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A Study of Resonances in the $^{58}Ni(p,\gamma)^{59}Cu$ Reaction below 2·15 MeV

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Abstract

The γ-ray spectra for seven resonances in the reaction $^{58}Ni(p,\gamma)^{59}Cu$ in the range E_p = 1400–2150 keV have been measured with a high resolution Ge(Li) detector. Consistent resonance decay schemes have been derived along with the decay schemes of bound levels. Decays to previously unreported bound levels at 2·459, 2·711 and 3·025 MeV have been observed, while results significantly different from the earlier reports have been obtained for the decay of most of the bound levels. The reported level at 1·865 MeV is confirmed. The decay schemes of the two resonances at E_p = 1424 and 1844 keV indicate that these are $T = 3/2$ analogue states associated with the levels at 0·880 and 1·301 MeV in ^{59}Ni. A new value of $Q = 3\cdot415\pm0\cdot003$ MeV for the reaction $^{58}Ni(p,\gamma)^{59}Cu$ was derived from the Ge(Li) spectra.

Introduction

The reaction $^{58}Ni(p,\gamma)^{59}Cu$ was first studied by Buttler and Gossett (1957) in the energy range E_p = 700–1900 keV. However, their measurements were made with NaI spectrometers. The existence of six low-lying bound levels was established and, from measurements of the angular distributions, assignments of spins and parities were made for five resonances. Holmberg and Kiuru (1970) investigated the same reaction at three resonances in the energy range E_p = 1370–1850 keV with a Ge(Li) detector. They established the existence of six levels below 2·4 MeV excitation energy in ^{59}Cu, and provided the first information on the decay properties of these levels. Manthuruthil *et al.* (1972) investigated the $^{58}Ni(p,\gamma)^{59}Cu$ reaction with a Ge(Li) detector at five resonances in the proton energy range E_p = 900–1900 keV. Information on the energy levels and possible spins was also obtained from the (^{3}He, d) and (d, n) reactions. The reaction $^{58}Ni(^3He,d)^{59}Cu$ was studied by Pullen and Rosner (1968) at 16·4 MeV helium-3 bombarding energy. Bommer *et al.* (1973) investigated the reaction $^{58}Ni(d,n)^{59}Cu$ at the deuteron bombarding energy of 7 MeV, and reported bound levels up to an excitation energy of 4 MeV.

The present work forms part of a program set up to systematically study radiative capture reactions with large-size and high-resolution Ge(Li) detectors. The objectives of this study were to extend the proton bombarding energy to 3·0 MeV and above, to determine the existence of new resonances and new bound levels, to verify the existence or non-existence of certain doubtful levels, to derive the decay properties of the bound states, and to locate and study the isobaric analogue states. The present paper describes the results of the analysis of seven resonances at E_p = 1424, 1844, 1883, 1923, 2064, 2105 and 2143 keV for the reaction $^{58}Ni(p,\gamma)^{59}Cu$.

Experimental Procedure

Proton beams of up to 10 μA were obtained from the 2 MeV Van de Graaff accelerator at the Australian National University. Tungsten was chosen as a target backing to minimize contamination. Blanks of the metal were heated in vacuum with an induction heater to clean the surface and to remove occluded gases. The ^{58}Ni targets were made by evaporating 90% enriched powder (obtained from Oak Ridge National Laboratory) onto the tungsten blanks to produce targets of nominal thicknesses of 10 and 25 μg cm^{-2}. The thinner target was used to locate the resonances and the thicker one was used to measure the γ-ray spectra. The targets were water-cooled and surrounded by a liquid nitrogen trap (Bashkin and Ophel 1962) to remove condensable vapours and minimize carbon buildup.

A 35 cm^3 Ge(Li) detector was used to locate the resonances as well as to measure γ-ray spectra at each resonance. The detector had a resolution of better than 3 keV for the 1173 keV γ-ray from ^{60}Co. The output from the amplifier was fed to a single-channel analyser to select pulses corresponding to γ-rays of energy greater than 2·6 MeV. The output from the single-channel analyser was fed to a scaler as well as to a rate meter. The proton energy was changed in steps of a few keV and singles were counted. Only strong resonances were picked out from the relative yield. At each strong resonance, the data were recorded at 1 keV intervals over the resonance. The γ-ray spectra at each resonance were stored in either a 2048- or 4096-channel Nuclear Data 2200 multichannel analyser. The decay schemes of the resonances and branching ratios (%) were derived from the γ-ray spectra measured at 55° to the beam direction. The relative intensities of the transitions were determined from the relative full energy and the single- and double-escape peak intensities in the spectrum. The intensity calibration for the Ge(Li) detector was determined from the ^{27}Al(p, γ)^{28}Si reaction at $E_p = 992$ keV as well as from a ^{56}Co radioactive source. The relative errors of the intensity calibration curve were 8% and 5% below and above 3 MeV respectively. For the prominent γ-ray peaks the relative intensity error was 10%, increasing to 15% for the smaller peaks. Where the decay scheme of a bound level could be determined from more than one resonance, the transition ratios were found to be consistent.

Results

The γ-ray spectra measured at 55° to the beam direction for the seven resonances at $E_p = 1424$, 1844, 1883, 1923, 2064, 2105 and 2143 keV are presented in Figs 1*a*–1*g*. The three resonances at $E_p = 1424$, 1844 and 1883 keV have been reported previously but we found some changes in the decay schemes. The other four resonances have not been reported previously. The background γ-rays were found at energies of 0·439 MeV from the reaction ^{23}Na(p, p′γ)^{23}Na, at 0·843 and 1·013 MeV from ^{27}Al(p, p′γ)^{27}Al, at 1·368 MeV from ^{27}Al(p, ^{4}Heγ)^{24}Mg, at 1·632 MeV from ^{23}Na(p, ^{4}Heγ)^{20}Ne and at 6·129 MeV from ^{19}F(p, ^{4}Heγ)^{16}O. There were also background γ-rays at energies of 1·459 MeV from ^{40}K and 2·614 MeV from ^{228}Th.

Resonance decay schemes

Measurements of the γ-ray spectra were performed twice at each resonance. For the resonances at 1424 and 1844 keV, the first measurements were stored in 2048 channels and the repeated measurements were stored in 4096 channels. To increase the statistics for the weaker transitions, the repeated spectra were stored for a higher proton charge than the first accumulation. The repeated spectra agreed with the first measurements, and consistent decay schemes were obtained. Table 1 lists the resonance energies E_p (keV) for the reaction ^{58}Ni(p, γ)^{59}Cu, excitation energies E_x (MeV) in ^{59}Cu, total intensities I_γ^T of the primary transitions from the resonance states, and the total integrated charge C_T (protons) for which the γ-ray spectrum was accumulated. The branching ratios (%) of the γ-rays from each resonance to the different bound levels are given in Table 2.

