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# $Ni^{58}(p,p')Ni^{58}$ Reaction in the 9.1- to 9.55-MeV Range*

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A detailed study of the $Ni^{58}(p,p')Ni^{58}$ reaction has been made in the 9.10- to 9.55-MeV incident-proton energy range. Angular distributions of ten resolved excited states below 4.2 MeV have been measured at 25-keV energy intervals. The energy-averaged angular distributions have been compared with Hauser-Feshbach predictions, and spins are suggested for several levels of $Ni^{58}$. Broad structure observed in the yield from the excitation of the 1.456-MeV state is discussed in terms of recently developed intermediate-resonance models.

## I. INTRODUCTION

INELASTIC-proton-scattering studies have provided much useful information concerning the properties of nuclear states and the reaction mechanisms by which they are excited. For medium-weight nuclei at low bombarding energies compound-nucleus formation and its subsequent decay is the principle reaction mechanism responsible for inelastic proton scattering. At higher energies direct excitation, excitation of intermediate structure, and vibrational collective motion in spherical nuclei become predominant. Just which of these mechanisms is operative in the energy region under study must of course first be established before effective use can be made of the $(p,p')$ reaction as a spectroscopic tool.

Several studies of the properties of levels in $Ni^{58}$ have been made using the $(p,p')$ reaction[1–5] at proton energies in the 15 to 25-MeV range where direct and collective excitation were found to be the principle modes of excitation. At lower energies a previous measurement[6] of the inelastic-proton-scattering yield from $Ni^{58}$ over the 7.0–15.3-MeV range has suggested the possible presence of intermediate structure in the yield curve near 9.25 MeV. The present study was motivated to a large measure by an interest in making a more detailed study of the intermediate structure in this energy region.

At still lower energies ($E<7$ MeV) compound-nucleus formation is expected to play a dominant role in the inelastic-scattering process. In this energy region the Hauser-Feshbach[7] procedure has been successfully applied to the study of angular distributions from the $(n,n')$ reaction[8,9] on heavy nuclei. Except for Seward's[10] early studies, little application of compound-nuclear theory has yet been made to inelastic-proton angular distributions. A comprehensive review of reaction studies in this energy region has recently been made by Sheldon and Van Patter,[11] who point out that the experimental situation regarding inelastic neutron distributions is much clearer than for inelastic proton distributions as far as comparison with compound-nuclear theory are concerned.

At low energies ($E=2$ to 5 MeV) properties of levels in $Ni^{58}$ and their gamma decays have been investigated using the $(n,n'\gamma)$ reaction[12] and the $(p,p'\gamma)$ reaction[13] and comparisons of the yield made with Hauser-Feshbach calculations. The gamma decays of the excited levels in $Ni^{58}$ have also recently been studied by using the $(p,p'\gamma)$ reaction[14] at $E_p=8$ MeV and by $(e,e')$ measurements[15] at 183 MeV. The properties of these levels have also been studied by employing the $(\alpha,\alpha')$ reaction[16–20] in the 30–44-MeV range and the $(d,d')$ reaction[21] at 15 MeV.

In an effort to further clarify the nature of the reaction mechanism in the intermediate energy range 9.1 to 9.55 MeV, a detailed study of the $Ni^{58}(p,p')$ reaction has been undertaken and is reported here. A preliminary report of a similar study has been given by Monahan *et al.*[22] It has been found that mechanisms of direct, compound-nuclear, and intermediate-structure excitation may be required to account for the yield of

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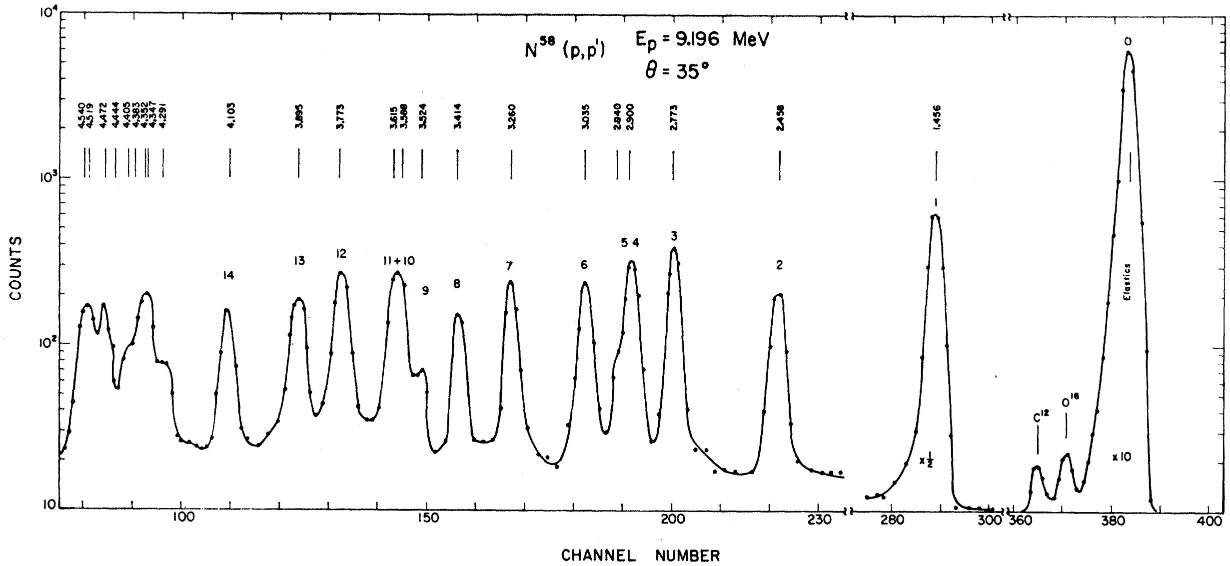


FIG. 1. Representative proton spectrum at 9.196 MeV and 35°. The excitation energies given in the figure are from Brown and Middleton and the expected level positions are indicated by the short vertical lines. Note the broken scale of the abscissa and the scaling of the ground state and 1.456-MeV-state groups.

the first excited 1.456-MeV $2^+$ state, while the excitation of the other states investigated can be accounted for by assuming compound nucleus formation and decay. The viewpoint is taken that spins of levels excited by the $(p,p')$ reaction at these bombarding energies may be indicated by comparing measured angular distributions with the predictions of Hauser-Feshbach theory.

## II. EXPERIMENT

Protons accelerated by the University of Pennsylvania tandem Van de Graaff accelerator were used to measure the angular distributions of protons inelastically scattered from $Ni^{58}$. The proton beam from the accelerator entered a 24-in.-diam scattering chamber,[23] after passing through a $\frac{1}{16}$-in.-diam collimating system, where it was incident upon a 0.5-mg/cm$^2$ self-supporting 99.9%-enriched $Ni^{58}$ foil. The over-all energy resolution including the beam energy spread and target thickness was 20 keV.

