[5] the optimum electron scattering angle for the detection of magnetic transitions with a minimum of electric multipole contributions is 180°.

An attendant feature of 180° electron scattering is the reduction of elastic scattering and the background spectrum of electrons resulting from scattering accompanied by radiation. This spectrum, sometimes referred to as the radiation tail, presents severe back-

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[1] J. H. Fregeau, Phys. Rev. **104**, 225 (1956).
[2] R. H. Helm, Phys. Rev. **104**, 1466 (1956).
[3] H. Crannell, R. Helm, H. Kendall, J. Oeser, and M. Yearian, Phys. Rev. **123**, 923 (1961); W. C. Barber, Ann. Rev. Nuclear Sci. (to be published).
[4] W. C. Barber, F. Berthold, G. Fricke, and F. E. Gudden, Phys. Rev. **120**, 2081 (1960).
[5] L. I. Schiff. Phys. Rev. **96**, 765 (1954).

ground problems at larger angles for low-energy excitations by low-energy (40-MeV) electrons.[4] At 180° inelastic peaks appear more clearly above the radiation tail, and it possible to detect weaker transitions, and to measure the larger ones more accurately than for smaller angles.

The magnetic dipole disintegration of the deuteron has been measured by 180° electron scattering by Peterson and Barber[6] by deflecting the incident and scattered beam so that electrons scattered at 180° entered a spectrometer for momentum analysis. This paper reports an extension of this method to the study of inelastic scattering from other nuclei.

II. EXPERIMENTAL APPARATUS

The same apparatus was used as that described in reference 6. For most of the runs the Stanford Mark II linear accelerator was used to give a beam of 41.5-MeV electrons with a full-width at half-maximum of 1.5%. A small magnet deflected the incident beam less than 10° before it hit the target. Electrons scattered at 180° returned through the small magnet and were deflected so that they entered a magnetic spectrometer set at 160° with respect to the incident beam. The fields of the small magnet and of the spectrometer were properly set so that inelastically scattered electrons were received by three counter telescopes. The only additional piece of equipment was a long vacuum tank beyond the target which reduced the background scattering about 30%.

Be^9 targets 0.0753 and 0.231 g/cm^2 were used for measurements near and far from the elastic peak, respectively. A 96% pure B^{10} target of 0.180 g/cm^2 and a 99% pure B^{11} target of 0.079 g/cm^2 were formed by compacting boron powder between two 2×10^{-3}-g/cm^2 aluminum foils. The thicknesses of the boron targets were determined by measuring the absorption of a collimated beam of beta rays. The carbon target was graphite 0.117 g/cm^2 thick. The nitrogen target was in the form of a compressed crystalline cyanoguanidine ($C_2H_4N_4$, 0.01 H_2O) disk 0.120 g/cm^2 thick. A water target 0.300 g/cm^2 was used in the oxygen experiment. A 0.408 g/cm^2 natural silicon target was employed. A polyethylene (CH_2) target of 0.153 g/cm^2 was used in the measurement of comparison electron-proton elastic scattering peaks.

The calcium data were obtained at 160° with the same counting apparatus. The calcium target was 0.117 g/cm^2 thick.

III. ANALYSIS

In previous low-energy electron scattering work by Barber *et al.*[4] at 160° and 132°, it was possible to compare inelastic peaks to the elastic peak of the same isotope in order to obtain experimental inelastic cross sections. Difficulties arise in 180° scattering which make this a somewhat uncertain procedure. In the case of electron scattering into the solid angle at 180° from a spinless nucleus, the area under the elastic peak is proportional to the fourth power of the spectrometer acceptance angle.[6] Multiple scattering effectively increases this angle in a way that is difficult to evaluate accurately. Also magnetic elastic scattering is present for nuclei with spin and magnetic moment, and only for a few cases has this been taken into account theoretically.[7] However, inelastic peaks may be compared to the proton elastic peak at 180° since it is not subject to the above uncertainties. Multiple scattering contributions are unimportant for 180° electron-proton scattering because the proton cross section is a slowly varying function of the far-backward angles. The magnetic scattering in the case of the proton is included in the Rosenbluth[7,8] formula, which we have assumed to be valid. A value of 7.65×10^{-32} cm^2 sr^{-1} was assumed for the proton cross section in the geometry of our experiment. Our results are shown in Table I.