Table 1. Properties of seven resonances in ^{58}Ni(p,γ)^{59}Cu

E_p (keV)	E_x (MeV)	I_γ^T	C_T (mC)
1424	4·815	417	120
1844	5·227	775	113
1883	5·266	563	100
1923	5·305	761	102
2064	5·444	1027	180
2105	5·484	576	133
2143	5·521	2086	90

Table 2. Branching ratios for decay of seven resonances in ^{58}Ni(p,γ)^{59}Cu

Bound level	Branching ratios (%) from resonances						
E_x (MeV)	E_p = 1424	1844	1883	1923	2064	2105	2143 keV
0	28	86	39	9	11		89
0·492	51	6	18		18	30	
0·916	6		4		14	4	6
1·397						3	4
1·865				3		9	
1·987	7				23	6	
2·265	3	5			5	16	
2·323	3		12	53	12	15	
2·459		1					
2·711					2		
2·714			7		2		1
2·929			8		10		
3·025		1		8	3	5	
3·043						3	
3·114			12			5	
3·128				9			
3·436	2	1					
3·580						4	
3·885				5			
3·900				13			

1424 keV Resonance (E_x = 4·815 MeV)

The γ-ray spectrum measured at E_p = 1424 keV is shown in Fig. 1*a*, and the decay scheme from the analysis of the spectrum is given in Fig. 2. The resonance level decays 51% to the first excited state and 28% to the ground state. In addition, there are transitions of smaller percentages to the levels at 0·916, 1·987, 2·265, 2·323 and 3·436 MeV. Holmberg and Kiuru (1970) reported the decay to a level at 1·386 MeV from the resonance level, whereas it was found in the present study that the transition from the resonance level was to the level at 3·436 MeV with a primary γ-ray of 1·386 MeV. The 3·436 MeV level was populated at other resonances as well.

1844 keV Resonance ($E_x = 5\cdot227$ MeV)

Fig. 1*b* shows the γ-ray spectrum obtained at the 1844 keV resonance. The strongest transition (86%) is to the ground state. Two transitions of 6% and 5% respectively are to the first excited state and to the level at 2·265 MeV. Three very weak transitions of 1% each were placed to the levels at 2·459, 3·025 and 3·436 MeV. There is good agreement for the stronger transitions with the reported work of Holmberg and Kiuru (1970). The simple decay scheme (Fig. 2) from this resonance with one very strong transition is characteristic of an analogue state.

1883 keV Resonance ($E_x = 5\cdot266$ MeV)

The resonance at 1883 keV was reported by Manthuruthil *et al.* (1972) but neither a γ-ray spectrum nor a decay scheme was given. The resonance level (Figs 1*c* and 2) populates six bound levels at 0·492, 0·916, 2·323, 2·714, 2·929, 3·114 MeV and the ground state. The decay scheme of the bound level at 2·714 MeV was supplemented from other resonances at $E_p = 2282$ and 3132 keV (details to be published by us). The relative intensities of these resonances were stronger and the percentage of the population of the level at 2·714 MeV was higher. In the present case, because of the low intensity of the 2·714 MeV γ-ray, the photo peak is not visible in the γ-ray spectrum.

1923 keV Resonance ($E_x = 5\cdot305$ MeV)

The resonance at 1923 keV has not been reported previously. The decay scheme obtained from the analysis of the γ-ray spectrum (Fig. 1*d*) is presented in Fig. 2. The strongest transition (53%) is to the bound level at 2·323 MeV. There are, however, transitions to the bound levels at 1·865, 3·025, 3·128, 3·885, 3·900 MeV and the ground state. The population of the bound levels at 3·885 and 3·900 MeV was observed for the first time in the proton capture reaction. The existence of the bound level at 1·865 MeV confirms the findings of Manthuruthil *et al.* (1972). The decay schemes of a number of bound levels were established.

2064 keV Resonance ($E_x = 5\cdot444$ MeV)

The γ-ray spectrum measured for the resonance at 2064 keV is shown in Fig. 1*e*. This resonance has not been reported previously. The decay scheme is derived from repeated measurements of the spectrum and is shown in Fig. 2. The resonance level populated nine bound levels at 0·492, 0·916, 1·987, 2·265, 2·323, 2·711, 2·714, 2·929, 3·025 MeV and the ground state. The population of the closely spaced bound levels at 2·711 and 2·714 MeV was confirmed by the decay schemes of the two bound levels, though the primary γ-rays from the resonance states could not be separated. The bound level at 2·711 MeV decays completely to the first excited

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Figs 1*a*–1*g* (pp. 507–15). Gamma-ray spectra measured at 55° with a 35 cm^3 Ge(Li) detector for resonances at $E_p = 1424$, 1844, 1883, 1923, 2064, 2105 and 2143 keV in the reaction ^{58}Ni(p, γ)^{59}Cu.

