Inelastic Alpha-Particle Scattering by Mn^{55} and Co^{59}†

H. W. BROEK*
Argonne National Laboratory, Argonne, Illinois
(Received 8 April 1965)

Angular distributions of 43-MeV alpha particles scattered by Mn^{55} and Co^{59} have been derived. The angular distributions for reactions leading to the levels at 0.98 and 1.88 MeV in Mn^{55} are out of phase with elastic scattering. The Mn^{55} spectra lack the very strong collective quadrupole group. Eight peaks from Mn^{55} and seven from Co^{59} were resolved. The Co^{59} spectra are similar to those from Ni^{60}, except that the excitation energies are slightly smaller in Co^{59}. The collective quadrupole group in Co^{59} is at least 0.3 MeV wide.

INTRODUCTION

RECENT experiments have studied the levels in Mn^{55} excited by 6.6-MeV protons[1] and by 2.21-MeV neutrons.[2] The levels of Co^{59} have been studied by inelastic scattering of 15-MeV deuterons.[3] Furthermore, high-energy electrons have been used to study collective excitations[4] in Co^{59}. In the present experiment, 43-MeV alpha particles were scattered from Mn^{55} and Co^{59}. In this experiment the collective spectrum from Mn^{55} could be followed to higher excitation energy than in the work at lower energies (although the resolution obtainable with 43-MeV alpha particles is not as good). On the other hand, Co^{59} could be studied with better resolution than in the electron-scattering experiment. However, the resolution in this experiment is not as good as the 80-keV resolution of the deuteron-scattering experiment.[3] The study of Co^{59} is of interest because two nearby nuclei Ni^{58} and Ni^{60} have been studied in detail with the same beam energy.[5,6]

Mn^{55} is noted for its unusual ground state in which $f_{7/2}$ protons are coupled to give a ground-state spin of $\frac{5}{2}-$. This coupling in the ground state may produce a different inelastic spectrum than is seen in the more normal case of Co^{59} with its ground-state spin of $\frac{7}{2}-$. It is possible that correspondence between Mn^{55} and Ti^{47} may be found, since Ti^{47} has a ground state in which $f_{7/2}$ neutrons are coupled to give a ground-state spin of $\frac{5}{2}-$. A report on alpha scattering by Ti^{47} and by the other Ti isotopes is in progress.[7]

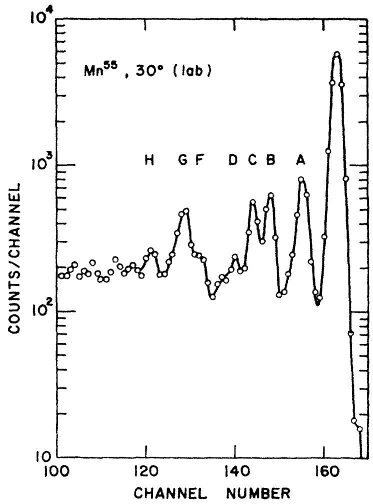

FIG. 1. Pulse-height spectrum of alpha particles scattered by Mn^{55} at 30°. Energies of the peaks are given in Table I.

EXPERIMENTAL PROCEDURE

The elastic and inelastic scattering of 43-MeV alpha particles was observed by use of solid-state detectors (without dE/dx gating) at angles from 14° to 50° (lab)

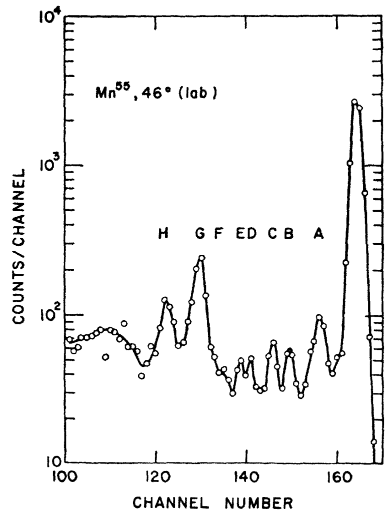

FIG. 2. Pulse-height spectrum of alpha particles scattered by Mn^{55} at 46°.