The scattered protons were detected with 2-mm-thick surface-barrier detectors between the laboratory angles 30° and 170° at 10° intervals for each bombarding energy. Difficulty was encountered in making measurements of the inelastic groups at angles smaller than 30° in the presence of the intense elastic group. The proton energy range 9.10 to 9.55 MeV has been covered in 25-keV steps. The over-all detection resolution was 50 keV. Protons were detected simultaneously at four angles and stored in 512-channel memory quadrants of a 2096-channel pulse-height analyzer.

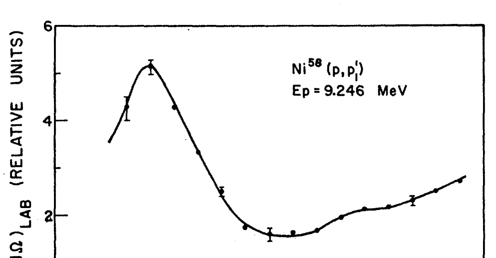


FIG. 2. Representative angular distribution at 9.246 MeV for the $P_1$ group.

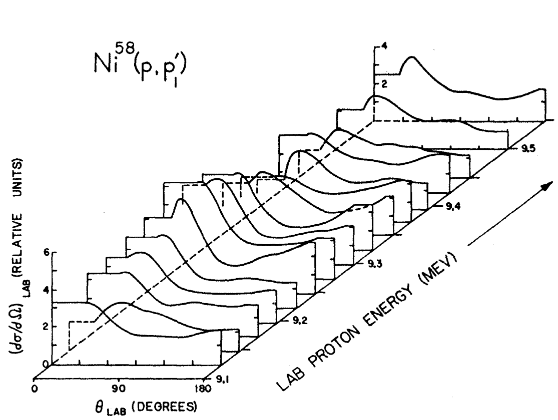


FIG. 3. $P_1$ group, corresponding to 1.456-MeV state of $Ni^{58}$. The differential cross section is shown as a function of the angle of detection and the proton bombarding energy in the laboratory. Smooth curves have been drawn through the data points. Dashed curves are used to indicate curves obscured by angular distributions at other energies.

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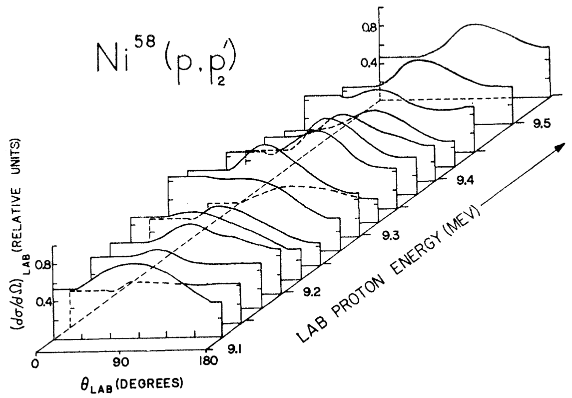


FIG. 4. $P_2$ group, corresponding to 2.458-MeV state of $Ni^{58}$. See Fig. 3.

## III. RESULTS

A representative proton spectrum is shown in Fig. 1 for a proton bombarding energy of 9.196 MeV at the laboratory angle of 35°. Angular distributions have been measured for states at 1.456-, 2.458-, 2.773-, 2.900-, 3.035-, 3.260-, 3.414-, 3.773-, 3.895-, and 4.103-MeV excitation. High-resolution spectrographic measurements of the energy levels in $Ni^{58}$ have been made by Paris and Buechner,[24] Cosman *et al.*,[25] and Brown and Middleton.[26] The excitation energies quoted here and in Fig. 1 are from the work of Brown and Middleton and agreement with energies obtained in the present experiment is within ±10 keV. States at 4.219, 3.524, and 2.940 MeV are only weakly excited. The states at 3.615 and 3.588 MeV were unresolved and hence their angular distribution have not been reported. The 2.940- and 2.900-MeV states were also not well resolved and the angular distribution of the 2.900-MeV state contains a small contribution from the 2.940-MeV state.

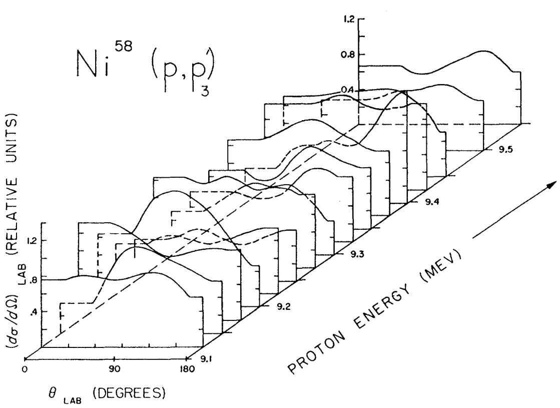


FIG. 5. $P_3$ group, corresponding to 2.773-MeV state of $Ni^{58}$. See Fig. 3.

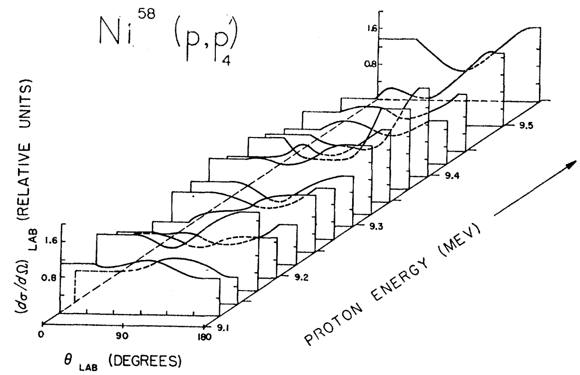


FIG. 6. $P_4$ group, corresponding to 2.900-MeV state of $Ni^{58}$. See Fig. 3.

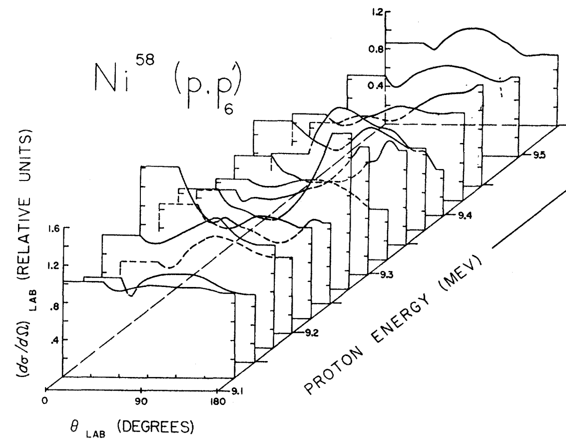


FIG. 7. $P_6$ group, corresponding to 3.305-MeV state of $Ni^{58}$. See Fig. 3.