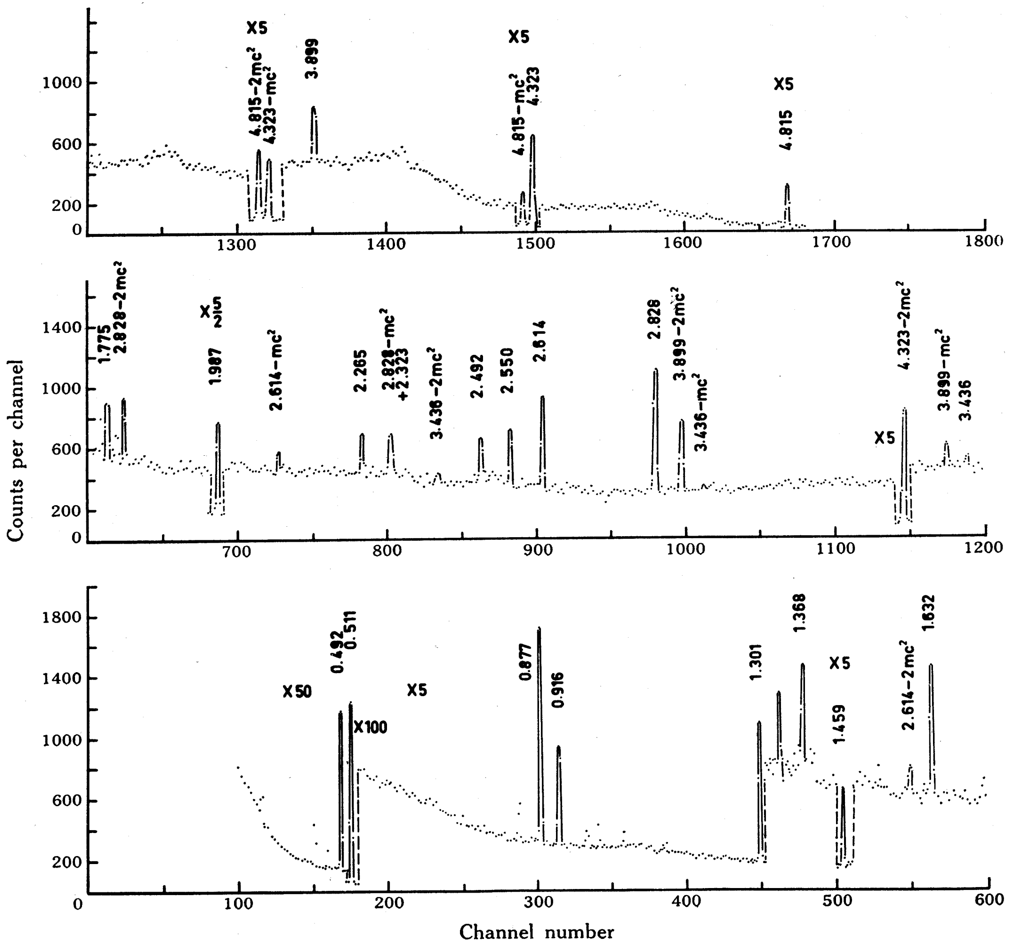


Fig. 1*a*. $E_p = 1424$ keV. The strongest transition (51%) from the resonance level is to the first excited state with a γ-ray of 4·323 MeV.

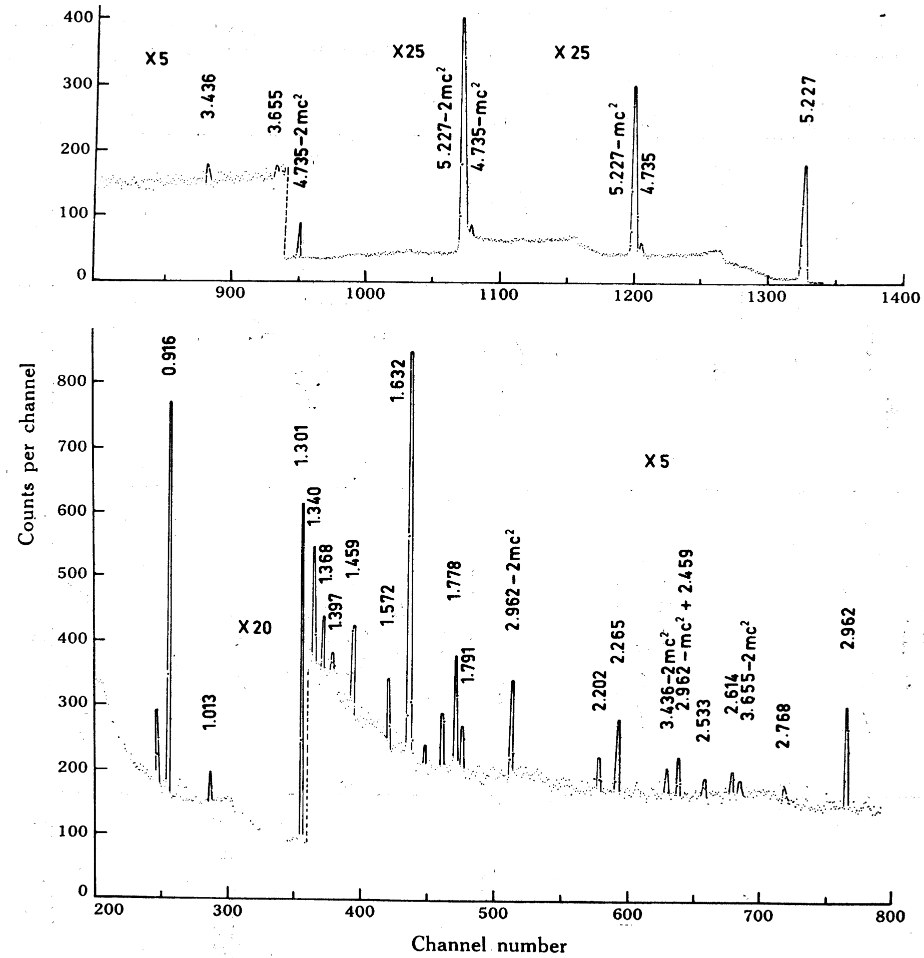


Fig. 1*b*. $E_p = 1844$ keV. Three transitions to three bound levels were observed in addition to those previously reported. The strongest transition (86%) from the resonance level is to the ground state.

