Elastic and Inelastic Scattering of 43-Mev Alpha Particles by Ni^{58} and Ni^{60}†

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Inelastic scattering and elastic scattering of 43-Mev α particles have been studied over the angular range from 17° to 53° c.m. The angular distributions of the prominent group from the 2^+ first excited level and the 3^- "anomalous" group are fitted well by calculations based on the distorted-wave Born approximation. The angular distribution of the 4^+ group at 5.5 Mev in Ni^{58} also agrees well with the calculations. Groups at low excitation, with angular distributions in phase with elastic scattering, were found at 2.2 and 2.50 Mev in Ni^{60} and at 2.47 Mev in Ni^{58}. These groups violate the phase rule from Fraunhofer diffraction theory, and hence are believed to be due to two-phonon excitations. Other groups with angular distributions in phase with elastic scattering were found at 4.45, 6.8, and 7.1 Mev in Ni^{58} and at 4.05, 5.6, 6.2, and 7.0 Mev in Ni^{60}. Groups with angular distributions out of phase with elastic scattering were found at 1.45, 3.3, 5.5, and 5.9 Mev in Ni^{58} and at 1.33, 3.2, and 5.1 Mev in Ni^{60}.

I. INTRODUCTION

INELASTIC scattering of electrons,[1] protons,[2] deuterons,[3] and alpha particles[4] is known to produce certain strongly-excited groups from many nuclei. Angular distributions for the most prominent of these groups, the 2^+ first excited state and the 3^- "anomalous" group, have been found in Ni^{58} and Ni^{60} by inelastic scattering of deuterons[5] and alpha particles.[6] Recently, experiments by Beurtey *et al.* with 44.4-Mev alpha particles[7,8] and by Crannell *et al.* with 183-Mev electrons[1] have obtained the angular distributions of these and of several other groups from Ni^{58} and Ni^{60}.

In the present experiment, data were taken under conditions of good energy resolution and good statistical accuracy in order to obtain the angular distributions of as many groups as possible, and to make the angular distributions of the strong 2^+ and 3^- groups accurate enough over a sufficient angular range for a valid comparison with calculations based on the distorted-wave Born approximation.

II. EXPERIMENTAL PROCEDURES

A. Equipment

A beam of 43-Mev alpha particles from the Argonne 60-in. cyclotron[9] was passed through a collimating system and into the 60-in. scattering chamber.[10] The targets were placed at an angle of $45°\pm0.1°$ to the beam. The thickness of the Ni^{58} target was 2.46 mg/cm^2 and that of the Ni^{60} was 3.16 mg/cm^2.

The particles were detected by silicon surface-barrier solid-state detectors.[11] The data were taken without the use of absorbers or of a dE/dx detector in order to eliminate corrections for energy lost in absorbers, and to facilitate the data analysis and the calculations of Q values. The sensitive thickness of the detector was made sufficient to stop the elastically scattered α particles and He^3 particles from the (α,He^3) reactions with nickel. The response was linear in energy at least to 43 Mev for α particles. No dE/dx counter was needed to distinguish the α particles of interest in this experiment from other reaction products because the (α,d), (α,t), and (α,He^3) reactions have highly negative Q values and protons from (α,p) reactions have a very small probability of producing large pulses in the detector since the sensitive thickness was not much greater than the range of the elastically scattered α particles. The use of a single counter was advantageous in these circumstances since the fluctuations in the energy loss of particles traversing a dE/dx counter would have degraded the energy resolution. The full width at half maximum for the elastic peak was about 0.65%. This width is almost wholly due to the energy spread of the incident particles from the cyclotron beam.

B. Derivation of Angular Distributions

The positions of peaks on the various runs were noted and the difference in channel number between each peak and the elastic peak was tabulated for each run. This procedure reduced shifts in peak position due to minor fluctuations in beam energy and due to the variation with laboratory angle of the kinetic energy of the scattered alpha particle. Only peaks appearing at the same position (relative to the elastic peak) in more than half the runs were analyzed. Other peaks may be due to