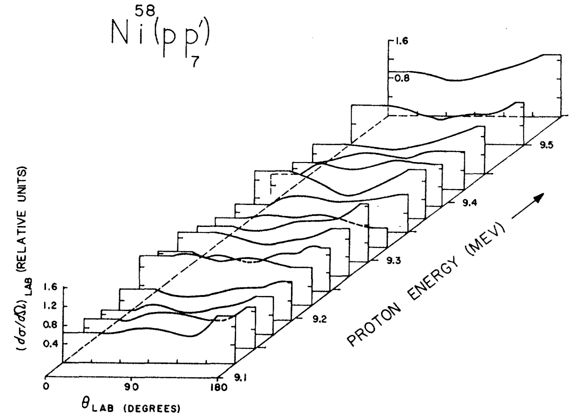


FIG. 8. $P_7$ group, corresponding to 3.260-MeV state of $Ni^{58}$. See Fig. 3.

A representative angular distribution is shown in Fig. 2 to illustrate the quality of the data. The error bars reflect, in addition to counting statistics, systematic effects and uncertainties in background subtraction.

[24] C. H. Paris and W. W. Buechner, in *Proceedings of the International Conference on Nuclear Physics, Paris*, edited by P. Gugenberger (Dunod, Cie., Paris, 1959), p. 515.

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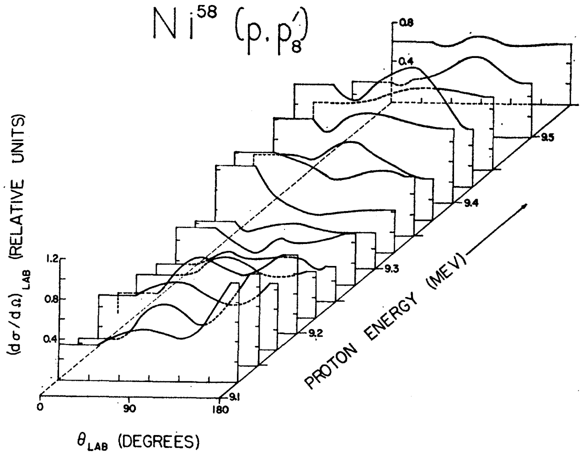


FIG. 9. $P_8$ group, corresponding to 3.414-MeV state of Ni[58]. See Fig. 3.

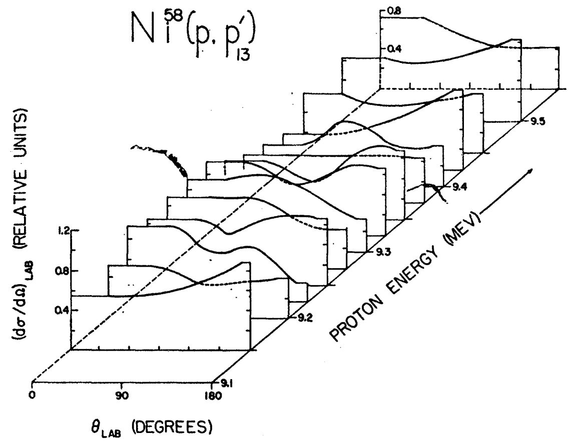


FIG. 11. $P_{13}$ group, corresponding to 3.895-MeV state of Ni[58]. See Fig. 3.

Systematic effects include such sources of uncertainty as reproducibility of data, reliability of analyzer dead-time corrections, small solid-angle uncertainties, and reproducibility of energy calibration. Counting statistics generally represent less than a 2% error and an over-all error limit of typically 5% is placed on the relative differential cross sections.

The angular distributions for the proton groups $P_1$, $P_2$, $P_3$, $P_4$, $P_6$, $P_7$, $P_8$, $P_{12}$, $P_{13}$, and $P_{14}$ are represented in Figs. 3–12 as a function of proton energy. Each slice in the figures represents an angular distribution. A few general features of these angular distributions may be pointed out. The shape of the $P_1$ angular distribution is quite regular in its energy dependence and is generally forward-peaked, reaching a maximum around 45°. Such a feature is generally characteristic of a direct process. A broad prominence in the cross section can be seen around 9.27 MeV. The shape of the $P_2$ angular distribution is also quite regular in its energy dependence with a broad maximum near 90°. The absence of strong energy dependence again suggesting the presence of a direct excitation process. The shapes of the angular distributions for the $P_3$, $P_4$, $P_6$, $P_7$, $P_8$, $P_{12}$, $P_{13}$, and $P_{14}$ groups are more random in character, often changing markedly over a 25-keV interval in bombarding energy. Such characteristics are usually associated with the formation of compound nuclear states. The cross-section scales in Figs. 3–12 are in relative units, but are all normalized by the same factor. Thus, the relative yields of the proton groups may be compared directly.

## IV. HAUSER-FESHBACH CALCULATIONS

Although the Hauser-Feshbach method may not be regarded *a priori* as a reliable spectroscopic tool, it was felt that it would be useful to make a comparison of the experimental results with the Hauser-Feshbach predictions, particularly in view of the fact that little previous application of compound-nucleus theory has yet been made to inelastic proton angular distributions.[11]

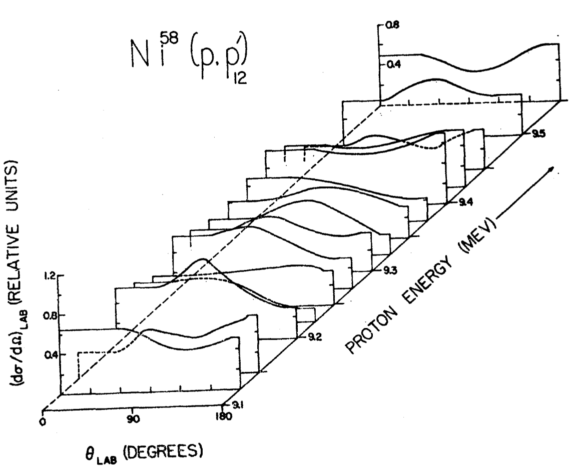


FIG. 10. $P_{12}$ group, corresponding to 3.773-MeV state of Ni[58]. See Fig. 3.