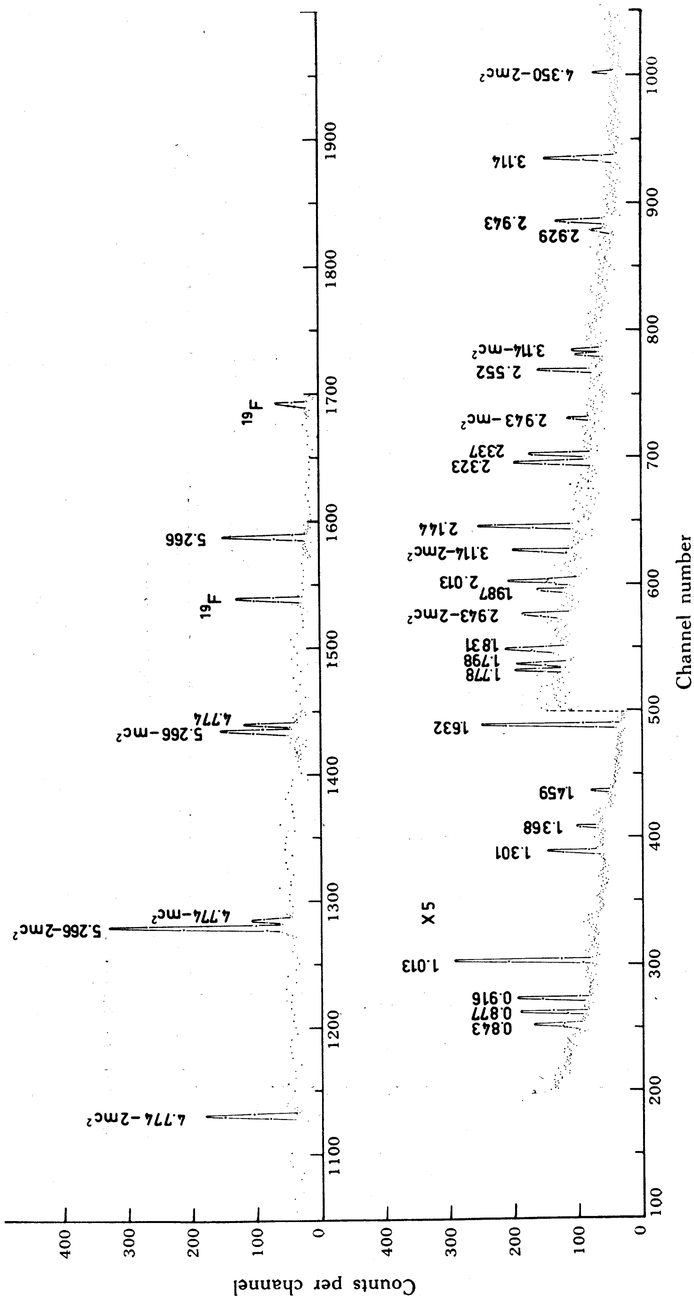
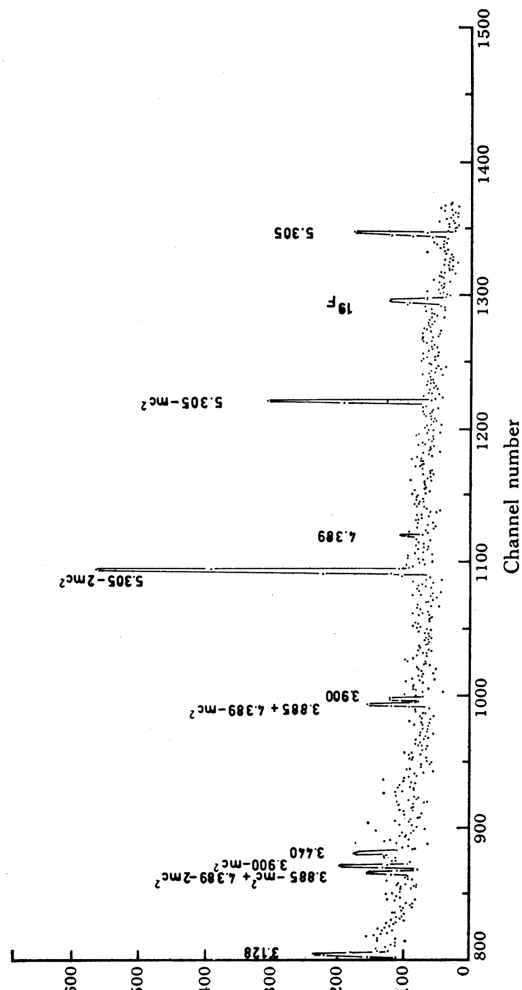


Fig. 1c. E_p = 1883 keV.



[Fig. 1d continued below]

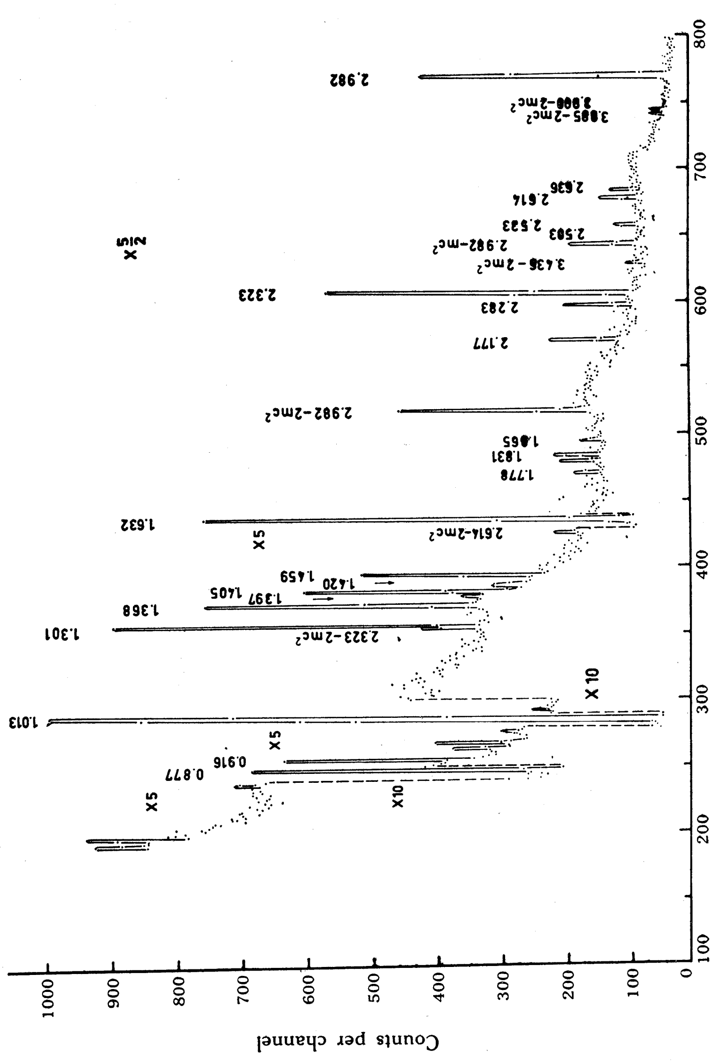


Fig. 1d. E_p = 1923 keV. The bound level at 3·128 **MeV** was populated at this resonance only, and its decay scheme was established from the existence of γ-rays with energies of 2·177, 2·636 and 3·128 MeV.