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] H. Crannell, R. Helm, H. Kendall, J. Oeser, and M. Yearian, Phys. Rev. **123**, 923 (1961).
[2] P. C. Gugelot, Phys. Rev. **93**, 425 (1954); B. L. Cohen, *ibid.* **105**, 1549 (1957); B. L. Cohen and A. G. Rubin, *ibid.* **111**, 1568 (1958).
[3] J. L. Yntema and B. Zeidman, Phys. Rev. **114**, 815 (1959).
[4] D. R. Sweetman and N. S. Wall, *Proceedings of the International Conference on Nuclear Physics* (Crosby Lockwood and Son, London, 1959), pp. 547.
[5] J. L. Yntema and B. Zeidman, Phys. Rev. Letters **2**, 309 (1959).
[6] M. Crut, D. R. Sweetman, and N. S. Wall, Nuclear Phys. **17**, 655 (1960); D. K. McDaniels, J. S. Blair, S. W. Chen, and G. W. Farwell, *ibid.* **17**, 614 (1960).
[7] R. Beurtey, P. Catillon, R. Chaminade, M. Crut, H. Faraggi, A. Papineau, J. Saudinos, and J. Thirion, J. phys. radium **21**, 399 (1960).
[8] R. Beurtey, P. Catillon, R. Chaminade, M. Crut, H. Faraggi, A. Papineau, J. Saudinos, and J. Thirion, Compt. rend. **252**, 1756 (1961).
[9] W. Ramler and G. Parker, Argonne National Laboratory Report ANL-5907 (unpublished).
[10] J. L. Yntema, Nuclear Instr. and Methods (to be published); Phys. Rev. **113**, 261 (1959).
[11] J. T. Heinrich and T. H. Braid, Bull. Am. Phys. Soc. **6**, 46 (1961).

statistical fluctuations, or, if real, are too small to yield significant angular distributions.

In the analysis of all peaks except the elastic peak, it is necessary to subtract a background. This background may result from (a) a small low-energy tail in the energy spectrum of the beam, (b) slit-edge scattering at the collimator or at the detector aperture, (c) reactions of alpha particles with nuclei in the detector, (d) reactions of other particles with nuclei in the detector, and (e) inelastic scattering to levels not preferentially excited. Obviously this background must be subtracted by some consistent procedure in order to find the net number of counts in a peak, and the uncertainty in establishing the background must be included in the error given with the data points. At small angles and at low excitations the background is mainly due to processes (a), (b), and (c) which serve to put a small tail on the low-energy side of any observed peak. The shape of this tail was measured up to about 7-Mev excitation by observing the scattering of alpha particles from C^{12}. The derived peak shape with its tail was then used in subtracting the background for inelastic groups at less than 5 Mev of excitation. It was necessary to subtract background counts associated with the first inelastic peak as well as those associated with the elastic peak.

At excitations above 5 Mev the dips between peaks do not go down to the background expected after subtracting the peaks. It is assumed that processes (d) and (e) are appreciable above 5 Mev of excitation. This background must be subtracted because otherwise all the angular distributions for groups at high excitation will tend to look alike. Lines representing the background, which were drawn through the dips between the peaks in the various runs, probably overestimate the background. The derived cross sections are therefore underestimated and hence should be regarded as lower limits. The data do not indicate how much the background is overestimated so no error bars are shown on the groups at excitations above 5 Mev. It is possible that future experiments with better resolution will show that the levels included in these peaks at high excitation have cross sections somewhat higher than given here. Nevertheless the phase relations of the relative angular distributions given here are believed to be correct.

In experiments on inelastic scattering, especially those using solid-state detectors, care must be taken to avoid multiple peaking. In this effect, a genuine peak is accompanied by one or more spurious peaks at lower energy because of such things as small defective regions in the detector,[12] or extraneous material between the accelerator and the target, or between the target and the detector. A satellite of the strong elastic peak would be particularly disadvantageous. To check against these possibilities, data on the scattering of alpha particles from carbon and gold were taken. For the conditions under which the data presented here were taken, no evidence of spurious peaks was found.

[12] G. L. Miller in *Semiconductor Nuclear Particle Detectors,* edited by J. W. T. Dabbs and F. J. Walter, Nuclear Science Series Report No. 32 (National Academy of Sciences—National Research Council, Washington, D. C., 1961), pp. 19 ff.