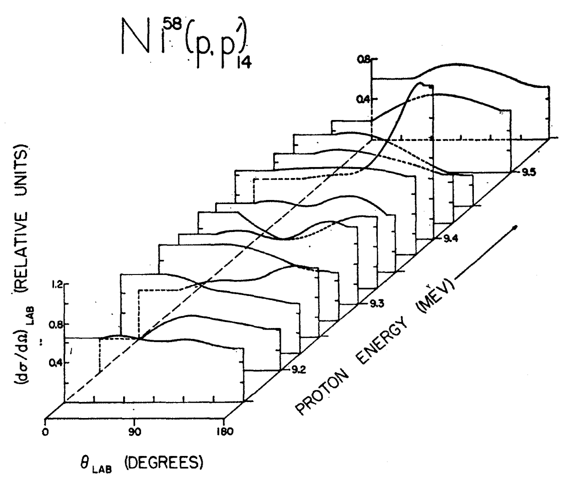


FIG. 12. $P_{14}$ group, corresbonding to 4.103-MeV state of Ni[58]. See Fig. 3.

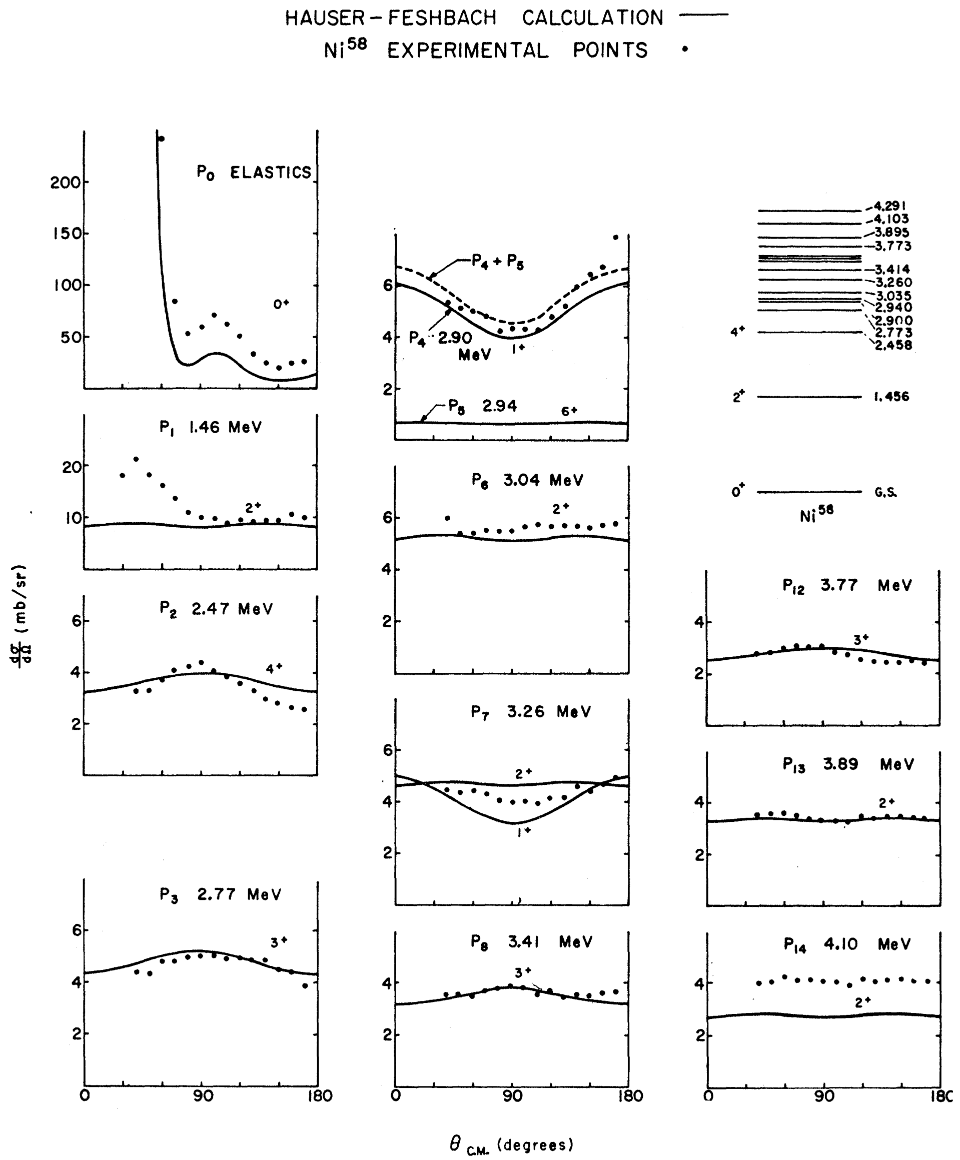


FIG. 13. A comparison between experimental energy-averaged angular distributions, represented by points, and the calculated angular distributions, represented by the solid curves. Experimental errors are estimated to be less than 5%. The assumed spins are indicated. A $Ni^{58}$ level diagram is also shown for easy reference. Note the change in scale for the $P_0$ and $P_1$ groups.

In general, a minimum condition for successful application of Hauser-Feshbach theory is that the reaction mechanism be compound nuclear and that the cross section be averaged over a statistically meaningful number of compound-nuclear states of different spins.

If compound-nucleus formation is the principle reaction mechanism, then the angular distributions of the various groups should exhibit symmetry about 90° (in the c.m. system) when an average is taken over a sufficient number of compound-nuclear states. Indeed, the energy-averaged angular distributions represented by the points in Fig. 13 are essentially symmetric about 90° with the exception of the first excited state, which shows a substantial direct-interaction contribution. Averaging the angular distributions over the entire range of incident energies also assures that the cross section has been averaged over a large enough number of states in the compound nucleus $Cu^{59}$ to permit a meaningful application of the Hauser-Feshbach method.

In view of the unusually high $(p,n)$ threshold of $Ni^{58}$, one might expect the $Ni^{58}(p,p')$ reaction to be dominated by the compound-nucleus process even in the relatively high proton energy region studied. Since over most of the energy range covered in the experiment the neutron channels are not accessible for compound-nuclear decay, proton emission will not be suppressed by competition from neutron emission.

The Hauser-Feshbach calculations were made using the ABACUS-II program.[27] The optical potential assumed

[27] The ABACUS-II program was supplied by E. H. Auerbach.