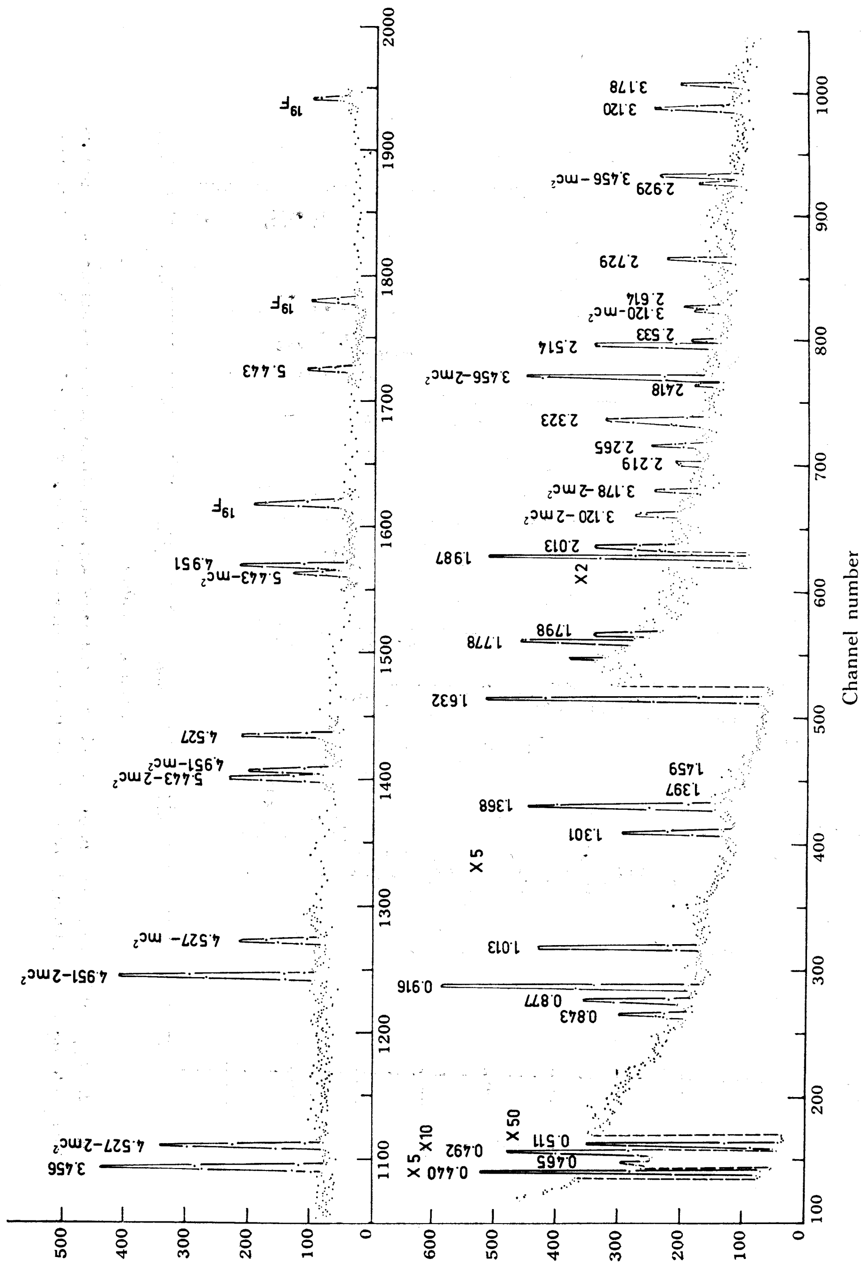


Fig. 1e. $E_p = 2064$ keV.

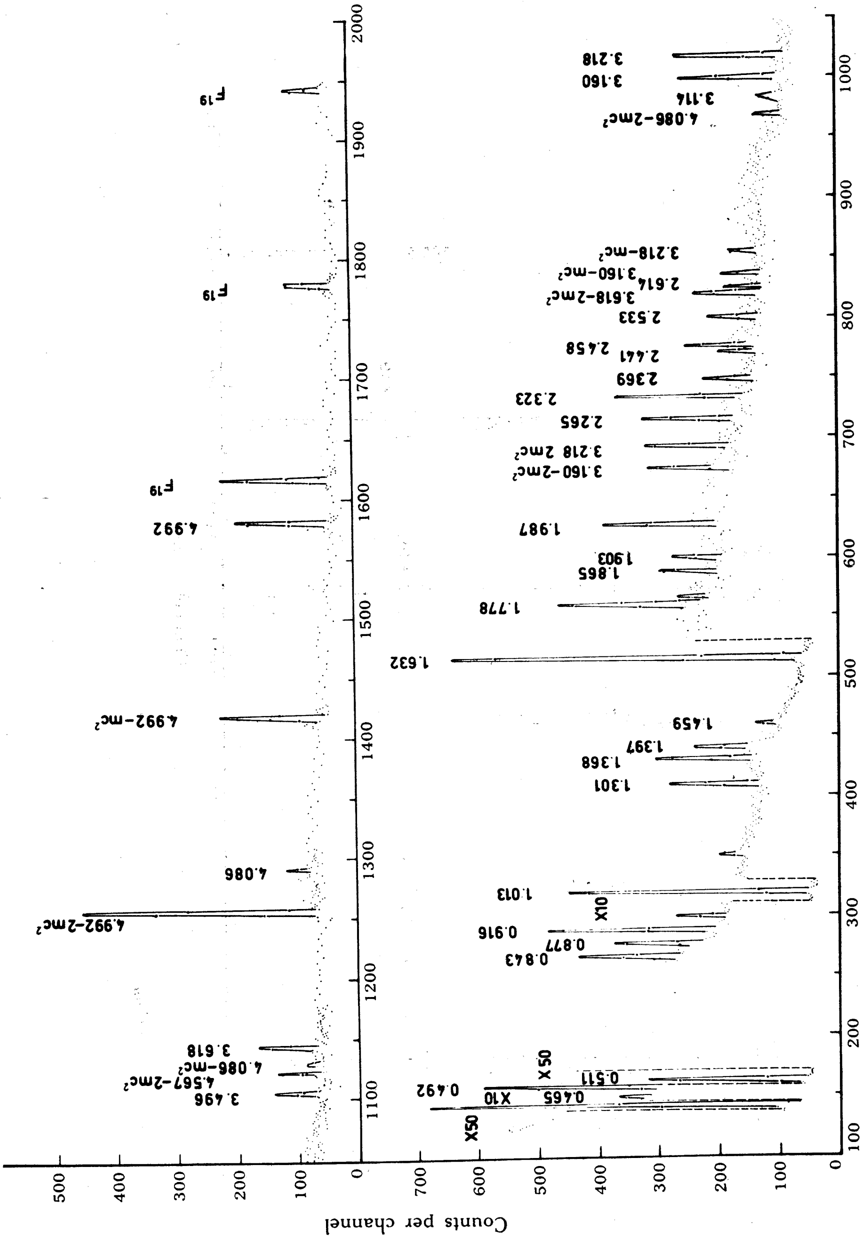
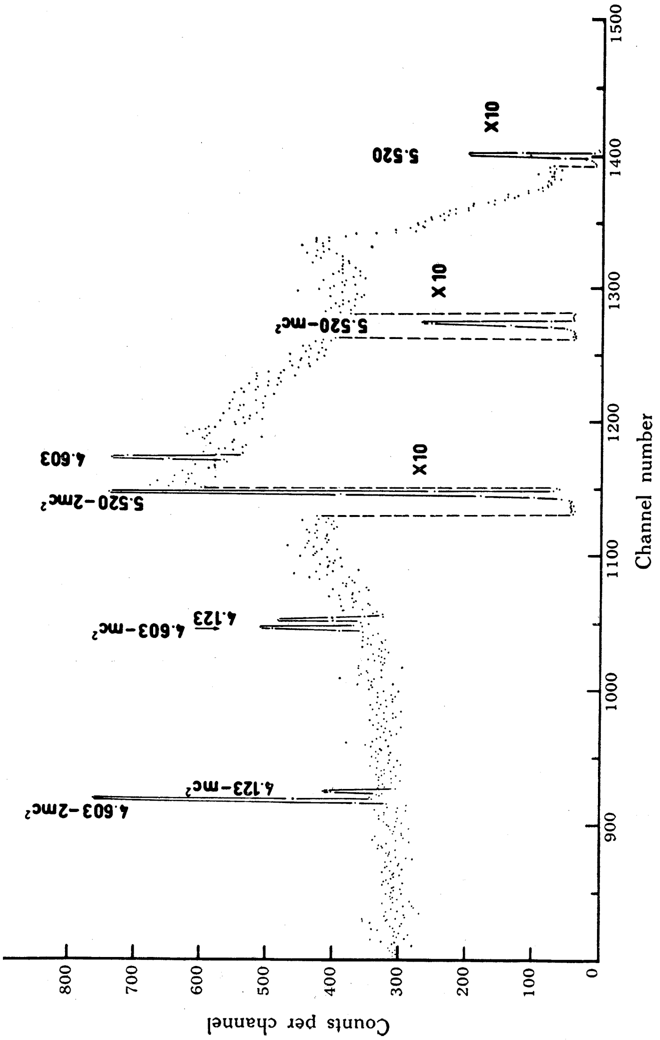