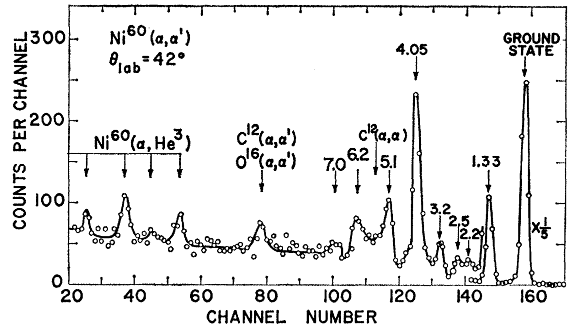


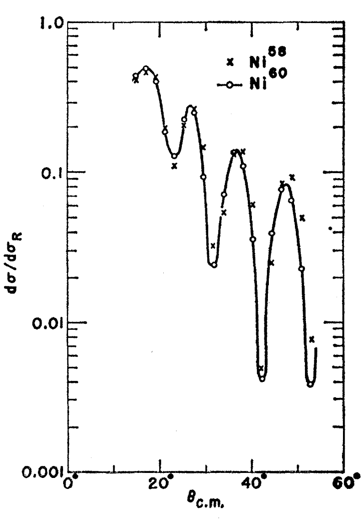
FIG. 1. Pulse-height spectrum of alpha particles and He^3 particles from reactions of 43-Mev alpha particles with Ni^{60}. These data were taken at 42° lab. The energies indicated for the peaks are in Mev. Errors in the data are not shown for reasons of clarity. The statistical errors may be estimated from the scale of the ordinate.

C. Determination of Q Values

Observation of the first four groups of alpha particles scattered from C^{12} (whose Q values are known accurately) indicated that the position of the peaks on the pulse-height analyzer was a linear function of energy and that the over-all constant of proportionality was 121.0 ± 0.6 kev/channel. This quantity was then multiplied by the distance from the elastic peak to the peak being analyzed. Corrections were made for the variation of nuclear recoil energy with Q value and with angle.

The first excited states of Ni^{58} and Ni^{60} were found at excitations of 1.42 ± 0.03 and 1.31 ± 0.03 Mev, respectively, in good agreement with the more accurate values of 1.452 and 1.332 Mev, respectively, obtained by mag-

FIG. 2. Ratios of the observed elastic scattering to the Rutherford scattering for Ni^{58} and Ni^{60} targets. Errors in the data are less than the size of the points.



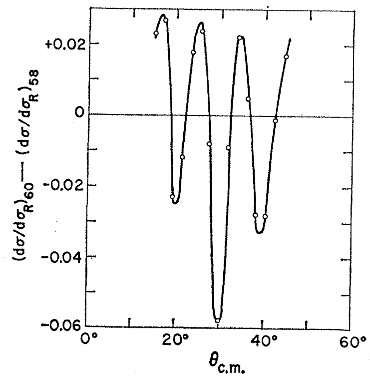


FIG. 3. Differences between the Ni^{60} ratio of the observed elastic scattering to Rutherford scattering and the Ni^{58} ratio. Errors in the data are believed to be smaller than 0.004.

netic spectroscopy.[13–15] The other observed inelastic groups from Ni^{58} lie at 2.47±0.06, 4.45±0.05, 5.1±0.1, 5.55±0.05, 5.95±0.05, 6.8±0.1, 7.1±0.1, and 8.1±0.2 Mev. A broad group extending from 2.9 to 3.5 Mev is also seen. The other inelastic groups from Ni^{60} lie at 2.2±0.1, 2.50±0.06, 3.2±0.1, 4.05±0.05, 5.1±0.1, 5.7±0.1, 6.2±0.1, 7.0±0.1, 7.6±0.2, and 8.9±0.2 Mev.

III. EXPERIMENTAL RESULTS

A. Pulse-Height Spectra

Figure 1 shows the pulse-height spectrum of 43-Mev alpha particles scattered by Ni^{60} at 42°. Each of the eight groups whose angular distributions are given below may be seen in Fig. 1, except for the group at 5.7-Mev excitation. In addition, four groups from the reaction $Ni^{60}(\alpha,He^3)$ are seen at the lower pulse heights. One of these groups is from the reaction to the ground state of Ni^{61} and the others are from reactions leading to states in Ni^{61} at about 1.0, 2.0, and 3.4 Mev. A contamination peak is seen at channel 78. This peak is due partly to inelastic scattering to the first excited state of C^{12} and partly to inelastic scattering to the (unresolved) first two excited states of O^{16}. Elastic scattering from the C^{12} contaminant produces counts at about channel 111 and obscures the 5.7-Mev group from Ni^{60} at this angle. Elastic scattering from the O^{16} contaminant produces counts at about channel 126 but is not seen there because of the much larger 4.05-Mev group of Ni^{60}.