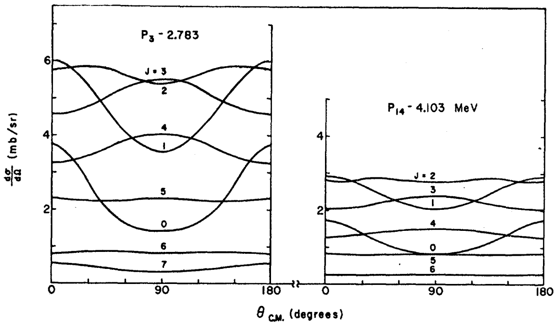


FIG. 14. The calculated curves are compared for different spin assumptions for two widely separated levels of $Ni^{58}$, illustrating the spin and excitation-energy dependence of the angular distribution anisotropy.

was of the form

$$V(r)=\frac{-V+iW}{1+\exp[(r-R)/a_1]} -i4W_Da_1\frac{d}{dr}\left\{\frac{1}{1+\exp[(r-R)/a_2]}\right\} +\begin{cases}\dfrac{Ze^2}{r}, & r\geq R,\\[2mm] \dfrac{Ze^2}{2R}\left(3-\dfrac{r^2}{R^2}\right), & r\leq R,\end{cases} \quad (1)$$

where $R=r_0A^{1/3}$, and with the parameters $V=52.0$ MeV, $W=0$, $W_D=11.0$ MeV, $r_0=1.25$ F, $a_1=0.65$ F, and $a_2=0.47$ F. The angular distributions were calculated for the first 16 levels of $Ni^{58}$ and are represented by the solid curves of Figs. 13 and 14. A preliminary account of these calculations was reported earlier.[11,28]

The experimental angular distributions have been normalized to the calculated curves with the same normalization applying to all angular distributions. The spins shown in Fig. 13 represent best fits, with all parities assumed positive. The calculation is not very sensitive to the choice of parity. The calculated curve for the $P_0$ group includes an optical-model-shape elastic contribution. A level diagram for $Ni^{58}$ is also shown in Fig. 13 for easy reference.

In Fig. 14 the angular distributions are compared for different choices of spin $J$ of the 2.773- and 4.103-MeV states of $Ni^{58}$. The anisotropy is largest for $J=0$ and decreases with increasing spin and excitation energy. The method's greatest usefulness as a spectroscopic tool for even-even nuclei would seem to be for low-spin states of not too high excitation energy. The method seems to be particularly useful for locating $J=0$ and $J=1$ states in even-even nuclei, as their calculated angular distributions show large anisotropies.

The $P_1$ state is a known $2^+$ state, which according to the spherical vibrational model would be the one-phonon quadrupole state. Such an assumption is confirmed by high-energy electron scattering[15] and $(\alpha,\alpha')$ measurements.[16–19] The agreement of the data with the calculated angular distribution at back angles, where the direct excitation contribution is not expected to be dominant, is acceptable.

The spin and parity of the $P_2$ state have also been determined as $4^+$ by high-energy electron scattering and $(\alpha,\alpha')$ measurements and is probably the $4^+$ member of the two-phonon triplet. Although the agreement between the shape of the experimental and calculated angular distributions is not quantitative, perhaps because of a direct excitation contribution, nevertheless they have the same character.

The shape of the $P_3$ angular distribution favors $J=3$, while the magnitude of the cross section is consistent with a $J=2$ or 3. Preliminary $Ni^{58}(p,p'\gamma)Ni^{58}$ gamma-ray angular distributions and $\gamma$-$\gamma$ angular-correlation measurements[29] suggested that the 2.773-MeV state was the $0^+$ member of a two-phonon triplet. The excitation cross section of this level is greater than the Hauser-Feshbach calculations predict for $J=0$. In view of the present results and the more recent $Ni^{58}(p,p'\gamma)Ni^{58}$ measurements of Hinrichsen *et al.*,[14] a spin of $0^+$ is unlikely for the 2.773-MeV state.

The $P_4$ and $P_5$ proton groups are not clearly resolved experimentally. However, the yield of the $P_4$ group is much greater than that of $P_5$. The choice of $J=1$ is preferred for $P_4$ and a high spin (6 is shown in the figure) assumed for $P_5$. Their respective computed angular distributions are shown by solid curves in Fig. 13 and their sum by the dashed curve. The assumption of $J=0$ for $P_4$ and $J=5$ for $P_5$ would also provide agreement between the shape of the angular distribution and the $P_4+P_5$ yield. However, a 1.46–1.46-MeV $\gamma$-$\gamma$ angular correlation measurement[30] of the decay of the 2.900-MeV state through the $2^+$, 1.456-MeV state does not allow $J=0$ for the 2.900-MeV state, assuming the 2.900-MeV level is the only member of the 2.900–2.940-MeV doublet significantly populated in the $Cu^{58}$ $\beta^+$ decay. The assumption of $J=1$ or 2 for the 2.900-MeV state is consistent with the $\gamma$-$\gamma$ correlation measurements. Our $J=1$ choice is also consistent with the observation, from $Ni^{58}(p,p'\gamma)$ studies,[14] that the 2.900-MeV level decays predominantly ($>95\%$) to the 1.456-MeV $2^+$ state.

The assumption $J=2$ seems best for the $P_6$, $P_7$, $P_{13}$, and $P_{14}$ states on the basis of the shapes of their angular distributions and, with the exception of $P_{14}$, their cross

[28] L. W. Swenson and R. K. Mohindra, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove, and R. L. Robinson (Academic Press Inc., New York, 1966).

[29] S. M. Shafroth, A. K. Sen Gupta, and G. T. Wood, Bull. Am. Phys. Soc. **9**, 93 (1964).

[30] S. M. Shafroth and G. T. Wood, *Proceedings of the Congrès International de Physique Nucléaire*, edited by P. Gugenberger (Editions du Centre National de la Recherche Scientifique, Paris, 1964), Vol. 2, p. 476.

sections. It may be noted that at these excitations, 3.035, 3.260, 3.895, and 4.103 MeV, respectively, the calculated angular distributions are nearly isotropic for $J=2$. The assumption of a low spin for these levels is consistent with the observation, from $(p,p'\gamma)$ measurements,[14] that all four levels decay to the $2^+$ state at 1.456 MeV and the $0^+$ ground state with comparable intensities. An assignment of $2^+$ for $P_6$ and $P_7$ is suggested by $(d,d')$ angular distribution measurements.[21] A spin of $2^+$ has also been assigned to the 3.260-MeV level on the basis of $(e,e')$ measurements[15] and is supported by angular distribution studies[29] of the deexcitation gamma rays from the $Ni^{58}(p,p'\gamma)$ reaction. The $P_{14}$ proton group is well resolved from neighboring groups and its measured cross section significantly exceeds the calculated cross section. The lack of agreement is not understood, but may reflect the presence of a hitherto unresolved doublet at 4.10-MeV excitation.

Although the choice $J=2$ is not definitely ruled out for the $P_8$ and $P_{12}$ levels, the assumption of $J=3$ provides better agreement with the shape and yield of the angular distributions. The higher spin is also consistent with the observation from $Ni^{58}(p,p'\gamma)$ studies,[14] that the 3.414-MeV level decays predominantly to the $4^+$ state at 2.458 MeV and the principle decay mode of the 3.773-MeV level is to either the 2.458- or the 2.773-MeV state. These decays stand in contrast to those of the 3.035-, 3.260-, 3.895-, and 4.103-MeV states which decay to the $2^+$ state at 1.456-MeV and the ground state. The shapes of the angular distributions for the $P_8$ and $P_{12}$ groups are not inconsistent with assuming $J=4$. However, the measured yields are much larger than the corresponding Hauser-Feshbach predictions.

