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Compound States of the System $Ni^{58}+p$*

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A Ni^{58} target was bombarded by protons from 2 to 5 Mev in energy. Approximately 70 resonances were observed in the yield of the γ radiation due to inelastic scattering from the state at 1.45 Mev. Angular distributions were obtained for this radiation at 37 resonances. Nineteen of the distributions are consistent with a $5/2^+$ assignment and seventeen fit a 3/2 assignment, while one distribution was isotropic. All the resonances observed had a width no greater than the target thickness of 4 kev. Absolute yields for the reaction have been determined. The level spacing for states formed by d-wave protons was found to be approximately 30 kev in the region studied. An estimate of the value of $\langle\gamma^2\rangle_{Av}/\bar{D}$ for these resonances gives 1.4×10^{-14} cm. In order to determine the energies of excitation in Cu^{59}, to which these resonances would correspond, the end point of the Cu^{59} beta spectrum was measured, and found to be 3.75 ± 0.1 Mev. This puts the range of excitation for the resonances observed between 6.3 and 7.9 Mev.

INTRODUCTION

A LARGE amount of experimental work has been done on excitation functions for charged-particle-induced reactions among the light nuclei ($Z\leqslant 20$) in order to locate states of the compound nucleus.[1] When information regarding spins, parities, and resonance widths of the states have also been obtained, these data, supplementing the more extensive results from slow neutron transmission experiments, have been of value in testing various models of the compound nucleus.[2] In general, such experiments differ significantly from slow-neutron experiments in that states may be formed by many l values of the incident particles over a wide range of excitation energy of the compound nucleus.

It is of interest to perform similar measurements on nuclei of medium weight, but since the density of states is then larger than in the light nuclei for comparable excitation energies, the resolution of individual levels taxes existing experimental techniques, as found for instance, in excitation curves for the (p,n) reaction on Sc, Cr, V, and Mn.[3] On the other hand, when attention is restricted to the reaction proceeding to a particular state of the final system, the penetrability factors may limit contributions to the cross section to a few l values for the incident charged particles. If in addition, the target nucleus has zero angular momentum, compound states having only a limited range of spins will be selected, resulting, possibly, in a density of levels well within the resolving power of beam experiments. Such circumstances were found in fact to hold in the case of inelastic scattering of protons from Ni^{58}, which is the subject of the present work.

The first excited state of Ni^{58} has been established at 1.45 Mev and no other levels up to an excitation of 2.15 Mev have been found.[4] In the present work, resonance states of the compound system, Cu^{59}, were located by observing the γ radiation following inelastic scattering to the 1.45-Mev level with bombarding energies ranging from 2.5 to 4.5 Mev. Other γ rays expected to be present from higher excited states or due to proton capture were of negligible intensity and did not interfere with the measurements. An attempt to observe the (p,n) reaction showed that it was not a competing process in the energy range used. Except for elastic scattering and capture, all other competing reactions could be excluded.

EXPERIMENTAL METHOD AND PROCEDURE

Thin targets of Ni^{58} were prepared by evaporating nickel oxide enriched to 98% in Ni^{58},[5] onto a spectroscopically pure gold backing. The targets were placed at 45° with respect to the incident proton beam in each of the several experimental arrangements. For the excitation curve measurements, the targets were backed by a thin brass plate making the vacuum seal at the end of the beam tube. The γ detector was located in a forward quadrant with respect to the beam direction, intercepting a solid angle of about one steradian. For the angular distribution measurements, a thin-walled copper chamber having cylindrical symmetry replaced this assembly. The γ detector in this case was mounted on a platform which could be rotated about the axis of the target chamber.

The γ radiation was detected with a conventional thallium-activated NaI crystal spectrometer used together with standard commercial electronic circuits.

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[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955); P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

[2] Brookhaven Conference Report, "Statistical Aspects of the Nucleus," Brookhaven National Laboratory (1955); F. L. Friedman and V. F. Weisskopf in *Niels Bohr and the Development of Physics* (Pergamon Press, Ltd., London, 1955); T. Teichman and E. P. Wigner, Phys. Rev. **87**, 123 (1952); Lane, Thomas, and Wigner, Phys. Rev. **98**, 693 (1955).