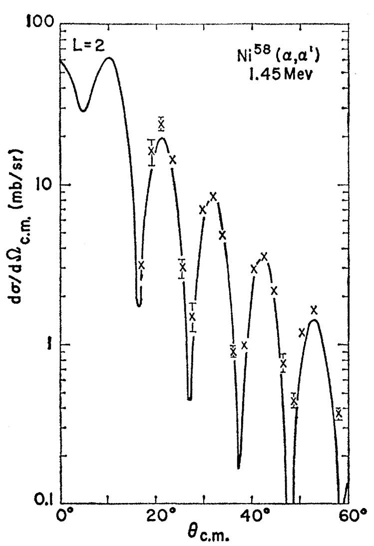


FIG. 4. Angular distribution for inelastic scattering to the 2^+ first excited state of Ni^{58}. Experimental uncertainties are shown in Figs. 4–8 except when they are smaller than the points. The theoretical curves in Figs. 4–12 were calculated by Satchler, Bassel, and Drisko.

The spectra from Ni^{58} show the well-known groups at 1.45- and 4.45-Mev excitation and several smaller groups between 2.5 and 8.1 Mev.

B. Elastic Scattering from Ni^{60} and Ni^{58}

Figure 2 presents the data for elastic scattering from Ni^{60} and Ni^{58} in the form of a ratio to the Rutherford

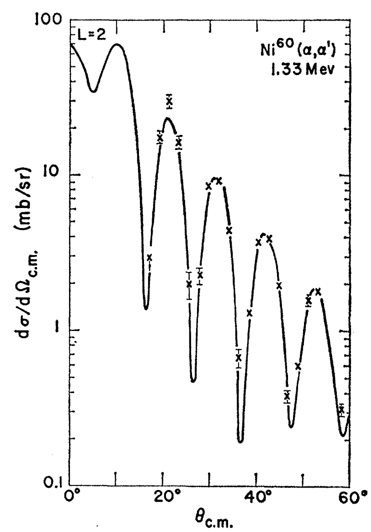


FIG. 5. Angular distribution for inelastic scattering to the 2^+ first excited state of Ni^{60}.

scattering cross section. The positions and heights of the maxima are nearly the same for the two isotopes. However, the maxima and minima of Ni^{60} are at slightly smaller angles than those of Ni^{58}.

In Fig. 3 are plotted the differences in the ratios to the Rutherford cross section of the two isotopes. These differences show an oscillation pattern with a period of about 10 deg/cycle, the period seen in all of the oscillatory angular distributions in this experiment. The angular distribution of Fig. 3 is about $\frac{1}{4}$ cycle out of phase with those of Fig. 2. Hence the isotopic difference in $d\sigma/d\sigma_R$ (the ratio to the Rutherford cross section) is largest where the ratio to Rutherford scattering is rising of falling sharply. The differences in $d\sigma/d\sigma_R$ have been taken at the same center-of-mass angle for both isotopes. A correction was made for the fact that the data points for the two isotopes were taken at the same laboratory

[13] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C., 1961); R. B. Day, Phys. Rev. **102**, 767 (1956).
[14] R. R. Spencer, G. C. Phillips, and T. E. Young, Phys. Rev. **108**, 69 (1957).
[15] M. Mazari, W. W. Buechner, and R. P. deFigueiredo, Phys. Rev. **108**, 373 (1957).

angle rather than at the same c.m. angle. This correction is small and has only a minor effect upon the curve.

C. Inelastic Scattering to the First Excited States

Figures 4 and 5 show the angular distributions of the 2^+ first excited states of Ni^{58} and Ni^{60}. The relative angular distributions are nearly identical over the angular range studied, but the absolute cross section is about 15% higher for Ni^{60}. Corresponding maxima and minima occur at slightly smaller angles in Ni^{60}.

The data have been fitted with calculations done by Satchler, Bassel, and Drisko[16] by means of the distorted-wave Born approximation.[17] The optical potential used in the calculation has the familiar Saxon-Woods radial dependence, and is given by

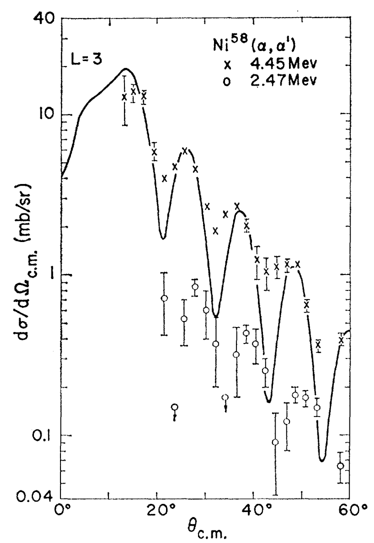


FIG. 6. Angular distributions for inelastic scattering to the 3^- 4.45-Mev group and to the 2.47-Mev group of Ni^{58}.