Fig. 1f. E_p = 2105 keV.



[Fig. 1g continued below]

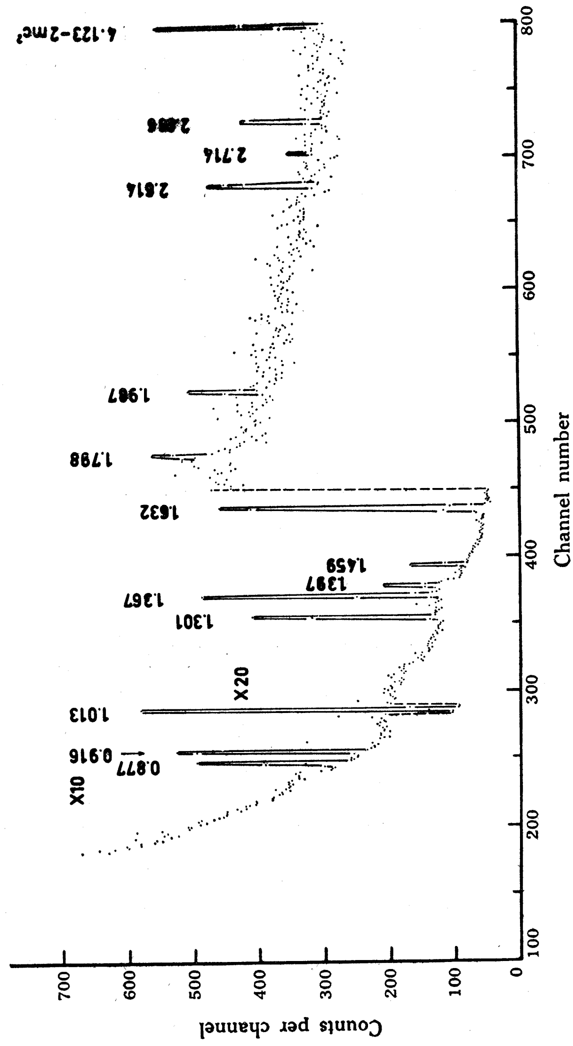
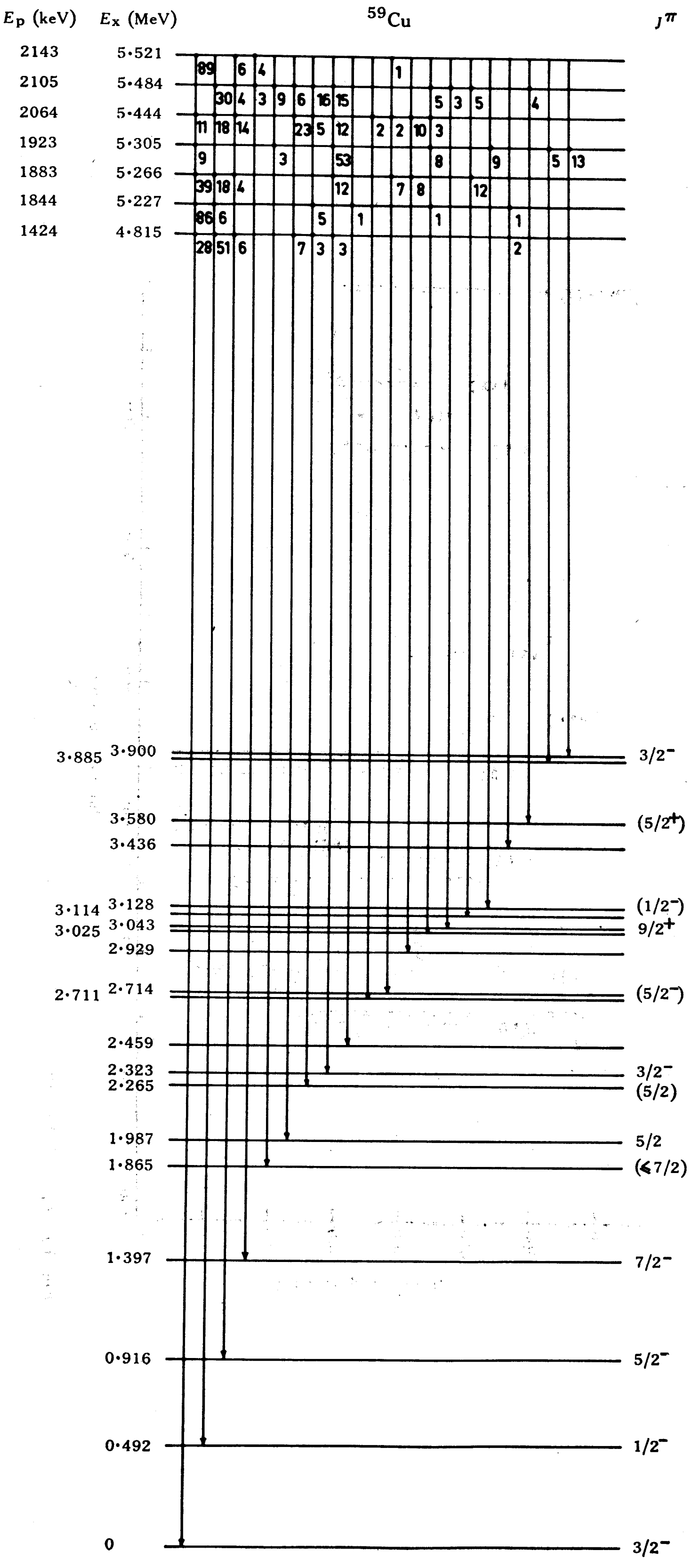


