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Spin Assignments of Neutron Resonances in Odd-Odd Silver Compound Nuclei

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The gamma-rays following the reaction $^{107,109}Ag(n, \gamma)$ $^{108,110}Ag$ have been studied with a time of flight neutron spectrometer. The method for determining spins of neutron resonances based on the gamma-ray cascade multiplicity dependence on the spin of the initial wmpound state, previously applied only to even-odd target nuclei with relatively high spin, is successfully used in the case of silver odd-even isotopes with spin 1/2. Single and coincidence γ ray counts were compiled separately for a neutron energy range from 7 to 440 eV. Spin 0 is ascribed to the 139.7 eV level of ^{110}Ag wmpound nuclei.

Os raios emitidos após a reação, lo7,109Ag (ny) 108.110 Ag, foram estudados como um espectrômetro de tempo de vôo de neutrons sendo a região de energia escolhida a que vai de 7 a, 440 eV. A totalidade das contagens simples e em coincidência dos raios y foram regis tradas separadamente e a partir de limiares de energia pré-fixados. O método de atribuição de spin a ressonâncias de neutrons baseado na dependência da multiplicidade da cascata y com o spin do estado composto inicial, previamente aplicado a núcleos alvos par-ímpar wm spin relativamente alto, foi empregado com sucesso no caso dos isótopos ímpar-par de Ag com spin 112. Spin 0 foi atribuido ao nível 139.7 eV do núcleo composto llOAg.

1. Introduction

It is well known that spin assignments of neutron resonances based on total cross sections and scattering measurements are hard to carry out, specially with weak resonances or high spin nuclei. Transmission techniques using polarized neutron beams, as well as polarized targets, provide a powerful tool for these determinations but require very elaborate apparatus[1,2].

Spin assignments, making use of gamma-ray spectrum characteristics, are generally obtained in a simple and rather straightforward way. They

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have been performed initially by means of intensity measurements of low-energy lines[3,4] or E1 high-energy transitions of gamma-ray spectra[5].

The two-step cascade method[6,7] is useful for spin determinations because it measures the relative intensity of the cascades, proceeding by just two transitions from the compound state to some low-lying level, which maintains a spin and parity dependence on the initial state. Other kinds of cascade measurements[8] and further systematic investigations concerning correlations between resonance parameters[9,10], are also successfully used for this purpose.

In addition to the above mentioned methods, Coceva *et al.*[11-14] have also attempted to determine the spin of the neutron resonances assuming that the average gamma-ray cascade multiplicity maintains a remarkable dependence on the spin of the initial compound state. This dependence is the basis of the gamma-ray cascade multiplicity method, the application of which can be qualitatively understood for even-even compound nuclei, if the initial part of the cascade is governed by a simple statistical relationship and the low-energy states have a band structure. In odd-odd compound nuclei there is no energy gap, so a prompt statistical equilibrium must be reached after neutron capture and a weak dependence on the spin parameter is expected[11].

The present experimental investigation was undertaken with the aim to provide additional information that might allow a wider and more critical utilization of this method.

^{108}Ag and ^{110}Ag nuclei were chosen because they are odd-odd nuclei having low spin (both with $I = 1/2$). These characteristics do not favour the application of the method. On the other hand, spins were also attributed to resonances of ^{108,110}Ag in previous experiments, using several experimental methods: self-induction, transmission and scattering. Such methods provide reliable values in the case of nuclei with low ground-state spin. So, the application of the γ ray cascade multiplicity method to the resonances of ^{108,110}Ag and the comparison between its results and those obtained by the remaining methods allow the effective verification of the applicability of the method to nuclei with similar characterisíics as ^{108,110}Ag.

2. Outline of the Method

The method in discussion is extensively described in Refs. 11, 12. We will confine ourselves here to a brief summary.