$$U=-\frac{V}{1+\exp x}-i\left(W-W'\frac{d}{dx'}\right)\frac{1}{1+\exp x'},$$

where

$$x=(r-r_0A^{\frac{1}{3}})/a,$$

and

$$x'=(r-r_0'A^{\frac{1}{3}})/a'.$$

Here V is the depth of the ordinary potential, W is the depth of the absorptive potential, and W' is the depth of a spin-orbit potential. The Coulomb potential was assumed to be that of a sphere (with uniform charge per unit volume) of radius $r_cA^{\frac{1}{3}}$. The parameters for the potential in Ni^{58} were $V=47.6$ Mev, $W=13.8$ Mev, $W'=0$, $r_0=r_0'=r_c=1.585$ f, and $a=a'=0.549$ f. For Ni^{60} the potential parameters were $V=44.1$ Mev, $W=17.4$ Mev, $W'=8.75$ Mev, $r_0=r_c=1.585$ f, $r_0'=1.443$ f,

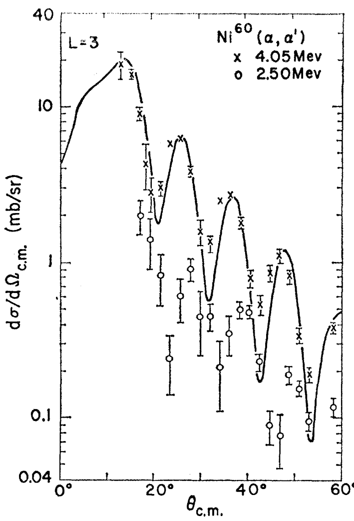


FIG. 7. Angular distributions for inelastic scattering to the 3^- 4.05-Mev group and to the 2.50-Mev group of Ni^{60}.

$a=0.555$ f, and $a'=0.620$ f. The difference in well parameters between Ni^{58} and Ni^{60} results from the removal of the simplifying assumptions used in fitting the Ni^{58} data. Satisfactory fits may be obtained for other combinations of well parameters. The radial form factor for the inelastic interaction was assumed to be

$$F(r)=\frac{d}{dx}\left(\frac{1}{1+\exp x}\right).$$

From the magnitude of the cross section, the nuclear deformation parameter β_2 was found to be about 0.165 for Ni^{60}. A value of $\beta_2=0.20$ may be derived from

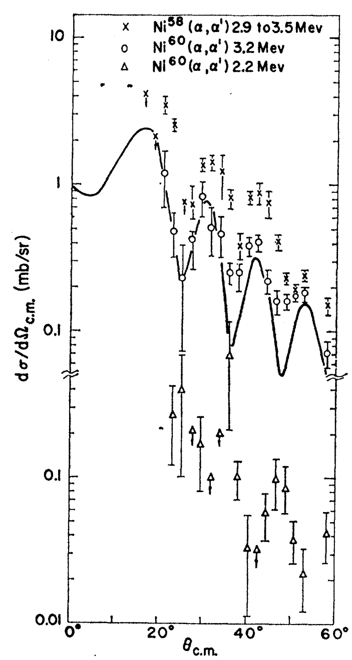


FIG. 8. Angular distributions for inelastic scattering to the groups in Ni^{60} at 2.2 and 3.2 Mev and to the broad 3-Mev group in Ni^{58}.

[16] G. R. Satchler, R. H. Bassel, and R. M. Drisko (private communication).

[17] E. Rost and N. Austern, Phys. Rev. **120**, 1375 (1960); E. Rost, Ph.D. thesis, University of Pittsburgh, 1961 (unpublished).

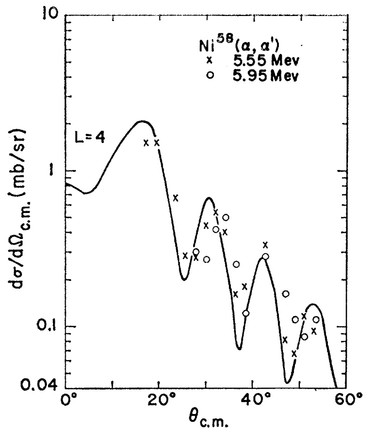


FIG. 9. Angular distributions for inelastic scattering to the groups in Ni^{58} at 5.55 and 5.95 Mev. No experimental uncertainties are given for the data of Figs. 9–12.