[3] Baker, Howell, Goodman, and Preston, Phys. Rev. **81**, 48 (1951); J. J. G. McCue and W. M. Preston, Phys. Rev. **84**, 1150 (1951); Lovington, McCue, and Preston, Phys. Rev. **85**, 585 (1952).

[4] Windham, Gossett, Phillips, and Schiffer, Phys. Rev. **103**, 1321 (1956).

[5] The enriched Ni^{58} isotope was obtained from the Stable Isotopes Division of the U. S. Atomic Energy Commission.

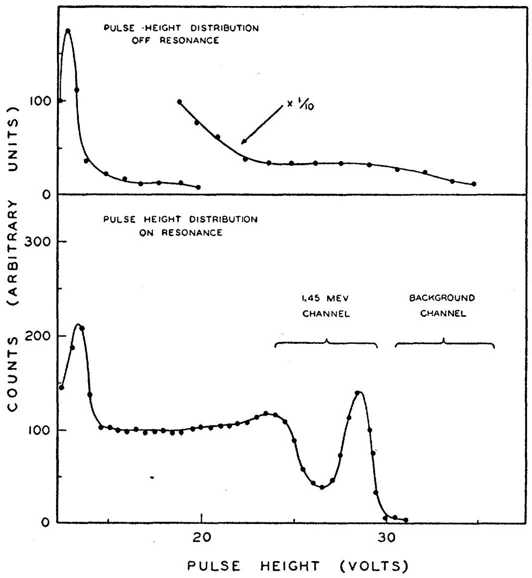

FIG. 1. Pulse-height distribution from a NaI crystal for γ-rays from the $Ni^{58}(p,p'\gamma)Ni^{58}$ reaction. The upper curve was taken at an energy where the yield curve showed no resonance; the lower curve was taken at the peak of a resonance. The peak on the left is due to the 550-kev Coulomb-excited γ ray from the thick Au target backing. The brackets indicate the pulse heights for which gates were set in taking the excitation curve on Fig. 2.

The spectrometer had a resolution of about 8% for the Co^{60} γ rays. A 5-mm-thick bismuth absorber attenuated x-rays and Coulomb-excited γ rays from the gold backing. Typical pulse-height distributions on and off a resonance are shown in Fig. 1. The yield of the reaction was measured by setting the differential channel of the pulse height analyzer to detect pulses in the photopeak and part of the Compton peak as marked on the figure. Other channels were set to observe any contributions from high-energy radiations and background effects. In order to relate the observed yield to the reaction cross section, a determination of the detecting efficiency of the counter was made by means of a standardized Co^{60} source. The source was located at the beam spot in the target chamber with other conditions reproducing, as nearly as possible, those obtained during the yield measurements. Appropriate corrections were made to the measured efficiency for the difference between the energies of the Co^{60} and Ni^{58} γ rays.

The proton beam from the 6.0-Mev electrostatic generator of the Rice Institute was used in these experiments. The energy of the incident proton beam was determined by measuring the field strength of the 90° analyzing magnet of the accelerator with a proton moment magnetometer. The magnetometer was calibrated with the $Li^7(p,n)$ threshold reaction. The assignment of absolute energies is accurate to about 20 kev, with the relative energies between resonances reliable to 5 kev. Data points on the excitation curve were taken at approximately 2-kev intervals as determined by the magnetometer. The spread in the beam energy was less than 2 kev.

The angular distributions were measured at 15° intervals between 0° and 90° with respect to the beam. Frequent measurements in opposing quadrants were made to check the symmetry of the system. The NaI crystal subtended a solid angle of 0.05 steradian at the target, and solid-angle corrections to the observed distributions were negligible. Because of the sharp resonances and thin target, small drifts in the mean voltage of the accelerator affected the observed yield appreciably. In order to monitor this effect, a second NaI crystal counter, also biased to detect the 1.45-Mev radiation, was kept at a fixed angle. Compensating adjustments to the voltage of the accelerator were made during the course of a measurement so that the counting rate never departed by more than 10% from the peak value.