A systematic error may arise in the evaluation of inelastic cross sections by comparing inelastic peaks to the electron-proton elastic scattering peak. This would not be present if comparison were made to the elastic peak of the same isotope. This results from uncertainties in target thicknesses, and may be rather large for the boron powder targets where it is difficult to measure the thickness accurately.

Inelastic electron scattering cross sections contain information not only about the strength of a transition but also about the spatial dependence of the wave function involved. Only in a few cases[9] have such cross sections been utilized directly to test assumed nuclear models with specific coupling schemes. In the absence of such detailed calculations, an interpretation of the data to obtain the transition strength in the form of the ground-state radiation width is desirable. This can be done in terms of an inelastic form factor analysis, as suggested by Schiff[5] and first applied by Helm,[2] which is useful where a wide range of momentum transfers is available. However, in this experiment we are restricted to a four-momentum transfer of about 0.4 F^{-1} or less, and the form-factor type of analysis is difficult to apply. A virtual photon interpretation[4,10] is more appropriate for the conditions of our experiment, and is equivalent to the form-factor analysis for low momentum transfers.[11] We repeat for completeness some of the virtual photon equations of Barber *et al.*[4] with a slightly modified notation.

The relation between the cross section for an electron-induced magnetic-multipole transition, $d\sigma_i/d\Omega$, and the corresponding integrated photon-induced cross section,

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[10] R. H. Dalitz and D. R. Yennie, Phys. Rev. **105**, 1598 (1957).

[11] J. Goldemberg (private communication).

TABLE I. Parameters of nuclear states excited by 180° electron scattering, assuming transitions are $M1$.

Isotope	Excitation energy, k (MeV)	Spin and parity: Ground state I_g	Spin and parity: Excited state I_e	Inelastic cross section $d\sigma_i/d\Omega$ (10^{-32} cm^2 sr^{-1})	$\int\sigma_\gamma dk$ (MeV-mb)	Percentage experimental error	Ground-state radiation widths, Γ_γ, (eV): This experiment	Weisskopf units	Other experiments
Be^9	2.4	$3/2^-$	$5/2^-$	1.3	0.12	15	0.12	0.30	0.13[a]
	14.7	$3/2^-$	$1/2^-$	0.042	0.3	50	36	67	
			$3/2^-$				18		
			$5/2^-$				12		
B^{10}	7.9	3^+	2^+	1.9	0.75	20	17	10	9.5[b]
			3^+				12		
			4^+				10		
	11.8	3^+	2^+	1.2	0.75	50	39	34	
			3^+				28		
			4^+				22		
	14.0	3^+	2^+	0.6	0.5	50	34	58	
			3^+				24		
			4^+				15		
B^{11}	2.1	$3/2^-$	$1/2^-$	0.72	0.72	20	0.17	0.21	0.15[c]
	4.4	$3/2^-$	$5/2^-$	1.5	0.34	40	1.1	1.8	0.602[c]
	4.9	$3/2^-$	$3/2^-$	2.4	0.59	40	3.7	2.5	
	7.3	$3/2^-$	$5/2^-$	0.4	0.12	50	1.0	8.1	
	9.1[d]	$3/2^-$	$7/2^+$	1.9	0.0097	20	0.10	4×10^{-3}	0.1[e]
	12.9	$3/2^-$	$1/2^-$	1.4	1.0	30	70	45	
			$3/2^-$				36		
			$5/2^-$				24		
C^{12}	15.1	0^+	1^+	1.82	1.95	10	39	73	40[a], 54.5[f], 59.2[g]
N^{14}	9.2	1^+	0^+	1.3	0.65	30	43	17	
			1^+				14		
			2^+				9		
	10.5	1^+	0^+	1.9	1.2	30	100	24	
			1^+				34		
			2^+				20		
O^{16}	No resonances detected below 16 MeV.								
Si^{28}	11.6	0^+	1^+	3.5	2.8	40	33	33	47[a], 68[h]