† Work performed under the auspices of the U. S. Atomic Energy Commission.
* Present address: Bell Telephone Laboratories, Whippany, New Jersey.
[1] S. S. Vasil'ev, E. A. Romanovskii, and G. F. Timushev, Zh. Eksperim. i Teor. Fiz. 42, 395 (1962) [English transl.: Soviet Phys.—JETP 15, 274 (1962)].
[2] R. C. Lamb and M. T. McEllistrem, Phys. Letters 4, 211 (1963).
[3] B. L. Cohen and R. E. Price, Phys. Rev. 123, 283 (1961).
[4] H. Crannell, R. Helm, H. Kendall, J. Oeser, and M. Yearian, Phys. Rev. 123, 923 (1961).
[5] H. W. Broek, T. H. Braid, J. L. Yntema, and B. Zeidman, Phys. Rev. 126, 1514 (1962).
[6] H. W. Broek, Phys. Rev. 130, 1914 (1963).
[7] J. L. Yntema and H. W. Broek (to be published).

at 2° intervals. The methods used were essentially the same as those of Refs. 5 and 6. The equipment was described in detail in Ref. 8. The linewidth in this experiment was 280 keV.

SPECTRA FROM Mn^{55}

Figure 1 shows the spectrum of alpha particles scattered by Mn^{55} at 30° (lab). The large peak contains elastic scattering and presumably some inelastic scattering to the unresolved first excited state at 0.13 MeV. The full-width at half-maximum for this peak is 0.30 MeV. The spectrum from Mn^{55} at 46° (lab) is shown in Fig. 2. At this angle the elastic scattering is near a maximum and hence little or no contribution from the unresolved first excited state is expected. The width of the elastic peak is less at 46° than at 30° and hence inelastic scattering may contribute at 30°. Peak A at 0.98±0.02 MeV excitation is due to the resolved second excited level and is out of phase with elastic scattering. The spin of the level is known[1,2] to be $\frac{9}{2}^-$.

Peak B at 1.88±0.05 MeV is due to the resolved fifth excited level and is out of phase with elastic scattering. According to the proton-scattering experiment,[1] the spin of the level is probably $\frac{7}{2}^-$.

Peak C at 2.32±0.05 MeV is out of phase with elastic scattering. Peaks D and E are rather weak but undoubtedly are real. Peak E is in phase with elastic scattering. "Peak" F is a shoulder which shows up consistently on the side of peak G.

The very strong peak G at 4.28±0.05 MeV is in phase with elastic scattering and is undoubtedly the $l=3$ collective octupole group. Peak H is in phase with elastic scattering. Beyond peak H there may be further groups, in particular one at channel 113 in Figs. 1 and 2. However, the evidence for such groups is inconclusive. A very weak peak is seen at much lower pulse height near where He^3 particles from the $Mn^{55}(\alpha,He^3)$ reaction would be expected. The excitation energies and phases are summarized in Table I. A plus sign indicates that the peak is out of phase with elastic scattering and a minus sign indicates that the peak is in phase.

TABLE I. Excitation energies, phases, and spins of levels and groups of levels excited by inelastic scattering of 43-MeV alpha particles.

Nuclide	Excitation energy (MeV)	Symbol	Phase	Spin
Mn^{55}	0.98±0.02	A	+	$\frac{9}{2}^-$[a]
	1.88±0.05	B	+	$(\frac{7}{2}^-)$[a]
	2.32±0.05	C	+	
	2.85±0.04	D		
	3.16±0.06	E	−	
	3.78±0.10	F		
	4.28±0.05	G	−	$l=3$
	5.17±0.04	H	−	
Co^{59}	1.23±0.03	A	+	
	(1.94±0.05)	B_1	(−)	
	2.18±0.05	B_2	+	
	3.1 ±0.2	C		
	3.85±0.05	D	−	$l=3$
	4.62±0.05	E	−	
	5.3 ±0.15	F	−	

[a] References 1 and 2.