ENERGY (eV)	Isotope	R_J	$R_J - \langle R_J \rangle$	J
16.30 ± 0.05	107	1.09 ± 0.02	−0.02	0
30.4 ± 0.1	109	0.90 ± 0.02	+ 0.01	1
44.8 ± 0.1	107	1.12 ± 0.05	+ 0.01	0
51.3 ± 0.1	107	0.88 ± 0.02	−0.01	1
55.6 ± 0.2	109	1.13 ± 0.03	+ 0.02	0
70.6 ± 0.2	109	0.85 ± 0.02	−0.04	1
87.4 ± 0.2	109	0.87 ± 0.03	−0.02	1
133.9 ± 0.2	109	0.89 ± 0.02	0.00	1
139.7 ± 0.2	109	1.10 ± 0.07	−0.01	0
144.2 ± 0.2	107	1.13 ± 0.06	+ 0.02	0
202.5 ± 0.2	107	0.91 ± 0.04	+ 0.02	1
209.6 ± 0.2	109	0.92 ± 0.04	+ 0.03	1

Table 1 - Spin assignments using the R_J-values, where (R,) is the average value of R_J associated with the spin 0 or 1 families.

ENERGY (eV) This work	ENERGY (eV) Ref. (20)
16.3 ± 0.1	16.30 ± 0.05
30.3 ± 0.2	30.4 ± 0.1
40.5 ± 0.3	40.1 ± 0.1
41.6 ± 0.3	41.5 ± 0.1
44.9 ± 0.3	44.8 ± 0.1
51.6 ± 0.4	51.3 ± 0.1
55.9 ± 0.5	55.6 ± 0.2
71.4 ± 0.7	70.6 ± 0.2
88.0 ± 0.9	87.4 ± 0.2
134 ± 2	133.9 ± 0.2
139 ± 2	139.7 ± 0.2
144 ± 2	144.2 ± 0.2
173 ± 3	173.1 ± 0.2
201 ± 3	202.5 ± 0.2
208 ± 3	209.6 ± 0.2
249 ± 4	251.3 ± 0.3
261 ± 5	264.7 ± 0.3
287 ± 5	290.9 ± 0.3
311 ± 6	310.9 ± 0.2
323 ± 6	327.8 f0.3
356 ± 7	361.8 ± 0.2
381 ± 8	387.0 ± 0.4
397 ± 9	398.0 ± 0.4
420 ± 9	428.4 ± 0.4

Table 2 - Identification of resonances.

E_0 (eV)	Garg (21)	Rae (22)	Singh (23)	Moxom (24)	Fluharty (25)	Chrien (26)	Desjardins (27)	Asghars (28)	This Work
16.3 ± 0.5		0	0	0				0	0
30.4 ± 0.1		1	1	1		(1)		1	1
40.1 ± 0.1		1		1		(1)		1	
41.5 ± 0.1				1				1	
44.8 ± 0.1				0				0	0
51.3 ± 0.1		1	1	1		(1)		1	1
55.6 ± 0.2		0	0	0	0	(0)		0	0
70.6 ± 0.2		1	1	1	1	(1)		1	1
83.5 ± 0.2									
87.4 ± 0.2		0		0		(1)		1	1
106.3 ± 0.2							*		
110.9 ± 0.2							*		
133.9 ± 0.2	1	1	1	1		(1)	1	1	1
139.7 ± 0.2									0
144.2 ± 0.2				(0), (1)			(0)	0	0
169.8 ± 0.2							*		
173.1 ± 0.2			1	1		(1)	1		
183.6 ± 0.2	*						*		
202.5 ± 0.2				1			1	1	1
309.6 ± 0.2				1		(1)	1	1	1

Table 3 - Comparison of spin assignments from various authors.