RESULTS

Excitation Curve

The yield of the 1.45-Mev γ radiation measured over the range of bombarding energies from 2.9 to 4.5 Mev is shown in Fig. 2, uncorrected for background effects. By using a target about 4 kev thick to the incident protons, approximately 70 resonances were resolved in the interval, the strongest being about 250 times as intense as the weakest. The lowest energy resonance clearly due to the 1.45-Mev radiation occurred at a bombarding energy of 2.95 Mev. Above 4.5 Mev the resonances became too closely spaced to be resolved satisfactorily. Only the resonances at 3.12 and 3.48 Mev have widths exceeding that of the target, and these were also the only ones that showed an appreciable yield of γ rays with energy higher than 1.45 Mev.

To get the cross sections for inelastic scattering corresponding to the observed yields, the assumption was made that the natural widths of the resonant states were small in comparison to both the target thickness and the energy spread of the incident beam of protons. The yield of 1.45-Mev radiation per proton, Y_p, is then related to the cross section by the expression

$$Y_p = (K/AS)\int \sigma(E)dE,$$

where $\sigma(E)$ is the cross section for the inelastic process at bombarding energy E, S is the stopping power of nickel (kev/mg/cm^2) at this energy, K is the detector efficiency, and A the atomic weight, in mg, of Ni^{58}. The integration is carried out over the energy interval corresponding to the target thickness.

The quantity $\bar{\sigma} \equiv \int \sigma(E)dE$ will then be independent of both the target thickness and the resonance width and can be calculated from the measured Y_p. It is tabulated for the 37 numbered resonances in Table I. Due to uncertainties in calibrating the detector and