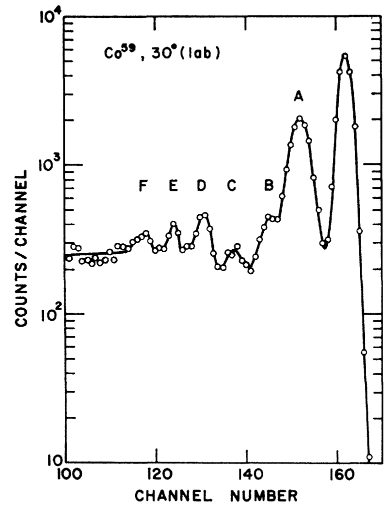

FIG. 3. Pulse-height spectrum of alpha particles scattered by Co^{59} at 30°. Energies of the peaks are given in Table I.

SPECTRA FROM Co^{59}

Figure 3 shows the spectrum of alpha particles scattered by Co^{59} at 30° (lab). The large peak is elastic scattering. The broad peak A, centered at an excitation energy of 1.23 MeV, is at least 0.3 MeV broad and thus contains contributions from more than one level in the region from 1.1- to 1.5-MeV excitation. Peak A is not quite so broad in Fig. 4, which shows the spectrum at 50° (lab). Peak A is out of phase with elastic scattering.

At angles for which elastic scattering is near a minimum, peak B is 18 channels away from the elastic peak; but it is only 15.5 channels away at angles where elastic scattering is near a maximum. Hence peak B

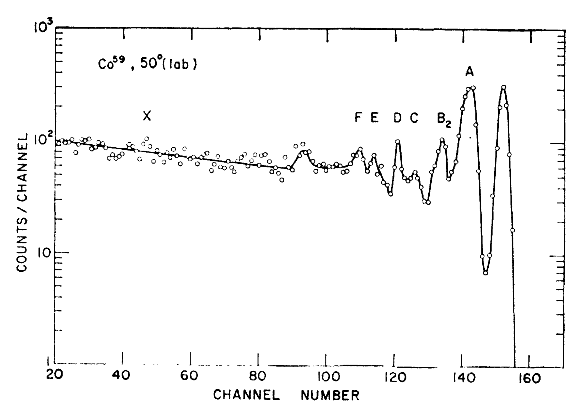

FIG. 4. Pulse-height spectrum of alpha particles scattered by Co^{59} at 50°.

can be split into two poorly resolved peaks: peak B_1, which is probably in phase with elastic scattering, and peak B_2, which is definitely out of phase with elastic scattering.

The excitation energies for Co^{59} shown in the table are in good agreement with those of the deuteron-scattering experiment[3] except for the poorly resolved peak B_1 at 1.94 MeV reported in the table. This peak may be produced by more than one level and the value of 1.94 MeV may be a weighted average of several near-by levels.

Peak D is the collective octupole level at 3.85 MeV that has been reported previously.[4] Peaks E and F are in phase with elastic scattering. The peak at channel 93 in Fig. 4 may be due to oxygen contamination of the target. Peak X occurs where He^3 particles from $Co^{59}(\alpha,He^3)$ would be expected to appear. Peak X is of doubtful significance here but tends to show up in most of the spectra.

ANGULAR DISTRIBUTIONS

The difference between the elastic-scattering cross sections (expressed as the ratio to the Rutherford cross section) for Co^{59} and Mn^{55} is shown as the dotted line in Fig. 5. The solid line represents the difference between the ratio-to-Rutherford cross sections for Cu^{63} and Co^{59}. In each case the two nuclei differ by two protons and two neutrons. The differences are taken at constant laboratory angle, since the laboratory angle can easily be made exactly the same by actuating a target changer while keeping the detector locked in place.[8] The ratios-to-the-Rutherford cross section (for elastic scattering of 43-MeV alpha particles by medium-weight nuclei) have a deep minimum approximately every 10°. This periodicity has been noted many times before.[5,6,9] As A increases from one target to the next,