[a] W. C. Barber, F. Berthold, G. Fricke, and F. E. Gudden, Phys. Rev. **120**, 2081 (1960).
[b] G. Fricke (private communications).
[c] F. R. Metzger, C. P. Swann, and V. K. Rasmussen, Phys. Rev. **110**, 906 (1958).
[d] This transition is assumed to be $M2$.
[e] L. Meyer-Schützmeister and S. S. Hanna, Bull. Am. Phys. Soc. **3**, 188 (1958).
[f] E. Hayward and E. Fuller, Phys. Rev. **106**, 991 (1957).
[g] E. L. Garwin, Phys. Rev. **114**, 143 (1959).
[h] A. B. De Nercy, thesis, University of Paris, Orsay Center, 1962 (unpublished).

$\int\sigma_\gamma dk$, may be written

$$\frac{d\sigma_i}{d\Omega}(E_0,k,\theta,l)=\frac{1}{k}\frac{dN}{d\Omega}(E_0,k,\theta,l)\int\sigma_\gamma dk, \quad (1)$$

where electrons of energy E_0 transfer the excitation energy k to the nucleus upon scattering through an angle θ, and induce a magnetic transition of multipole order l. $dN/d\Omega$ is the virtual photon intensity which only has a component transverse to the momentum q transferred to the nucleus $[q\hbar c=(E_0^2+E^2-2E_0E\cos\theta)^{1/2}$, $E=E_0-k]$ for magnetic transitions

$$\frac{dN}{d\Omega}(E_0,k,\theta,l)=\frac{\alpha}{4\pi^2}\frac{p_0^2+p^2+p_0p(1-\cos\theta)}{p_0^2(1-\cos\theta)}\times\left(\frac{q\hbar c}{k}\right)^{2l-2}\frac{F^2(qr)}{F^2(kr)}, \quad (2)$$

where p_0 and p are the electron's momenta before and after scattering, respectively. The factor $F^2(qr)/F^2(kr)$ is a correction for nuclear size, where r is the root-mean-square radius of a transition operator density requiring the postulation of a nuclear model. Isabelle and Bishop[12] assume that particles contributing to the transition are in a shell of radius r, where r is chosen to be the rms charge radius. They developed an approximation quadratic in qr and kr,

$$\frac{F^2(qr)}{F^2(kr)}=\frac{\left(1-2\frac{l+3}{l+1}\beta q^2r^2\right)}{\left[1-2\frac{l+3}{l+1}\beta\left(\frac{k}{\hbar c}\right)^2r^2\right]}, \quad (3)$$

where $\beta=1/6$ for $l=0$, $1/10$ for $l=1$, and $1/14$ for $l=2$.

[12] D. E. Isabelle and G. R. Bishop, Laboratoire de l'Accelerateur Lineaire Report *LAL-1017*, Orsay, France, 1961 (unpublished).

For electric multipole transitions a longitudinal virtual photon intensity enters at all angles except 180°. At 180°, the electric multipole virtual photon intensity has the same form as Eq. (2), except the factor $(q\hbar c/k)^{2l-2}$ is replaced by $(q\hbar c/k)^{2l-4}$. Thus for the same l and k, the virtual photon intensity for electric multipole transitions is reduced with respect to that for magnetic multipole transitions for 180° scattering by a factor of $(k/q\hbar c)^2$. This factor is about 10^{-3} for the 2.43-MeV transition in Be^9 and about 5×10^{-2} for the 15.1-MeV transition in C^{12} for 41.5-MeV incident electrons.

The Breit-Wigner formula for the photon case gives the ground-state radiation width

$$\Gamma_\gamma=\left(\frac{k}{\pi\hbar c}\right)^2\left(\frac{2I_g+1}{2I_c+1}\right)\int\sigma_\gamma dk, \tag{4}$$

where I_g and I_c are the spins of the ground state and the excited state, respectively.