Coulomb-excitation data[18] if a radius of $1.27A^{\frac{1}{3}}$ f is assumed.

D. Inelastic Scattering to the Prominent 3^- Groups

Figures 6 and 7 show the angular distributions of alpha particles in the strongly-excited "anomalous" groups, which are known to be 3^- groups[19] and which occur at 4.45±0.05 Mev in Ni^{58} and at 4.05±0.05 Mev in Ni^{60}. The data are compared with curves calculated by Satchler *et al.*[16] for the case of Ni^{58}. The agreement is very good at the maxima in the angular distributions. The corresponding maxima in the two isotopes have the same experimental cross sections (to an accuracy of about 10%). The minima in the experimental angular distributions are not as deep as in the theoretical curve. Also the minima in the Ni^{58} data are not as deep as those in the Ni^{60} data. The differences between the data and theory at these minima are too large to be explained by a background effect. It is possible that levels whose angular distributions are out of phase with elastic scattering may be unresolved from the 3^- groups and thus fill in the minima of the observed angular distributions.

E. The Low-Lying Groups in Phase with Elastic Scattering

Also shown in Figs. 6 and 7 are the angular distributions for the low-lying in-phase groups at 2.47±0.06 Mev in Ni^{58} and at 2.50±0.06 Mev in Ni^{60}. These energy values agree well with the known levels at 2.458 and 2.483 Mev [14] in Ni^{58} and at 2.505 Mev [13,14] in Ni^{60}. The experimental energy spread (280 kev full width at half-maximum) is small enough so that the levels at 2.458 and 2.483 Mev in Ni^{58} are the only known levels that can contribute to the observed group in Ni^{58}. Similarly, in Ni^{60} only the levels at 2.505 and 2.625 can contribute to the observed group.

The angular distributions from both isotopes are in phase with elastic scattering. Therefore the phase rule from Fraunhofer diffraction theory[20] indicates that both groups have negative parity. However, both groups occur where there are known 4^+ levels.[13] This discrepancy has previously been observed[8] for the 2.47-Mev group in Ni^{58} and for a group at 2.04 Mev in Fe^{56}. It is possible that a different scattering process, such as excitation of two phonons, may be required to explain these results. An attempt at such an explanation has been made recently by Lemmer, de Shalit, and Wall.[21]

The observed angular distributions are very similar to one another but that for Ni^{60} appears to be roughly 10% more intense. The cross sections at the maxima in these observed angular distributions decrease with angle as rapidly as do the cross sections at the maxima in the angular distributions of the prominent 2^+ and 3^- states (Figs. 4–7).

Figure 8 shows the angular distribution of a group at 2.2±0.1 Mev in Ni^{60}. Relative errors are large for this angular distribution because the group is very weakly excited. This group may contain contributions from both the 2.159-Mev level and the 2.286-Mev level. The level at 2.159 Mev is 2^+ while that at 2.286 Mev is probably a 0^+ level.[13,22] However, the angular distribution observed for the 2.2-Mev group is in phase with the elastic scattering, has its maxima at smaller angles than does the 2.50-Mev group, and fits the theoretical $L=3$ curve. The cross section at the maximum at 47° is only half as large as that for the 2.50-Mev group.

If the assumption is made that the 2^+ first excited states of Ni^{58} and Ni^{60} are one-phonon vibrational states, then some of the low-lying in-phase states (which occur at roughly twice the energy of the first excited state) may be regarded as possible two-phonon states. The fact that their angular distributions disagree in phase with Fraunhofer diffraction may mean that the

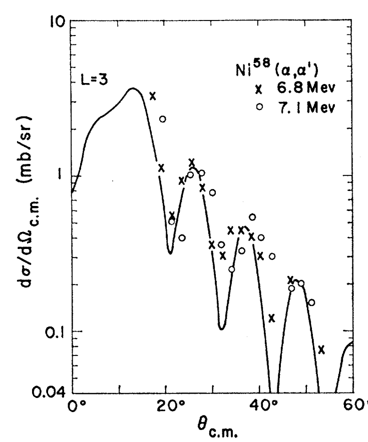


FIG. 10. Angular distributions for inelastic scattering to the groups in Ni^{58} at 6.8 and 7.1 Mev.