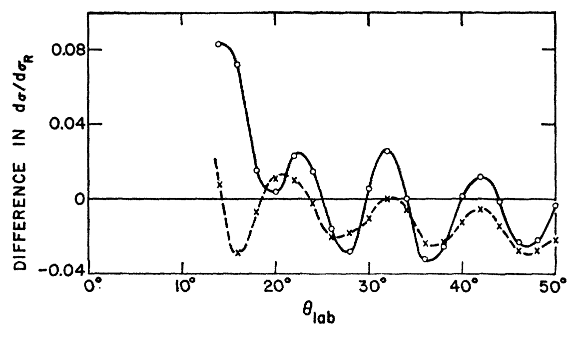

FIG. 5. Differences between the ratio of the elastic-scattering cross section to the Rutherford-scattering cross section for Cu^{63} and the ratio for Co^{59} (solid curve), and between the ratios for Co^{59} and Mn^{55} (broken curve). No correction for the unresolved first excited state of Mn^{55} has been made.

the positions of the minima tend toward slightly smaller angles. Since these regularly spaced deep minima shift gradually in angle, the difference between ratios-to-Rutherford for near-by isotopes must oscillate with the same periodicity. Figure 5 shows this oscillation. The difference between the Cu^{63} and Co^{59} ratios-to-Rutherford oscillates about an average that is close to zero at the higher angles. On the other hand, the difference between the Co^{59} and Mn^{55} ratios-to-Rutherford oscillates about an average that steadily becomes more negative as the angle increases. This negative average may be due to inclusion of scattering to the unresolved first excited state of Mn^{55} at 0.13 MeV. A distorted-wave analysis of the elastic scattering is in progress.[10]

The upper curve in Fig. 6 is the cross section for inelastic scattering to the collective octupole state at 4.28±0.05 MeV in Mn^{55}. The angular distribution has

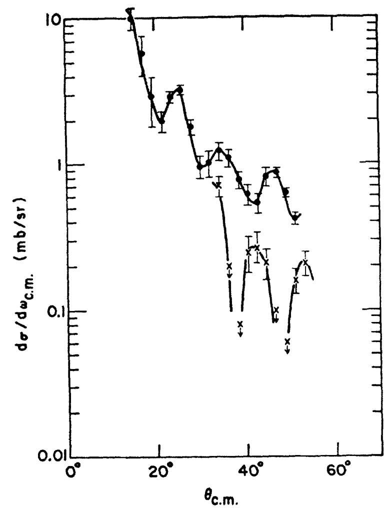

FIG. 6. Cross section for the 4.28-MeV collective octupole transition in Mn^{55} (upper curve) and for excitation of the 1.88-MeV fifth excited level of Mn^{55} (lower curve).

the familiar in-phase oscillations, and at 35° (c.m.) the envelope of the oscillations lies at about 1.5 mb/sr. This value is less than the values of 2.8, 2.9, and 3.5 mb/sr found in the even-even nickel nuclei.[6]

The lower curve in Fig. 6 is the cross section for inelastic scattering to peak B which lies at 1.88±0.05 MeV in Mn^{55}. The angular distribution is strongly out of phase with elastic scattering.

The cross sections for inelastic scattering by the collective $l=2$ and $l=3$ transitions in Co^{59} are shown in Fig. 7. As was the case in Ni and Zn, the $l=2$ transition is more prominent than the $l=3$ transition, and both angular distributions obey the Blair phase rule. The collective $l=3$ transition has about the same cross section in Mn^{55} as in Co^{59}. However, the collective $l=2$

[8] J. L. Yntema and H. W. Ostrander, Nucl. Instr. Methods 16, 69 (1962).

[9] G. Igo, H. E. Wegner, and R. M. Eisberg, Phys. Rev. **101**, 1508 (1956); J. L. Yntema, B. Zeidman, and B. J. Raz, Phys. Rev. **117**, 801 (1960).

[10] G. R. Satchler (private communication).

transition (presumed to be peak A in both cases) has about 3 times as great a cross section in Co^{59} as in Mn^{55}. In all cases the collective $l=2$ and $l=3$ transitions have smaller cross sections in Co^{59} and Mn^{55} than they have in the even-even Ni and Zn nuclei.

SUMMARY

Figure 8 compares the energies of the various peaks found in this experiment with those of Ni^{58} and Ni^{60}.