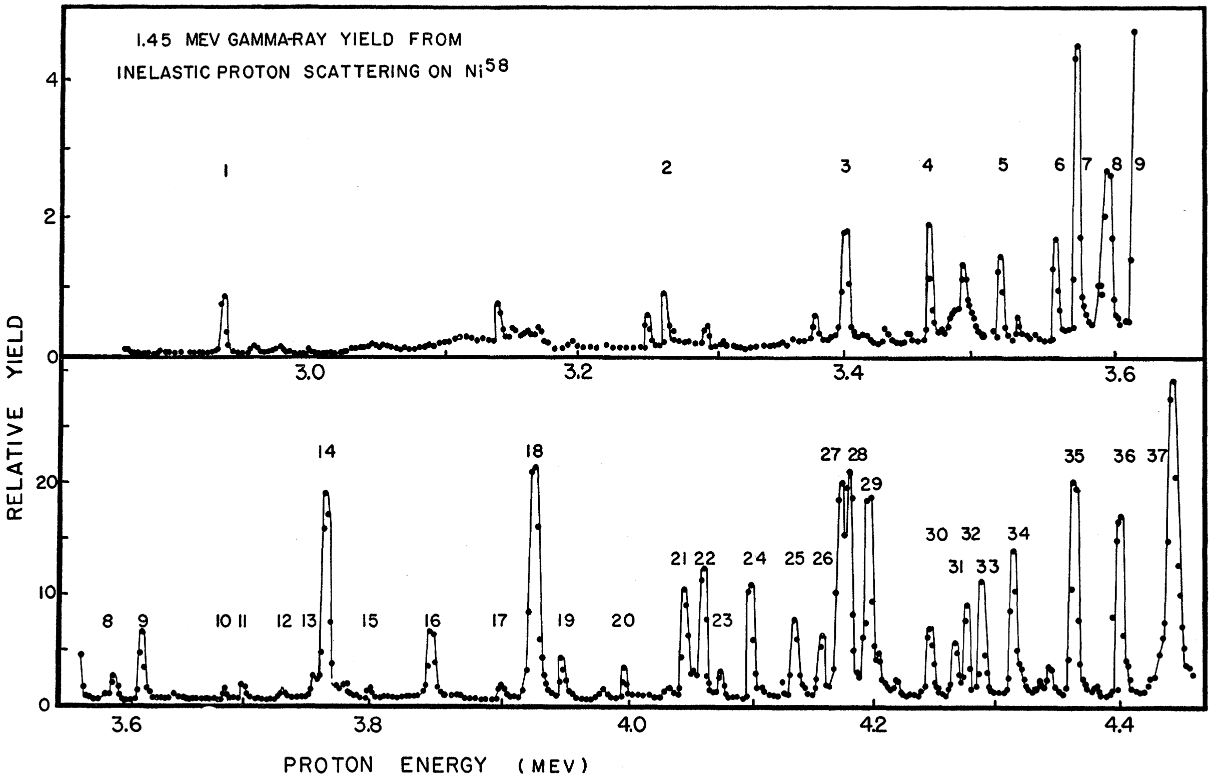

FIG. 2. Excitation curve for the $Ni^{58}(p,p'\gamma)Ni^{58}$ reaction. The target was ~4 kev thick Ni^{58} on Au backing. No background subtraction has been made. Some of the weaker resonances included on Fig. 4 do not appear in this curve because of the small scale.

measuring intensities at the peaks of the resonances, the cross sections listed are believed accurate to about 30%.

Angular Distributions

The 37 numbered resonances on Fig. 2 were the only ones sufficiently intense to allow angular distributions of the 1.45-Mev γ radiation to be measured. Of these distributions one was isotropic, 19 were of the form $W(\theta)=1+A\cos^2\theta+B\cos^4\theta$, and 17 were of the form $W(\theta)=1+A\cos^2\theta$. When one uses the well-known rules governing the complexity of such distributions,[6] the lowest possible spin values for the compound states are given in Table I. The spins and parities of the ground and first excited state of Ni^{58} were taken to be 0^+ and 2^+ in accordance with the systematics of the even-even nuclei and consistent with the results of these measurements.

Further analysis of the distributions consisted of an attempt to compare the measured values of the coefficients of $W(\theta)$ with those calculated for the inelastic scattering processes most favored from the standpoint of penetrability. In the range of proton energies of interest here, the most probable inelastic scattering process is due to the absorption of a d-wave proton followed by emission of an s-wave proton to the 2^+ state of Ni^{58}. The absorption of a p-wave proton with p-wave emission to the excited state is less probable by about an order of magnitude due to the reduced penetrability of the emitted proton. States formed by s-wave protons and decaying by d-wave inelastic emission are even weaker for the same reason and make the lack of isotropic angular distributions plausible.

Using the expression for the angular distribution of a two-stage particle reaction followed by γ emission as given by Kraus *et al.*,[7] one gets for the present case, assuming isolated resonances,

$$\sigma(\theta)=\sum_{S_1'S_2'} a(S_1'S_2')[(2S_1'+1)(2S_2'+1)]^{\frac{1}{2}}(-1)^{S_1'-S_2'} \times C(221-1,\nu 0)Z(lJlJ,\tfrac{1}{2}\nu)W(JS_1'JS_2',l'\nu) \times W(S_1'2S_2'2,2\nu)P_\nu(\cos\theta),$$

where S_1' and S_2' are the outgoing channel spins with relative amplitudes $a_{S'}$, l and l' are the incoming and outgoing proton angular momenta, J is the spin of the compound state, and ν is a summation index which is even and ranges from 0 to 4. In general, for such a process there is no coherent interference between outgoing l values, if the γ-ray distribution alone is ob-

[6] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

[7] Kraus, Schiffer, Prosser, and Biedenharn, Phys. Rev. (to be published).

TABLE I. Level parameters for resonances observed in $Ni^{58}(p,p'\gamma)Ni^{58}$ reaction.