Among the uncertainties of this type of analysis are the assumption of plane wave initial and final electron states, neglect of recoil, the consideration of only single virtual photon exchanges, the neglect of exchange currents, and an approximate method of accounting for nuclear size. The last of these is very likely the most severe approximation. However, if the data are treated by comparing inelastic peak areas to the elastic peak area of the same nucleus, a form factor similar to $F(qr)$ enters for elastic scattering which effectively cancels out the strong size dependence of the virtual photon intensity.[4] In our case we compare our inelastic peaks to the proton elastic peak, and a large uncertainty resulting from the strong r dependence enters into our results, especially for larger nuclei. Also, there may exist anomalies, according to the detailed theory,[9] where interference between radial wave functions might greatly reduce the inelastic cross sections. However, this is unlikely for the low q values of this experiment.

Ordinarily angular distributions of the scattered electrons are measured in determining the character of a transition.[1–4] When all of the measurements are made at the same angle, as in our case, the incident beam energy may be varied instead, since each virtual photon intensity for a given order l has a specific dependence on the momentum transfer. For example, if the 7.9-MeV excitation found in B^{10} is pure $M1$, the ratio of the inelastic cross section for $E_0=41.5$ MeV to that obtained for $E_0=27.7$ MeV is 0.88 according to Eq. (1), whereas if it is $M2$, the ratio is 2.46.

Low-energy $E1$ transitions are strongly suppressed at 180° because of small $E1$ virtual photon intensities. However, virtual photon intensities are the same for $M1$ and $E2$ transitions at 180°. Nevertheless, we expect small $E2$ contributions if the $E2$ matrix elements have their estimated theoretical sizes. If any of the transitions measured were $E1$ or $E2$, they would exceed the Weisskopf[13] single-particle estimate of Γ_γ by large factors. Higher magnetic multipole transitions may not be excluded by such arguments.

The data were corrected for counting losses, variations in counter efficiencies, and for variation of spectrometer window width with energy. We have not made radiation corrections to the data, but have assumed that they are equally important to the inelastic peaks and to the proton elastic peak. Also, no attempt was made to compute the radiation tail since even for the proton, disagreement with theory is found for the thick target conditions of this experiment.[6] Instead, a reasonable estimate was made by drawing a smooth curve beneath the inelastic peaks. In some cases this could be drawn with little ambiguity, but in other cases our resolution was too coarse to separate adjacent levels. The background with the target out, which was a smooth function of energy, was automatically subtracted by this method of determining the area of inelastic peaks.

IV. RESULTS

The results of the data analysis are summarized in Table I. The stated errors resulted from uncertainties in the area of the inelastic peaks, in the area of the comparison electron-proton peak, and in the target thicknesses. The $M1$ assignments are all comparable with the Weisskopf[13] single-particle width. Errors in the ratio of the peaks for the same element are considerably less than those given in the table.

A. Be^9

The peak at $E=38.5$ MeV of Fig. 1 corresponds to the excitation of the 2.43-MeV level. Our assignment of $M1$ agrees with data taken at smaller angles.[4] A group at Orsay[14] using higher energy electrons and smaller scattering angles have measured an $E2$ mixing of 1 or 2%

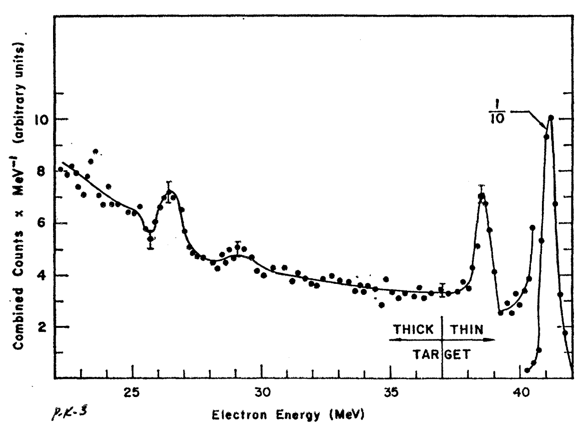

FIG. 1. Energy distribution of electrons, which were initially 41.5 MeV, after scattering through 180° from a Be^9 target.

[13] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

[14] H. Nguyen Ngoc, J. Perez y Jorba, and M. Hors (private communications).

and obtained an $E2$ radiation width of $(2.3\pm0.2)\times10^{-3}$ eV. Our experiment is not sensitive to such a small $E2$ radiation width.