The gamma-ray cascade multiplicity method consists of the study of the cascade originating from the de-excitation of the compound nucleus formed by neutron capture. The assumption that the difference between the spins of the initial and final states after each transition must be 1 or 0 is based on the fact that dipole radiation prevails in y ray capture spectra, except in transitions between low-lying levels. Such conclusions justify the hypotheseis that the spin difference AJ between the initial and final states of the cascade affects the average multiplicity, if isomeric states are not present. Indeed, in several nuclides[16] variations of as much as 25% on multiplicity have been found.

A quantity directly related to average multiplicity can be obtained measuring simultaneously, for s-wave resonances, the single and coincidence counting rates from two gamma-ray detectors placed symmetrically to the target. Since good energy resolution is not required, very efficient gamma-ray detectors can be used.

Single and coincidence counting rates (A_γ^S and A_γ^C), related to a resonance λ, are equal to

$$A_\lambda^S = k_J^S I_0(E_n) Y_\lambda(E_n, E_0, \tau_0, \Gamma),$$
$$A_\lambda^C = k_J^C I_0(E_n) Y_\lambda(E_n, E_0, \tau_0, \Gamma),$$

where

$I_0(E_n)$ = incident neutron flux, with energy E,. integrated over the target surface; $Y_\lambda(E_n, E,, \tau_0, \Gamma)$ = observed number of radiative captures per incident neutron of energy E, ; E,, r,, Γ -- parameters of the λ resonance; k_J^S, k_J^C – single and coincidence average numbers of counts per radiative capture.

The coefficient k_J^C depends on the cascade characteristics, i.e. on the average multiplicity v,. Consequently, it is directly affected by the spin J. The ratio r, of A_λ^S to A_λ^C corresponds to the ratio of the coefficients k_J^S and k_J^C, since both counting rates are proportional to the same factor $I_0(E_n) \times$ $\times\ Y_\lambda(E_n, E_0, \tau_0, \Gamma)$:

$$r_J = \frac{A_\lambda^S}{A_\lambda^C} = \frac{k_J^S I_0(E_n) Y_\lambda(E_n, E_0, \tau_0, \Gamma)}{k_J^C I_0(E_n) Y_\lambda(E_n, E_0, \tau_0, \Gamma)} = \frac{k_J^S}{k_J^C}.$$

The ratio r, depends strongly on the spin of the resonance through the average multiplicity. This results in the separation of its values into two different groups, related to the two possible spin values.

The determination of the r,-value distribution. then. allows spin assignments for the s-wave resonances.

The absolute r, values. because of their dependence on the characteristics of the detection system used, are normalized relative to the average value $\bar{r}$. that is.

$$\bar{r} = \frac{\langle r_0 \rangle + \langle r_1 \rangle}{2}, \qquad R_J = \frac{r_J}{\bar{r}}$$

where (r,) and (r,) are the average values of the ratios r,. each one associated to a spin resonance family.

It is then possible to define the spin effect index as being equal to the difference between the normalized average vaiues:

$$d = (R,) - (R,).$$

3. Experimental Conditions

Our measurements were obtained using the C.B.P.F. electron linear accelerator with:

electron énergy: 28 MeV.
r.m.s. current: *25* μA,
pulse width: *500* ns,
repetition frequency: 360 Hz.

The experimental set-up is shown in Fig. 1. Neutrons are produced by *Bremsstrahlung* radiation in a water cooled Pb target. 6.5 cm high and

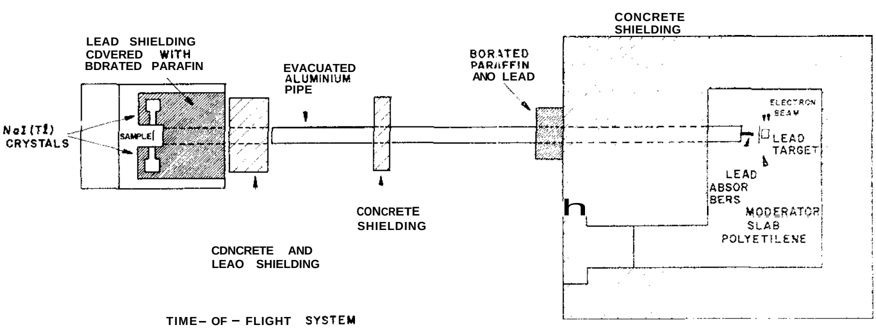


Fig 1 - I he experimental arrangement.