[18] D. S. Andreyev, A. P. Grinberg, K. I. Erokhina, and I. Kh. Lemberg, Nuclear Phys. **19**, 400 (1960).
[19] M. Crut and N. S. Wall, Phys. Rev. Letters **3**, 520 (1959).
[20] J. S. Blair, Phys. Rev. **115**, 928 (1959).
[21] R. H. Lemmer, A. de Shalit, and N. S. Wall, Phys. Rev. **124**, 1155 (1961).
[22] D. M. Van Patter, Bull. Am. Phys. Soc. **5**, 76 (1960).

process by which two-phonon levels are excited in inelastic scattering can not be approximated by simple Fraunhofer diffraction. If it is further assumed that all members of the two-phonon triplet have approximately the same cross section, then the fact that in Ni^{60} the 2.50-Mev group is twice as intense as the 2.2-Mev group may indicate that two members of the triplet are contained in the former and one in the latter. On the basis of present data it would not be possible to tell whether the two-phonon character of the 2.2-Mev group is due to the 2.159-Mev level or the 2.286-Mev level. However, the 2.50-Mev group is probably produced by the levels at 2.505 and 2.625 Mev, since these are the only known levels whose energies are consistent with the present observation that the *center* of the stronger group is at 2.50 ± 0.06 Mev.

The 2.47-Mev group in Ni^{58} has approximately the same cross section and angular distribution as the 2.50-Mev group in Ni^{60}. Therefore the 2.47-Mev group in Ni^{58} may be produced by two members of the two-phonon triplet. The levels at 2.458 and 2.483 Mev are the only known levels which can contribute to this group. The third member of the triplet would probably be one of the four known levels between 2.7 and 3.1 Mev, but it is impossible to determine which one from the present data. The angular distribution for the region around 2.9 Mev indicates that both in-phase and out-of-phase groups are present in the region around 2.9 Mev.

F. The 3-Mev Region

In Ni^{58} a broad group occurs at about 3-Mev excitation, and is mainly due to levels between 2.9 and 3.5 Mev. In this region the known levels are too closely spaced to be resolved in this experiment. The angular distribution for Ni^{58}, shown in Fig. 8, is thus a sum over about eight known levels. The angular distribution is out of phase with elastic scattering and may be fitted with either an $L=2$ curve or an $L=4$ curve. Angular distributions derived for parts of this peak show that the

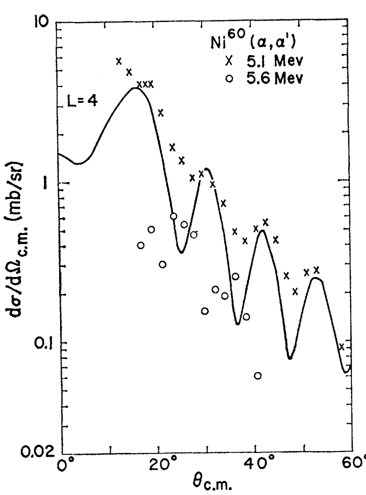


FIG. 11. Angular distributions for inelastic scattering to the groups in Ni^{60} at 5.1 and 5.6 Mev.

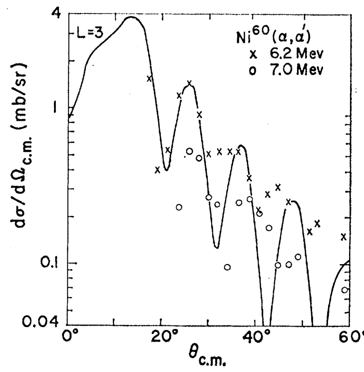


FIG. 12. Angular distributions for inelastic scattering to the groups in Ni^{60} at 6.2 and 7.0 Mev.

region around 3.2 Mev and the region around 3.5 Mev are out of phase with elastic scattering while the region around 2.9 Mev is of uncertain phase. The electron-scattering experiment of Crannell *et al.*[1] found a 2^+ group at 3.2 Mev, a 4^+ group at 3.5 Mev, but no group at 2.9 Mev. In the alpha-scattering experiment of Beurtey *et al.*,[8] a group was seen at 2.9 Mev which was out of phase with elastic scattering.

Figure 8 also shows the angular distribution for the group in Ni^{60} at 3.2 ± 0.1 Mev. There are six known levels in Ni^{60} in this energy region.[13] This group is out of phase with elastic scattering and may be fitted with either an $L=2$ curve or an $L=4$ curve. The cross section is only half as great as that for the wide 3-Mev group in Ni^{58}. Groups also occur between 3.6 Mev and the 3^- group at 4.05 Mev but their cross sections were too small to permit an angular distribution to be obtained.