The peak at 0.98 MeV in Mn^{55} is due to the resolved second excited level, which has a spin[1,2] of $\frac{5}{2}^-$. The transition is presumably $l=2$ but has a much smaller cross section than that observed in other isotopes in this region of the periodic chart.[5,6] The isotope Zr^{91} lacks a strong $l=2$ transition,[11] but lacks it for a different reason. (Presumably the collective model does not give a good description of Zr^{91} because it is next to the double-closed-shell nuclide Zr^{90}.)

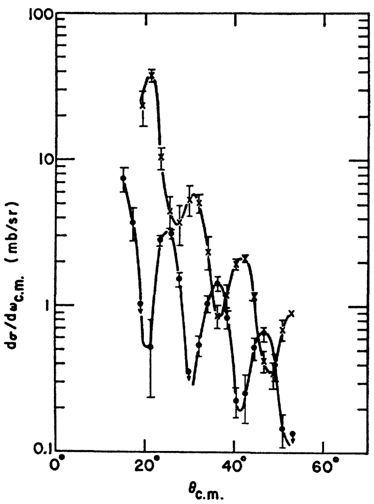

FIG. 7. Cross section for the 1.23-MeV collective quadrupole transition in Co^{59} (upper curve), and for the 3.85-MeV collective octupole transition in Co^{59} (lower curve).

No sign of the third and fourth excited levels (at 1.291 and 1.523 MeV, respectively) was seen in any of the data, even though the resolution was good enough to see them had they been present. These levels must have less than 0.2 times the cross section for peak A. This fact is consistent with the single-particle character[1] of the fourth excited level.

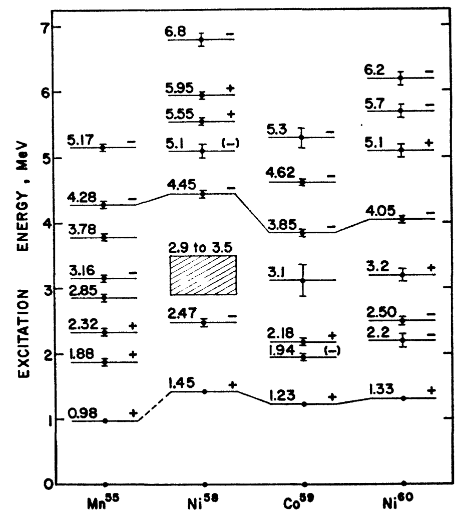

FIG. 8. Peaks observed in this experiment and in Ref. 4. The numbers are excitation energies in MeV. A minus sign signifies that the angular distribution is in phase with elastic scattering; a plus sign signifies that it is out of phase. The signs do not necessarily indicate parity of levels. The upper line connects the collective $l=3$ groups, the lower line the collective $l=2$ groups.

The peak at 1.88 MeV is out of phase with elastic scattering. It is a transition to the resolved fifth excited level of Mn^{55}, which has a probable spin[1] of $\frac{7}{2}^-$.

Above this excitation the levels in Mn^{55} are much too close to be resolved.

In the Co^{59} data, none of the peaks are due to a single resolved level. The first peak at 1.23 ± 0.03 MeV is broad and might contain contributions from any of six known levels. Nevertheless, the major part of this peak must come either from the known $\frac{3}{2}^-$ level at 1.29 MeV or from the level at 1.19 MeV or from both. The deuteron-scattering experiment[3] shows strong excitation of these two levels and also strong excitation of near-by levels at 0.85, 1.09, and 1.47 MeV. The spectrum from Co^{59} bears a strong resemblance to that from Ni^{60}; indeed the excitation energies in Co^{59} seem to be consistently slightly less than in Ni^{60}.

The ratio of the energy of the $l=3$ transition to that of the $l=2$ transition is 3.13 ± 0.08 for Co^{59}. This value for the ratio is the same (within experimental uncertainty) as those[6] for Ni^{58}, Ni^{60}, Ni^{62}, and Zn^{64}.

ACKNOWLEDGMENTS

The author wishes to thank W. Ramler, W. J. O'Neill, and the cyclotron crew for their help in performing these experiments.

[11] H. W. Broek and J. L. Yntema, Phys. Rev. **138**, B334 (1965).