Fig. 1g. $E_p = 2143$ keV.


E_p (keV)
E_x (MeV)
^{59}Cu
J^{π}
2143 5·521
2105 5·484
2064 5·444
1923 5·305
1883 5·266
1844 5·227
1424 4·815
3·885 3·900 3/2⁻
3·580 (5/2⁺)
3·436
3·114 3·128 (1/2⁻)
3·025 3·043 9/2⁺
2·929
2·711 2·714 (5/2⁻)
2·459
2·323 3/2⁻
2·265 (5/2)
1·987 5/2
1·865 (≤7/2)
1·397 7/2⁻
0·916 5/2⁻
0·492 1/2⁻
0 3/2⁻

state with a γ-ray of $2 \cdot 219$ MeV whereas the bound level at $2 \cdot 714$ MeV decays with equal intensities to the ground and the second excited states with γ-rays of $2 \cdot 714$ and $1 \cdot 798$ MeV. As for the 1883 keV resonance, the relative intensity of the population of the bound level at $2 \cdot 714$ MeV was weak (only 2%), so that the $2 \cdot 714$ MeV γ-ray photo peak is not visible in the spectrum. One of the closely spaced levels at $2 \cdot 711$ MeV has been observed in the proton capture reaction only.

2105 keV Resonance ($E_x = 5 \cdot 484$ MeV)

The analysis of the spectrum (Fig. 1*f*) measured at the 2105 keV resonance, resulted in the decay scheme presented in Fig. 2. This is the only resonance state observed in the present work which does not decay to the ground state, but populates eleven levels including $1 \cdot 397$, $1 \cdot 865$, $1 \cdot 987$, $3 \cdot 043$, $3 \cdot 114$ and $3 \cdot 580$ MeV. The bound level at $3 \cdot 580$ MeV has been observed to be populated for the first time in the proton capture reaction.

2143 keV Resonance ($E_x = 5 \cdot 521$ MeV)

The γ-ray spectrum for the resonance at 2143 keV is shown in Fig. 1*g* and the decay scheme is presented in Fig. 2. The strongest transition (89%) from the resonance level is to the ground state. The weaker transitions from the resonance level are 6% to the second excited state and 4% to the level at $1 \cdot 397$ MeV. There is also a 1% transition to the level at $2 \cdot 714$ MeV.

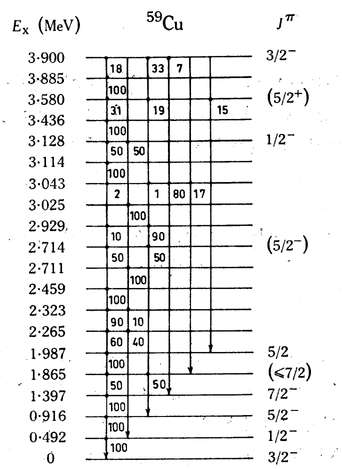


Fig. 3. Decay schemes of low-lying bound levels of ^{59}Cu up to an excitation energy of $3 \cdot 9$ MeV, as determined in the present investigation.

Decay schemes of bound levels

In the present study, a number of bound levels were populated at more than one resonance with different intensities (see Table 2). This made it possible to determine the decay scheme of a bound level from the resonance which populated it with relatively stronger intensity. The decay schemes of the bound levels were found to be consistent from one resonance to another and are shown in Fig. 3.

Fig. 2 (*opposite*). Decay schemes of seven resonances for $E_p = 1424$–2143 keV ($E_x = 4 \cdot 815$–$5 \cdot 521$ MeV) to bound levels in ^{59}Cu. Spins and parities of the levels were obtained from the reactions $^{58}Ni(^3He, d)^{59}Cu$ by Pullen and Rosner (1968) and $^{58}Ni(d, n)^{59}Cu$ by Bommer *et al.* (1972).

0·916 MeV Level

The bound level at 0·916 MeV was populated at a number of resonances but it was populated most strongly at the 2064 keV resonance. The decay of the 0·916 MeV bound level is 100% to the ground state.

1·397 MeV Level

The bound level at 1·397 MeV was excited at two resonances, one at 2105 keV and the other at 2143 keV. It was found that the 1·397 MeV level decays 100% to the ground state.

1·865 MeV Level

The bound level at 1·865 MeV was populated at two resonances at $E_p = 1923$ and 2105 keV. It decays to the second excited state and the ground state with equal intensities.

2·265 MeV Level

The relatively strongest transition to the level at 2·265 MeV was found from the resonance at 2105 keV. The decay scheme for the 2·265 MeV level was derived from the two γ-rays of energies of 2·265 and 1·773 MeV, leading to the ground-state and the first-excited-state transitions with branching ratios of 60% and 40% respectively. This is in agreement with the results of Holmberg and Kiuru (1970), who reported the decay of the level with equal intensities to the ground and first excited states.

2·323 MeV Level

The bound level at 2·323 MeV is populated strongly at the 1923 keV resonance. The level decays 90% to the ground state and only 10% to the first excited state. This is also in agreement with the results of Holmberg and Kiuru (1970).