Resonance No.	Resonance energy (Mev)	Compound state angular momentum	$\bar{\sigma}$[a] kev mb/sterad	$\left(\frac{\Gamma_p\Gamma_{p'}}{\Gamma_p+\Gamma_{p'}}\right)$ 10^{-3} kev	γ^2 10^{-14} kev cm
1	2.950	3/2	0.52	2.4	550
2	3.285	5/2+	0.53	1.8	85
3	3.410	5/2+	1.0	3.5	64
4	3.470	3/2	1.0	5.6	65
5	3.525	3/2	0.78	4.4	55
6	3.570	3/2	0.89	5.1	85
7	3.585	5/2+	2.1	8.3	78
8	3.610	3/2	1.4	8.0	74
9	3.630	3/2	5.6	31	260
10	3.700	3/2	0.83	4.8	28
11	3.715	5/2+	1.4	4.4	22
12	3.740	3/2	0.75	4.3	21
13	3.755	3/2	1.5	8.8	86
14	3.765	5/2+	15	60	230
15	3.810	5/2+	1.0	4.0	14
16	3.850	3/2	5.4	32	91
17	3.915	3/2	1.2	6.7	17
18	3.940	3/2	17	102	250
19	3.960	5/2+	3.0	12	27
20	4.015	5/2+	2.3	9.2	18
21	4.060	5/2+	8.2	34	52
22	4.075	3/2	9.5	60	91
23	4.100	5/2+	2.4	15	15
24	4.130	5/2+	8.3	35	45
25	4.145	3/2	6.1	38	44
26	4.165	1/2	4.8	31	33
27	4.185	5/2+	15	66	70
28	4.190	3/2	16	104	107
29	4.210	3/2	14	92	87
30	4.260	5/2+	5.3	23	20
31	4.275	3/2	4.4	29	23
32	4.285	5/2+	6.8	30	26
33	4.295	5/2+	8.4	38	29
34	4.320	5/2+	10	47	32
35	4.370	5/2+	15	69	43
36	4.395	5/2+	13	59	33
37	4.450	5/2+	22	100	51

[a] Computed from the yield of the resonances with background effects subtracted.

served. Such interference would exist only if the $p'-\gamma$ correlation were to be studied. Coherent interference does exist, however, for the two possible outgoing channel spins, 3/2 and 5/2. For the most probable case of $l=2$, $l'=0$, only one channel spin is possible for either angular momentum for the compound state. This gives

$$\sigma(\theta)=1+\cos^2\theta \text{ for } J=3/2^+, \quad (1)$$

and

$$\sigma(\theta)=1+6\cos^2\theta-5\cos^4(\theta) \text{ for } J=5/2^+. \quad (2)$$

For $l=l'=1$ and a $3/2^-$ compound state, interference between channel spins has to be considered and one gets

$$\sigma(\theta)=a_{3/2}5(19+3\cos^2\theta)+a_{5/2}20(4+3\cos^2\theta) \pm a_{3/2\ 5/2}2(1-3\cos^2\theta), \quad (3)$$

where the first term is that due to 3/2 channel spin, the second is due to 5/2 channel spin, and the final term is due to interference effects. For $l=l'=2$, one gets

$$\sigma(\theta)=a_{3/2}12(12-\cos^2\theta)+a_{5/2}(151-138\cos^2\theta +175\cos^4\theta)\pm a_{3/2\ 5/2}24(1-18\cos^2\theta+25\cos^4\theta). \quad (4)$$

Figure 3 shows the plot of Eqs. (1) and (2) as well as the two pure channel spin terms from Eq. (3).

All but 5 of the angular distributions which are designated as $5/2^+$ in the table fit the theoretical distribution of $1-5\cos^2+6\cos^4$ as shown in Fig. 3. The remaining 5, numbers 15, 20, 23, 30, and 36 showed a yield that was the same or higher at 90° than at 0°. These can be explained by assuming some d-wave admixture as given in Eq. (4) in the outgoing inelastic protons. No unique fit can be obtained since d-wave outgoing protons would go with two channel spins, thus giving one too many fitting parameters, but admixtures of the order of 30 to 50% would be needed to fit the data.