The $P_{10}$ and $P_{11}$ groups were not resolved and appear to be excited with comparable strength, hence little can be said about these two levels. The level $P_9$ at 3.524 MeV was only weakly excited and partially resolved. This level can probably be identified with the $4^+$ level observed around 3.5 MeV in $(e,e')$ and $(d,d')$ studies. Such an assumption is strengthened by the observation of Hinrichsen *et al.*,[14] that it decays primarily to the $2^+$ 1.456-MeV level. In concluding this discussion, we remark that, although spins of several levels are indicated by the Hauser-Feshbach method, these spins should be checked by other established methods before they are considered as positive assignments.

## V. INTERMEDIATE STRUCTURE CALCULATION

In view of the results of the previous section, it may be said that a major part of the $Ni^{58}(p,p')$ cross section around 9 MeV can be attributed to compound-nucleus formation. It is, therefore, not surprising to find that the yield curves of the differential cross sections show considerable and irregular narrow structure as a function of the proton bombarding energy.

Under the experimental conditions reported here the over-all energy resolution ($\Delta E=20$ keV) was of the order of 10 times greater than the expected average width ($\Gamma\simeq1$–$5$ keV) of the compound-nuclear levels[31] encountered in $Cu^{59}$. Under these conditions, the compound-nuclear fluctuations[32] are considerably damped. Further damping is effected by integrating the differential cross section over all angles. The experimental resolution $\Delta E$ is, however, good enough that any intermediate ($\Gamma\approx100$ keV) structure, if present, should not be obscured.

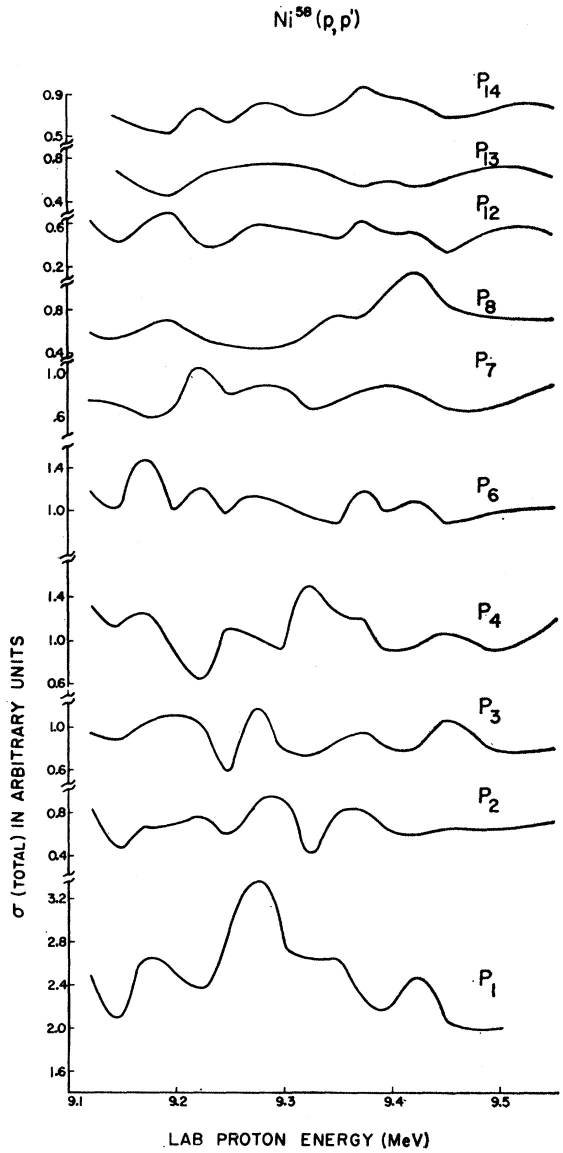


FIG. 15. Yield of differential cross section integrated over all angles as a function of incident proton energy in the laboratory.

The yields of the integrated cross sections are shown

[31] L. W. Swenson and K. Izumo, Phys. Letters **19**, 49 (1965).
[32] P. Fessenden, W. R. Gibbs, and R. B. Leachman, Phys. Rev. Letters **15**, 796 (1965).

for all the resolved proton groups in Fig. 15 as a function of the incident proton energy in the laboratory. The structure in these yield curves shows no noticeable regularity from group to group with the possible exception of the $P_1$, $P_2$, and $P_3$ groups, which have a common prominence between 9.25 and 9.30 MeV. The broad structure, with width $\sim$100 keV, in this region displayed by the $P_1$ group will be singled out for further discussion in terms of recent intermediate resonance models.[33–35] It was felt that a useful comparison might be made between the angular distributions of the $P_1$ group in the neighborhood of the prominence and intermediate resonance calculations, particularly since a previous calculation has been made[35] for the less complete data of Kobayashi *et al.*[6] Interest is further motivated by the observation of a $p_{1/2}$ intermediate resonance[31] at 9.25 MeV in the elastic scattering of protons from $Ni^{58}$. If this resonance is "intermediate" in nature[33–35] it may be expected to be evident in other outgoing channels in addition to the elastic channel. A careful study of the $Ni^{58}(p,\alpha_0)Co^{55}$ reaction has also recently been made and evidence found for the presence of intermediate structure in the 9.1- to 10.8-MeV region.[36]

Angular distribution calculations have been carried out based on the partial-equilibrium model of Izumo.[35] In this model the nucleus is treated as a Fermi gas and the target nucleons are divided into two groups: the $N$ inert-core nucleons and the $A-N$ extracore, surface nucleons. It is assumed that only these surface nucleons interact strongly with the incident particle, while the inert core remains in its ground state, producing an average potential for the incident particle. The direct reaction and intermediate resonance amplitudes contribute coherently to the inelastic-scattering cross section. An incoherent contribution (fluctuation term) accounting for compound-nuclear formation is also included in the calculation.

Some of the assumptions made in adopting this model might be regarded as extreme or at least restrictive. For example, the assumptions of a Fermi gas and an inert core would seem to restrict the validity of the model to very general predictions of average resonance properties which do not involve the detailed nuclear structure of individual nuclei. Nonetheless, the model represents the only theoretical result currently available with which comparisons may be readily made to experimental angular distribution data involving intermediate resonances.