Jakobsen[15] and a group of MIT[16] have measured the cross section for Be^9 (γ,n). The peak heights for the (γ,n) resonances at 1.75, 2.43, 3.04, and 4.74 MeV are all prominent. The nucleus, once excited by radiation, most likely will decay by neutron emission, so that for these experiments the peak height is an indication of the ground-state radiation width. In our experiment only the 2.43-MeV level is excited. Since the (γ,n) experiments indicate large values of $\int\sigma_\gamma dk$ for the other levels and we do not detect them by inelastic electron scattering at 180°, we may rule out magnetic multipole excitations. Since only the 2.43-MeV level is seen at 132° and 160°, we may rule out electric quadrupole and higher multipoles. This leaves electric dipole as the only means of excitation of these levels. No outstanding levels were detected at higher excitation energies except perhaps at 14.7 MeV. An experiment by Barber[17] showed that there were not large $E2$ contributions in the range from 6 to 17 MeV, although it was not sensitive to differences between $E1$ and $M1$. Our experiment suggests that strong $M1$ contributions in this range can be excluded.

B. B^{10}

An inelastic electron scattering peak at an excitation energy of 7.45 ± 0.3 MeV had been found previously by Fricke[18] for $E_0=41.5$ MeV, and $\theta=160°$. We found the peak at a slightly higher excitation energy, 7.9 MeV, as shown in Fig. 2. The large value of the inelastic cross section for this peak suggests that it is of magnetic character. In order to determine its multipolarity, we found the ratio of the inelastic cross section for $E_0=41.5$ MeV to that for $E_0=27.7$ MeV to be 1.02. According to the previous section we expect a ratio of 0.88 if the transition is $M1$ and a ratio of 2.46 if the transition is $M2$. Our result suggests an $M1$ assignment. Also, this excitation was not seen at smaller angles and higher energies, which also rules out higher electric multipoles.[18]

Kurath[19] has predicted a 2^+ state in this energy region by employing an intermediate strength spin-orbit coupling and a central two-body interaction. This could be what we observed. An elastic proton scattering study by Mozer[20] suggests there is a 2^+ state at 7.47 MeV. However, Seward[21] does not see any levels in a study using resonant gamma-ray scattering.

Excitations at 11.8 and 14.0 MeV were also observed. It is likely that these are of magnetic character. There is a possibility that there may be more levels in this region which could not be resolved with our experimental arrangement.

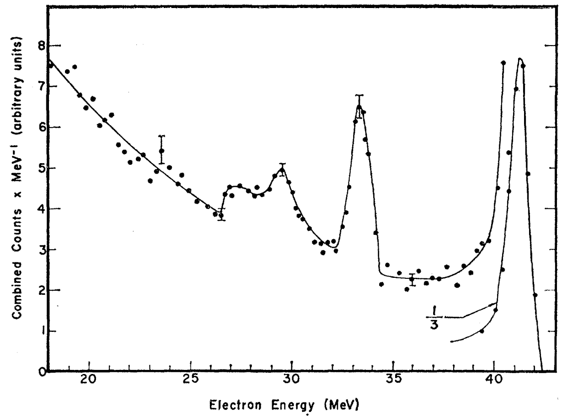

FIG. 2. Energy distribution of electrons, which were initially 41.5 MeV, after scattering through 180° from a B^{10} target.

$M1$ excitations of the 3.58- and 4.77-MeV levels are greatly inhibited according to Morpurgo's[22,23] $\Delta T=0$ inhibition rule for self-conjugate nuclei. The transition to the 4^+ 6.02-MeV level is probably $E2$[24] with a small value of Γ_γ.