2·459 MeV Level

The bound level at 2·459 MeV was excited once only, at the 1844 keV resonance, and the intensity was very low. It decays 100% to the ground state.

2·711 and 2·714 MeV Levels

The bound level at 2·714 MeV was populated at three resonances at 1883, 2064 and 2143 keV, whereas the 2·711 MeV bound level was populated at the 2064 keV resonance. As mentioned in the description of the 2064 keV resonance (above), the existence of the two levels at 2·711 and 2·714 MeV was confirmed by the different decay transitions of these bound levels. Further confirmation of the existence of these two closely spaced bound levels was provided by the population of the levels with higher intensities from the resonances studied at 2282 and 3132 keV. We intend to present these results in a future publication. The higher intensity population of the bound level at 2·714 MeV from the 3132 keV resonance definitely showed the photo peak of the 2·714 MeV γ-ray to be the transition from the level to the ground state.

2·929 MeV Level

Both resonances at 1883 and 2064 keV excited the level at 2·929 MeV. The two γ-rays of energies of 2·929 and 2·013 MeV de-excited the level to the ground state and the second excited state with 10% and 90% branching ratios respectively.

3·025 MeV Level

The bound level at 3·025 MeV was populated at four resonances. The decay scheme of the bound level was obtained, however, from the resonance at 1923 keV where the intensity of the population was the highest. The bound level decays completely to the first excited state with a γ-ray energy of 2·533 MeV.

3·043 MeV Level

The bound level was populated at only one resonance at 2105 keV. It was even weakly populated at this resonance. The information on the decay of this level was, however, obtained at resonances at higher proton bombarding energies. These results will be presented in a future publication by us. The decay scheme of the level was found to be 80% to the level at 1·397 MeV, 17% to the level at 1·865 MeV, 1% to the level at 0·916 MeV and 2% to the ground state.

3·114 MeV Level

The relatively strong transition to the level at 3·114 MeV from the decay of the resonance at 1883 keV provided the information on the decay of the bound level. It was found that the level at 3·114 MeV decays completely to the ground state.

3·128 MeV Level

The bound level at 3·128 MeV was populated relatively strongly at the 1923 keV resonance. The level decays with equal intensities to the ground state and first excited state.

3·436 MeV Level

The bound level at 3·436 MeV was excited at two resonances at 1424 and 1844 keV. The level decays 100% to the ground state.

3·885 and 3·900 MeV Levels

The two bound levels at 3·885 and 3·990 MeV were populated at only the 1923 keV resonance. The level at 3·885 MeV was found to decay 100% to the ground state. The decay scheme of the level at 3·900 MeV was derived from the three γ-rays of energies 3·900, 2·984 and 2·503 MeV, leading to the ground state and to the levels at 0·916 and 1·397 MeV respectively. The branching ratios were 18%, 33% and 7% respectively.

Discussion

The present study of seven resonances for the reaction $^{58}Ni(p, \gamma)^{59}Cu$ in the proton energy range from 1·400–2·150 MeV has provided extensive information on the energy levels and decay properties of the bound levels of ^{59}Cu and also the analogue states. In Table 3, the values found here for the excitation energies of the levels of ^{59}Cu are compared with previously reported values. With a large-volume high-resolution Ge(Li) detector, it has been possible either to establish the revised decay schemes of both resonances and bound levels or to determine the decay properties of the levels. Nineteen bound levels above the ground state up to 3·900 MeV excitation energy are populated from the seven resonances, and their accurate energies and decay schemes have been established. Also three levels which had not been reported previously either in the proton capture reaction or charged particle reactions have been found at 2·459 2·711, and 3·025 MeV, and decay properties have been established for the eight bound levels at 2·459, 2·711, 2·714, 2·929, 3·025, 3·436, 3·885 and 3·900 MeV, for which no previous data were available. Also, a doublet level at 2·71 MeV has been established from the different decay schemes of the two levels.

It is generally observed that an analogue state shows a simple decay scheme with a strong transition to one of the bound levels. In the present investigation, the two resonances at E_p = 1424 and 1844 keV have shown strong transitions (51 %) to the first excited state and (86 %) to the ground state respectively. Browne *et al.* (1970) found a resonance at 1841 keV from the elastic scattering of protons from ^{58}Ni.

Table 3. Comparison of values for E_x ($\leqslant$ 3900 keV) of ^{59}Cu bound levels
Data are from the (p, γ), (^{3}He, d) and (d, n) reactions of ^{58}Ni

	Excitation energy E_x (keV)*			
Present work (p, γ)	BG (p, γ)	HK (p, γ)	PR (^{3}He, d)	B (d, n)
492 ± 1	492	491	497	491
916 ± 1	908	910	921	911
1397 ± 1	1380	1386	1401	1394
1865 ± 1	1780			1826
1987 ± 1	2000	1989		1964
2265 ± 1		2267	2275	
2323 ± 1	2320	2325	2325	2319
2459 ± 3				
2711 ± 2				
2714 ± 2			2709	2699
2929 ± 1				
3025 ± 1				
3043 ± 1			3046	3040
3114 ± 1				
3128 ± 2			3134	3128
3436 ± 3			3453	3435
3580 ± 3			3591	3586
3885 ± 3			3904	3901
3900 ± 3				3916

* References to data: BG, Buttler and Gossett (1957); HK, Holmberg and Kiuru (1970); PR, Pullen, and Rosner (1968); B, Bommer *et al.* (1972).

The J^π of the excited level was determined to be $1/2^-$. They associated the resonance with the analogue of the fifth excited state (1·303 MeV) of ^{59}Ni. The simple decay scheme and the strong transition from the resonance, as found in the present study, agree very well with their findings. The same general comments also apply to the other resonance at 1424 keV. The values of the Coulomb displacement energy ($\Delta E_c = E_p^{cm} + B_n - E_x$) for the two resonances at E_p = 1424 and 1844 keV are 9·520 and 9·519 MeV respectively, taking the neutron binding energy B_n as 9·000 MeV. Buttler and Gossett (1957) reported the spin of the resonance at E_p = 1424 keV as $3/2^-$. The two resonance levels at E_p = 1424 and 1844 keV are thus possibly $T = 3/2$ analogue states associated with the two levels at 0·880 MeV ($3/2^-$) and 1·301 MeV ($1/2^-$) respectively in ^{59}Ni. The Q value for the reaction ^{58}Ni(p, γ)^{59}Cu was determined from the proton bombarding energy at a number of resonances and the γ-ray spectra with the Ge(Li) detector to be 3·415 ± 0·003 MeV.

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