Not all the states designated as 3/2 can be fit by a pure d-wave in, s-wave out process as given in Eq. (2) and Fig. 3(b). All these states could, however, be fit either by assuming some d-wave inelastic admixture or a resonance formed by a p-wave incident proton and decaying by p-wave inelastic emission as given in Eq. (3). Since p states tend to be somewhat weaker, a $3/2^+$ assignment is slightly more favored for all the 3/2 resonances. Also, $p_{3/2}$ and $p_{1/2}$ states would be expected in approximately equal numbers, yet only the one isotropic resonance, number 26, could be considered a $p_{1/2}$ state. Nevertheless, since a p-wave fit can be obtained for all the 3/2 resonances, definite parity assignments cannot be made for them.

Resonance 26 was the only one observed with an isotropic distribution and is, therefore, probably spin 1/2, although interference effects for p or d states could also give an isotropic distribution. Higher angular momentum fits to all these states can also be made, but they may be ruled out on the basis of penetrability since they should be at least two orders of magnitude less probable than the assignments given. A higher angular momentum state would give the distribution shown in Fig. 3(a), for instance, only for particular

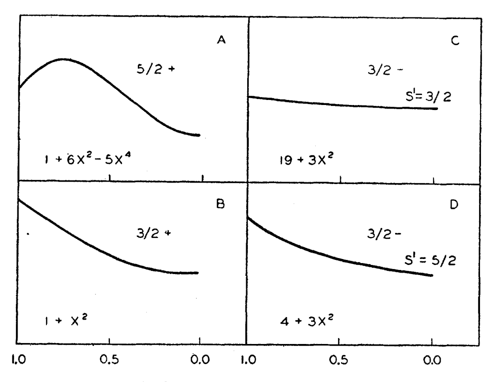

FIG. 3. Angular distributions for the $(p,p'\gamma)$ reaction assuming a 0^+ initial state and a 2^+ γ-emitting state. The distributions on the left correspond to D-wave incoming and S-wave outgoing particles forming compound states of $3/2^+$ and $5/2^+$. The distributions on the right are calculated for P-wave incoming and outgoing protons, a compound state of $3/2^-$, and channel spins, s', of 3/2 and 5/2.

combination of the two channel spins. Since angular distributions on only the more prominent resonances could be studied, it is not surprising that they should have spin and parity assignments which are consistent with the most probable inelastic processes from the point of view of penetrabilities.

Level Spacings

Since spin assignments have been obtained for 37 states in an energy interval of 1.5 Mev, it would be of interest to investigate the level spacing as a function of spin and as a function of excitation energy. However, the data are not complete enough to support such an analysis. Apart from the ambiguity in the spin assignments as discussed above, there is the further difficulty that all states in the interval belonging to these spins could not be identified. Some could occur among the levels for which no spins could be assigned; others are almost certainly missed due to inadequate experimental resolution or to too low intensity.

As a result, level spacing as a function of excitation energy was considered for all levels, regardless of spins. This is perhaps less meaningful theoretically, but, if predominantly only two spin states are involved, and the dependence of the average level spacing, $\bar{D}$, on spin is not too strong, fairly reliable results may still be obtained.

In Fig. 4 the total number of levels observed up to a bombarding energy E is plotted as a function of E. It is seen that this number is an essentially linear function of the energy, or equivalently, that D is roughly constant over most of the interval of E. The straight line drawn in the figure corresponds to an average spacing of 18 kev for states of all spin or to about 35 kev for states of a single spin assuming that only two spin states are involved. The latter value should then be approximately the lower limit of $\bar{D}$ unless an appreciable number of states have been missed. The upper limit of $\bar{D}$ is obviously obtained from the number of states identified with a single spin in the energy interval and is about 80 kev. For purposes of comparison, the Weisskopf level density formula[8] for levels of all spins gives an average spacing of 2.5 kev for these conditions. This formula also predicts an increase in the level density of about 20% over the range of excitation energy involved in these measurements.

Level Widths

The reduced partial widths of the levels having known spins can be obtained from the intensities measured for the resonances. The cross section given by the single-level Breit-Wigner formula for the process is

$$\sigma=\pi\lambda\!\!\!^{-2}(J+\tfrac{1}{2})\frac{\Gamma_p\Gamma_p'}{(E-E_0)^2+(\Gamma/2)^2},$$

[8] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. VIII.