In our treatment of the direct contribution, a surface direct interaction has been assumed and treated in plane-wave approximation.[37] Such an assumption was made in the interest of keeping the calculation simple enough that it could be accomplished without the aid of a computer. A more exact calculation should be treated in the distorted-wave Born approximation or perhaps as a coupled-channel problem.

For inelastic proton scattering the differential cross section for such a process is given in the form

$$\frac{d\sigma}{d\Omega}=\frac{\pi}{k_p^2}(2s+1)^{-1}\sum_{\nu\nu'}\int_0^{2\pi}|A(p,p_1')+B(p,p_1')|^2d\phi+\left\langle\frac{d\sigma}{d\Omega}\right\rangle_{\text{fluct}}, \quad (2)$$

where the intermediate resonance term $A(p,p_1')$ is given by

$$A(p,p')=\sum_{Mll'm's'}(2l+1)^{1/2}(\tfrac{1}{2}l\nu 0|JM)(s'l'\nu'm'|JM)\times\frac{(\Gamma_{\mu p}\Gamma_{\mu p'})^{1/2}}{E-E_\mu+\frac{1}{2}i\Gamma_\mu}Y_{l'm'}(\Theta,\Phi). \quad (3)$$

The incoming channel spin $s=\frac{1}{2}$ couples to the orbital angular momentum $l$ of the incoming proton to give the spin $J=l\pm\frac{1}{2}$ of the resonance with the projection $M=\nu\pm m$. The projection of the incoming channel spin is $\nu$ and for our plane-wave assumption the projection of $l$ is $m=0$. All the corresponding primed quantities refer to the outgoing channel. The resonance parameters are the resonance energy $E_\mu$, the total width $\Gamma_\mu$, and the partial widths $\Gamma_{\mu p}$ and $\Gamma_{\mu p'}$ for the incoming and outgoing channels, respectively. The partial widths have been assumed to be constant except for the $l$-dependent factor $(2l+1)T_l$, where $T_l$ is the transmission coefficient for the $l$ partial wave. The usual 6-$j$ symbols and spherical harmonics appear in Eq. (3).

The direct interaction term $B(p,p')$ appearing in Eq. (2) has the form

$$B(p,p_1')=Ce^{i\phi}(k_pk_1')^{1/2}j_2(QR). \quad (4)$$

The wave numbers in the center-of-mass system for the incoming and outgoing protons are $k_p$ and $k_1'$, respectively, and $\phi$ is the phase between the direct and compound-nuclear amplitudes. The momentum transfer $Q$ and the interaction radius $R$ appear in the argument of the spherical Bessel functions $j_2(QR)$. The interaction radius was adjusted to make the principle maximum of the Bessel function coincide with the peak position of the angular distribution.

The cross section consists of both rapidly and slowly varying energy terms. The intermediate resonance and interference contributions to the cross section constitute the rapidly varying part while the direct and the energy-averaged compound-nucleus (fluctuation) terms form the slowly varying part. The relative strength of

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[35] K. Izumo, Progr. Theoret. Phys. (Kyoto) **26**, 807 (1961); Nucl. Phys. **62**, 673 (1965).
[36] R. K. Mohindra and L. W. Swenson, Bull. Am. Phys. Soc. **10**, 496 (1965); (to be published).
[37] N. Austern, S. T. Butler, and H. M. McManus, Phys. Rev. **92**, 350 (1953).

the direct-reaction contribution is determined by comparison with the experimental value of $[\langle d\sigma/d\Omega\rangle - \langle d\sigma/d\Omega\rangle_{\rm fluct}]$ in the energy region away from the resonance position. The energy-averaged compound-nuclear contribution $\langle d\sigma/d\Omega\rangle_{\rm fluct}$ has been estimated by comparing the calculated Hauser-Feshbach cross sections with the averaged experimental angular distributions at angles greater than 120° and at energies off resonance. Under these conditions the calculated Hauser-Feshbach cross section may be taken as a measure of $\langle d\sigma/d\Omega\rangle_{\rm fluct}$. The choices $\pi$ and zero of the phase have been considered and $\phi=0$ found to result in the best fit to the experimental angular distribution. The value of the factor

$$\left(\frac{\Gamma_{\mu p}}{\Gamma_\mu}\right)^{1/2}\left(\frac{\Gamma_{\mu p'}}{\Gamma_\mu}\right)^{1/2}\Big/\left[\left(\frac{E-E_\mu}{\Gamma_\mu}\right)^2+1\right]$$

has been estimated by comparing the experimental cross section with Eq. (2) at the peak position of the angular distribution (40° in this case).

The shape of the resonant part of the angular distribution depends upon the $l$ value of the incident proton and the transmission coefficients through the intermediate resonant term of Eq. (2). The direct term of Eq. (2), however, plays the dominant role in determining the over-all shape of the angular distribution and hence, the angular distributions are not as sensitive to the choice of $l$ as might be desired. Each value of $l$ gives rise to two values of $J=l\pm\frac{1}{2}$. The transmission coefficients[38] were computed with the aid of the ABACUS-II code[27] and an optical potential of the form given by Eq. (1) with the parameters $V=52$ MeV, $W=0$, $W_D=11$ MeV, $r_0=1.25$ F, $a_1=0.65$ F, and $a_2=0.47$ F.

Comparisons between the experimental and calculated angular distributions have been made for $l=0$, 1, 2, and 3 with $J=l\pm\frac{1}{2}$. The cases of a $p_{1/2}$ and $d_{5/2}$ resonance are shown in Fig. 16. The points are experimental and the dashed curves are calculated. The best-fit parameters $E_\mu=9.27$ MeV, $\Gamma_\mu=120$ keV, $R=1.7A^{1/3}$ F and $\phi=0$ were used in the calculations. Comparisons are shown at resonance and 100 keV above and below resonance. The estimated contribution from energy-averaged compound-nuclear fluctuations is indicated by the horizontal dashed line in each plot. The theoretical curves have been normalized to the experimental angular distribution at the resonance energy to give the best over-all fit.