G. Groups in Ni^{58} at Higher Excitation than the 3^- Group

Fairly intense groups were seen in Ni^{58} at 5.55 ± 0.05, 5.95 ± 0.05, 6.8 ± 0.1, and 7.1 ± 0.1 Mev. The angular distributions are given in Figs. 9 and 10. The group at 5.55 Mev is out of phase with elastic scattering and is fitted best by the $L=4$ curve. The 5.95-Mev group is out of phase with elastic scattering but has its peaks at slightly larger angles than does the 2^+ first-excited state. Hence neither the $L=2$ curve nor the $L=4$ curve will provide a good fit. The peak at 6.8 Mev is fitted well by the $L=3$ curve. The peak at 7.1 Mev is in phase with elastic scattering. However, the maxima in its angular distribution fall at larger angles than those of the $L=3$ curve, but occur at the same angles as those of the elastic scattering and those of the group at 2.47-Mev excitation. The relative angular distribution for the group at 7.1 Mev is thus nearly the same as that for the group at 2.47 Mev. The electron-scattering experiment[1] has found 4^+ groups at both 7.0 [23] and 2.48 Mev, but neither the 7.1- nor the 2.47-Mev group presented in Figs. 6 and 10 can possibly be fitted with the $L=4$ curve calculated by the distorted-wave Born approximation.

[23] H. Kendall, Proceedings of the Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, October 5–7, 1961 (to be published).

A small group in Ni^{58} was also seen at 5.1-Mev excitation. Its maximum cross section is less than 0.1 mb/sr. Another group was seen at 8.1-Mev excitation. Both of these groups are probably in phase with elastic scattering.

H. Groups in Ni^{60} at Higher Excitation than the 3^- Group

Angular distributions for the groups in Ni^{60} at 5.1, 5.6, 6.2, and 7.0 Mev are shown in Figs. 11 and 12. The angular distribution of the 5.1-Mev group is compared with the $L=4$ theoretical curve. The observed angular distribution is out of phase with elastic scattering. The data fit an $L=4$ curve better than an $L=2$ curve because the first maximum is at 19° c.m. rather than at 21° c.m. (where the $L=2$ curve has a maximum). The minima in the observed angular distribution are very shallow. This fact indicates that this group probably contains contributions from more than one level, and that some of these levels probably have angular distributions that are in phase with elastic scattering.

The group at 5.6 Mev is in phase with elastic scattering. The group at 6.2 Mev resembles the $L=3$ curve fairly closely. The 7.0-Mev group is in phase with elastic scattering. Moreover, the positions of the maxima in its angular distribution agree better with those of the 2.50-Mev group than with those of the $L=3$ curve. This group also resembles the 7.1-Mev group of Ni^{58}.

IV. ACKNOWLEDGMENTS

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Decay of 2.1-Hour Ta^{178}

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The allowed decay of 2.1-hr Ta^{178} has been reinvestigated, and the previously reported decay scheme has been almost completely confirmed. The multipolarity of the 331.7-kev transition between the 1480- and 1148-kev states has been reassigned as $M1$ on the basis of a measurement of its internal conversion coefficient. On the basis of the reassigned multipolarity, the beta-decay transition rates, and the recently measured spin 8 of the 1148-kev level, the 1148- and 1480-kev levels are interpreted, respectively, as two-proton and two-neutron states which are strongly admixed. The analysis in terms of two-particle states is based on ideas discussed in the following paper.

INTRODUCTION

IN the experimental attempt to achieve a clearer understanding of the intrinsic states of deformed even-even nuclei, the allowed decays of both members of the Ta^{178} isomeric pair are excellent cases for study, as the allowed rate of the decays implies close similarity between the initial and final states. In an earlier paper the allowed decay of 9.3-min Ta^{178} was discussed.[1] The decay scheme of the 2.1-hr isomer has been studied in detail,[2–5] but, because of the importance of the Hf^{178} levels it populates to the general understanding of the problem of energy levels in even-even nuclei, we have thought it worthwhile to make some additional measurements. In the present paper we, therefore, review the previous experimental work on the 2.1-hr Ta^{178} decay, and report additional experimental data.

In the previous experiments the multipole assignments of the transitions were based largely on L-sub-

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