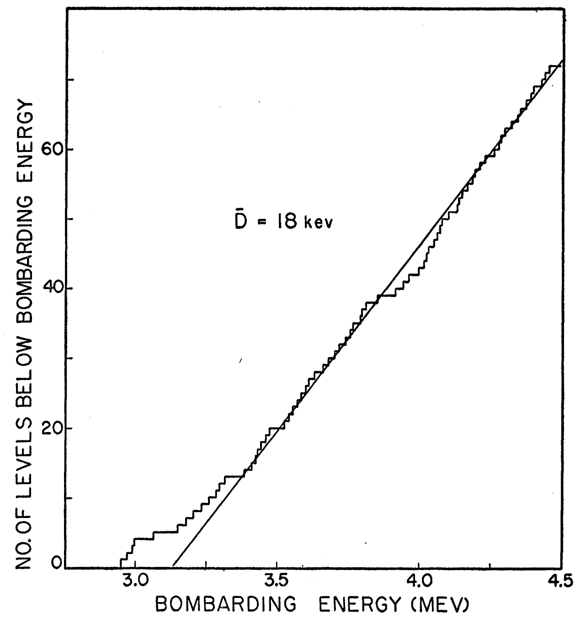

FIG. 4. Number of resonance observed in the $Ni^{58}(p,p'\gamma)Ni^{58}$ reaction *vs* bombarding energy. All observed resonances from this reaction are plotted for the region of bombarding energies shown, including some that were too weak to show up on the plot of the excitation curve in Fig. 2. The line corresponds to a level density of 18 kev.

where $2\pi\lambda\!\!\!^{-}$ is the wavelength of the incident proton of energy E, E_0 is the bombarding energy at resonance, J is the spin of the compound state, and Γ_p, Γ_p' and Γ are the elastic, inelastic (1.45-Mev channel) and total widths respectively of the compound level. With the only other partial width Γ_γ taken to be negligible in comparison to Γ_p and Γ_p', $\Gamma\simeq\Gamma_p+\Gamma_p'$.

Under the conditions for which these measurements were made, the observed yield for a resonance corresponds to that given by the Breit-Wigner formula integrated over the resonance. This integral is proportional to the quantity $\Gamma_p\Gamma_p'/(\Gamma_p+\Gamma_p')$, which can thus be calculated from the experimentally determined $\bar{\sigma}$. This has been done for the numbered resonances, and is given in Table I. If it is now assumed that $\Gamma_p'\leq\Gamma_p$, which is plausible on the basis of relative penetrabilities, then $\Gamma_p'/2\leq\Gamma_p\Gamma_p'/(\Gamma_p+\Gamma_p')\leq\Gamma_p'$, so that this quantity may be taken as a fairly good measure of the inelastic partial width.

For these partial widths, the inelastic reduced widths, $\gamma^2=\Gamma_p'/[2k_p'P(l)]$ for all the numbered levels are also tabulated. $P(l)$[9] is the penetrability of the emitted proton having a wave number k_p'. For this calculation it was assumed in accordance with the results of the angular distribution measurements that each state was formed by d-wave protons and that the outgoing protons were retarded by s-wave penetrabilities. The

[9] Coulomb penetrabilities were computed from graphs based on the W.K.B. approximation using a radius $r_0=1.4\times10^{-13}$ cm, as given by P. Morrison, *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. 2.