C. B^{11}

The large number of $M1$ transitions in B^{11} makes this an interesting nucleus to study using 180° scattering. As will be seen from Fig. 3, several inelastic peaks stand out clearly above the background. In the case of the excitation of the 4.43- and the 5.03-MeV levels, the experimental peaks overlap because of our poor resolution. They were graphically resolved by taking into account the known resolution of the equipment. Reasonable agreement with previous results[25–27] was obtained for the 2.13- and the 4.43-MeV levels. Seward[21] found levels at 4.4, 5.0, 7.3, and 8.8 MeV by elastically scattering gamma rays. At 7.3 MeV we detected a peak which was much less prominent than that seen by Seward. The next large peak occurred at an excitation energy of 9.1 MeV. This may correspond to the excitation of the positive parity 9.19- or 9.28-MeV states.[28] The first of these is the more likely and would indicate an $M2$ transition. Evidence from an experiment now in progress supports this assignment.[29] Since other levels at

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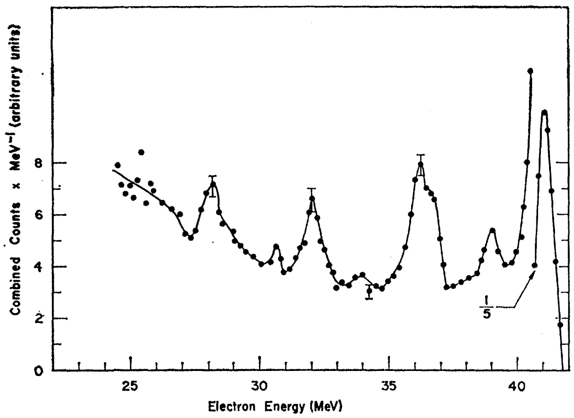

FIG. 3. Energy distribution of electrons, which were initially 41.5 MeV, after scattering through 180° from a B^{11} target.

6.8 MeV and in the region between 10.4 and 12.9 MeV were not excited, these may be of electric rather than magnetic character, or they may have small ground-state radiation widths.

D. C^{12}

The only excitation observed below the giant resonance region was the *M*1 15.1-MeV level. We obtained a value for the ground-state radiation width (39 eV) in agreement with Barber *et al.*[4] (40 eV), but lower than the values obtained by elastic scattering of photons (54.5 and 59.2 eV).[30,31] The 12.73-MeV level was not excited, as is expected from the $\Delta T=0$ inhibition rule.[22,23]

E. N^{14}

A cyanoguanidine ($C_2H_4N_4$, 0.01 H_2O) target was employed for the study of N^{14}. There was no confusion with the excitation of carbon or oxygen levels, since only the carbon 15.1-MeV level was excited for the conditions of our experiment.

We observed two peaks at 9.2- and 10.5-MeV excitation energy. The level at 9.2 MeV may well be that seen from the C^{13} (p,γ) reaction.[32] However, the excitations are most likely of magnetic character and not *E*1. If they are *M*1, we are in agreement with Strassenberg *et al.*[33] and with Kashy *et al.*[34] We may not exclude the possibility that the two levels observed are of higher order than dipole. However, if the excitations to the 9.2- and 10.5-MeV levels are *M*2, the experimental values of Γ_γ exceed the single-particle estimates by factors of 16 and 24, respectively. A rise beyond the 10.5-MeV level was noted, but there were no excitations below 8.5 MeV. The 3.95-MeV level has the correct parity and spin for an *M*1 transition from the ground state, but is inhibited by the $\Delta T=0$ inhibition rule.[22,23] The 2.312-MeV level has a value of Γ_γ too small to allow observation within the statistical accuracy of this experiment.[35]

F. O^{16}

No levels were excited below the giant resonance region by 180° electron scattering. This is in complete agreement with previous data.[27]

G. Si^{28}

The excitation previously seen at smaller angles[4] at 11.6 MeV appeared again in this study. Our result for Γ_γ is somewhat smaller than the previous result (46 eV) and is also smaller than a recent result obtained by the resonant scattering of gamma rays (68 eV).[36] However, a wide latitude of uncertainty results from our choice of a transition radius *r*. We have used the rms charge radius,[37] although this may not represent the nucleons which participate in the *M*1 transition.

H. Ca^{40}

We observed no excitations below the giant resonance for 160° electron scattering. None of the closed shell nuclei investigated thus far by inelastic electron scattering have had *M*1 transitions.

ACKNOWLEDGMENTS

One of us (R. D. E.) wishes to thank Dr. W. C. Barber for his hospitality extended at the High Energy Physics Laboratory, and both of us wish to thank him for his advice.

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