Although, as the fits of Fig. 16 indicate, it is possible to account for the qualitative features of the angular distributions near resonance on the basis of the Izumo partial-equilibrium model, the model in this application is not very sensitive to the choice of resonance spin and $l$ value for a particular resonance. For this reason, a unique spin cannot be assigned to the resonant-like structure in the $P_1$ group. This stands in contrast to

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

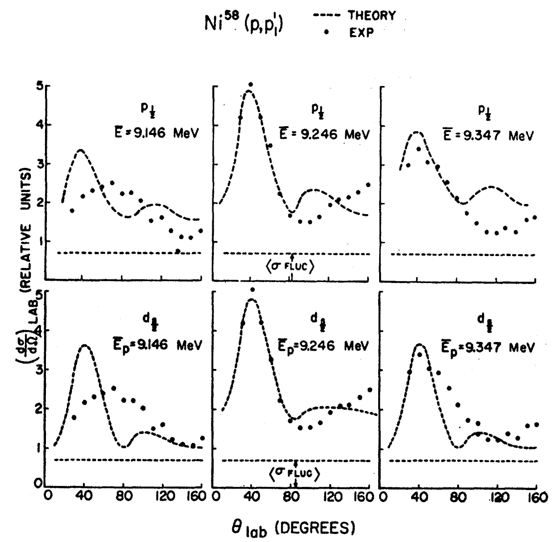


FIG. 16. The experimental angular distribution for the $P_1$ group is compared with the intermediate resonance theory prediction at the resonance and off resonance. The points represent experiment and the dashed curves represent the theoretical predictions. The amount of fluctuation contribution included in the calculations is indicated by the horizontal dashed lines. The comparison is made for a $p_{1/2}$ and a $d_{5/2}$ resonance. The resonance energy was taken as 9.246 MeV in these comparisons.

the application of the model to the $Ni^{58}(p,\alpha_0)Co^{55}$ reaction,[36] where the model has been successfully applied. In the case of the $Ni^{58}(p,p_1')Ni^{58}$ reaction the method becomes less selective due to the large amount of the direct interaction contribution (approximately 30% in the resonance region and 60% in the region 100 keV away from the resonance), while the $Ni^{58}(p,\alpha_0)Co^{55}$ reaction proceeds mainly by compound-nucleus formation at the energies under consideration. That the $Ni^{58}(p,p_1')Ni^{58}$ reaction has a significant direct-reaction contribution is evident from the fact that at forward angles in Fig. 13 the Hauser-Feshbach calculations cannot account for a major part of the energy-averaged cross section.

The calculation for the $(p,p_1')$ reaction would likely be improved by employing the more realistic distorted-wave Born approximation (DWBA) in treating the direct-reaction amplitude of Eq. (2). To pursue such a calculation it would be necessary to write a computer program to evaluate Eq. (2) which would incorporate a DWBA code (such as the Oak Ridge code JULIE) to evaluate the direct amplitude $B(p,p')$. One must also be aware of the uncertainties and difficulties involved in trying to determine how much direct amplitude to incorporate into Eq. (2). In view of the limited nature of the present experimental data such an effort did not seem justified. The results of the calculations undertaken do, however, have the value of demonstrating that if such intermediate resonance calculations are to be made in the future, for cases involving a substantial direct-reaction contribution, it will be necessary to treat the calculation in this manner.

If the broad resonant-like structure in the yield of the $P_1$ group is an intermediate resonance, or "doorway state" in the treatment of Block and Feshbach,[33] then it is natural to expect similar structure in other exit channels. The structure observed in the $P_1$ group at 9.27 MeV may correspond to the $p_{1/2}$ resonance observed in the elastic scattering[31] at 9.25 MeV. No recognizable corresponding structure is evident in the inelastic scattering to higher excited states (with the possible exception of the $P_2$ group) in the same energy range. However, the partial widths for exciting the resonance through these states may be too small to be observed in the $(p,p')$ reaction.

## VI. SUMMARY

It has been established from the present investigation that compound-nucleus formation dominates the $Ni^{58}(p,p')Ni^{58}$ reaction between 9.1 and 9.55 MeV. The energy-averaged angular distributions (with the exception of the $P_1$ group) are symmetric about 90° and in reasonable agreement with Hauser-Feshbach calculations for states of known spin. Spins of several other levels are suggested on this basis. The usefulness of this method as a spectroscopic tool appears promising, particularly for $J=0$ and 1 states. Final evaluation of the method's reliability must await further testing on other nuclei and perhaps at lower bombarding energies.

An intermediate-resonance and direct-reaction contribution is observed in the yield of the $P_1$ group. The calculation employed here was, however, not sufficiently sensitive to establish a unique spin for the resonant structure, as the study of the intermediate-resonance component is complicated by the presence of a direct-interaction contribution.

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# Decay of a New Isotope: $Cu^{69}$†

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Sources of $Cu^{69}$ have been produced by $\gamma$-$p$ reactions in Zn (enriched to 78.3% $Zn^{70}$) and their decay has been studied with scintillation and semiconductor detectors. The half-life of $Cu^{69}$ has been determined to be 3.0±0.1 min. Seventy-nine percent of the decay is by direct beta decay to the ground state of $Zn^{69}$ ($E_0=2.48\pm0.07$ MeV, $\log ft=5.1$). The remaining decay modes exhibit a complex spectrum for which a level scheme has been established. The proposed $Zn^{69}$ levels that are fed by the $Cu^{69}$ decay are at 0.5307, 0.8340, 1.0065, 1.1795, 1.428, 1.825, and 2.026 MeV. Other suggested but more tentative levels are at 0.615, 2.17, and 2.4 MeV. Of the beta-decay modes, those to the 0.5307- and 0.615-MeV levels have the highest $\log ft$ values, namely ~6.7 and 6.8, respectively. The $\log ft$ values of the other branches are smaller than 5.7 and all indicate allowed beta decay.

## I. INTRODUCTION

INVESTIGATION of the radioactivities created by photonuclear reactions with a 7-mg Zn sample, enriched to 78.3% $Zn^{70}$, yielded a previously unreported activity with a half-life of about 3 min. It decayed predominantly by beta decay to the ground state of the daughter nucleus, but the NaI(Tl) scintillation spectrum also showed gamma lines at 1.00, 0.84, and 1.43 MeV and suggested the presence of other weaker lines. The activity was assigned to $Cu^{69}$ and described in a preliminary report.[1] Thereafter, a more complete investigation was made with a larger amount of source material and with improved detection techniques.

For these improved measurements, two samples of metallic Zn with the same enrichment of 78.3% in $Zn^{70}$ were obtained from the Oak Ridge National Laboratory. One, mainly for beta-ray measurements, consisted of 25 mg of metal powder; the other, for the gamma-ray investigation, was a 22.9-mg metal bead.

In the course of the investigation, both samples were irradiated many times with ~200 000 $R$/min of bremsstrahlung from the 70-MeV Iowa State University synchrotron. Typically, a 3-min irradiation produced about 0.1 $\mu$Ci activity in these samples. Since the sample container also became activated, it was necessary to transfer the samples after irradiation into another nonradioactive container. The powder was transferred into a gelatin capsule of wall thickness 9 mg/cm², which was grounded by a thin wire. The metal bead was placed in an aluminum (in some cases, brass) container with a wall thickness of 2 mm.

Of the competitive activities created in the sample, the longest living non-negligible one is the 14-h isomeric transition of 0.439 MeV in $Zn^{69}$. The dominant $(\gamma,n)$

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