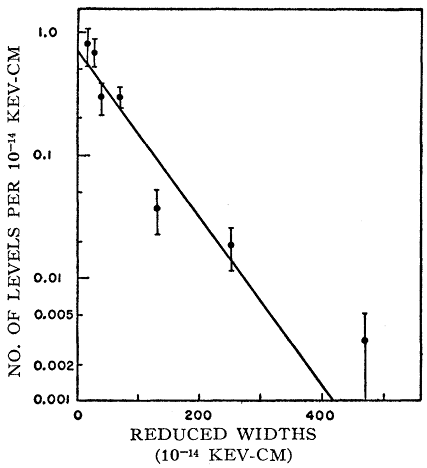

FIG. 5. Logarithmic plot of the size distribution of reduced widths. The intervals of reduced width were arbitrarily chosen so that each interval was twice as large as the previous one. The error bars represent ± 0.67 times the square root of the number of counts in that interval. The straight line was drawn as an approximate best fit to the points.

distribution of reduced widths thus obtained is shown in Fig. 5. It is interesting to compare this distribution to that given by Hughes and Harvey[10] for neutron widths, even though the number of levels in the present plot is small compared to the 145 levels shown in their curve. It appears that a straight line would fit the present data but it is not possible to eliminate other possibilities as suggested, for instance, by Porter and Thomas.[11] If a straight-line fit were correct, then an upper limit of twelve to fifteen can be set on the number of states which were too weak to be included in the angular distribution measurements. This brings the number of states formed by *d*-wave protons to approximately fifty for the energy interval studied, and if they are equally divided between the two spins, leads to a value of $\bar{D}$ of about 60 kev which is midway between the limits estimated above. Since a total of 72 resonances were observed in the yield curve, it would appear probable that a number of the weakest resonances might be due to *s*-, *p*-, or *f*-wave entry.

[10] D. J. Hughes and J. A. Harvey, Phys. Rev. **99**, 1032 (1955).
[11] C. E. Porter and R. G. Thomas, Phys. Rev. **104**, 483 (1956).

The separate distributions of γ^2 for states of spin 5/2 and 3/2 are also roughly exponential but have somewhat different slopes. While this difference suggests a dependence of $\langle\gamma^2\rangle_{\mathrm{Av}}$ on spin, it is not necessarily real in view of the poor statistics. The range of values for the reduced inelastic partial widths is 0.14 to 5.5×10^{-12} kev-cm, corresponding to 1.5×10^{-4} to 6×10^{-3} of the Wigner independent particle limit. The average value of γ^2 considering all states is 0.8×10^{-12} kev cm. The value of the strength function, $\langle\gamma^2\rangle_{\mathrm{Av}}/\bar{D}$ for states of each spin is about 1.4×10^{-14} cm where a $\bar{D}$ of 60 kev has been used. This is to be compared with 3×10^{-14} cm calculated for a black nucleus[12] and is about a factor of three lower than the value of $\Gamma_n^0/\bar{D}$ obtained by Bollinger in neutron scattering experiments on Co^{59} and Cu^{63}.[13]

Excitation Energy in Cu^{59}

In order to obtain the range of excitation energies of the observed states in Cu^{59}, a determination of the ground state mass for this isotope was needed. At the time these experiments were started the only known constant for the Cu^{59} decay was the half-life of 81 sec. A flat-sector-type double-focusing beta-ray spectrometer, to be described elsewhere, was used to obtain the end point of the positron spectrum from this activity.[14] The activity was produced by the (d,n) reaction on Ni^{58} with 4-Mev deuterons. The target was bombarded for approximately three half-lives and the activity counted for about one half-life against a fixed number of counts on an external monitor counter. The end point of the spectrum occurs at $3.75+0.10$ Mev. This places the resonance state at 2.95-Mev bombarding energy at 6.35 ± 0.1 Mev excitation energy in Cu^{59}, if one takes the Q value for the $Ni^{58}(n,\gamma)Ni^{59}$ reaction[15] to be 9.00 Mev. This value is in agreement with that reported by Gossett.[16]

[12] Using $\langle\gamma^2\rangle_{\mathrm{Av}}\sim\bar{D}/\pi K$ ($K=10^{13}$ cm^{-1}). See reference 8.
[13] L. M. Bollinger (private communication).
[14] Prosser, Moore, and Schiffer, Bull. Am. Phys. Soc. Ser. II, **1**, 163 (1956).
[15] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).
[16] Gossett, Butler, and Holmgren, Bull. Am. Phys. Soc. Ser. II, **1**, 40 (1956).