2.5 cm in diameter, as shown in Fig. 2. These neutrons. after being moderated by a 2 cm thick polyethylene slab, strike a silver sample placed at about 12 m from the neutron moderator. Pb absorbers were conveniently placed on the axis of the neutron beam in order to reduce the gamma flash due to ***Bremsstrahlung*** in the target and the fast neutron flux viewed by the detector.

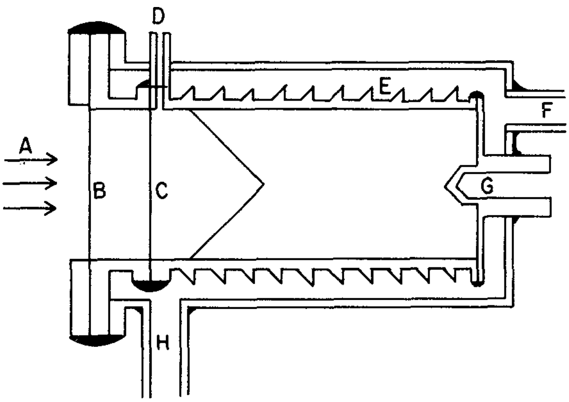


Fig. 2 - The experimental arrangement: A - Electron beam; B - Window; C - Safety window: D - Pressure Indicator; E - Fins: F - Water in: G - Thermometer: H - Water out.

The detection system is shown in Fig. **3.** Two 12.5 cm × 12.5 cm NaI(Tl) crystals. connected to *56* AVP photomultipliers were used. A 1 mm thick lead foil and a 1.5 cm absorber of borated paraffin were used to shield the crystais from scattered neutrons in the detectors and in surrounding building materials.

In order to get a better separation between the two groups of R_J vaiues. energy thresholds in the gamma-ray measurements are introduced in both detection systems (E_S and E_C). The choice of their most convenient values depends on the nuclei studied. There is a compromise between the emphasis given to the effect of spin dependence by the choice of convenient thresholds values and the interna1 dispersion of the two R, groups due to the reduction of the number of transitions which are detected.

The selected value of E_S was obtained with the aid of Fig. 4 and the data of Ref. 11 (the threshold values indicated in Fig. 4 always allowed a complete separation between the two groups of resonances).

The E_S and E_C values were 2.5 MeV and 300 keV. respectively. The choice of the E, = 2.5 MeV energy threshold is justified by the fact that. for this

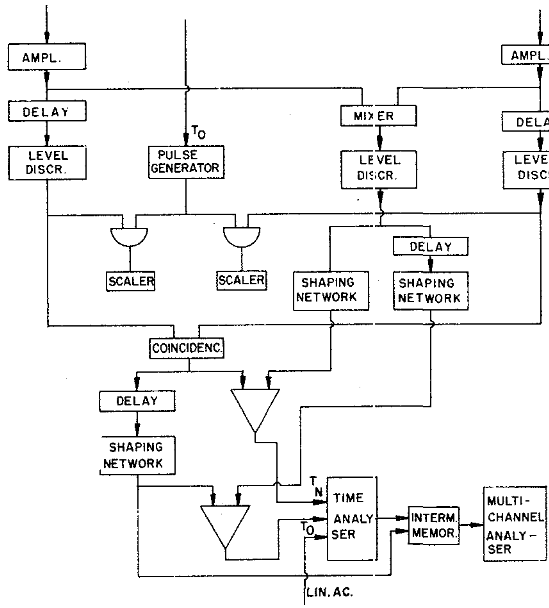


Fig. 3 - Circuit block diagram.

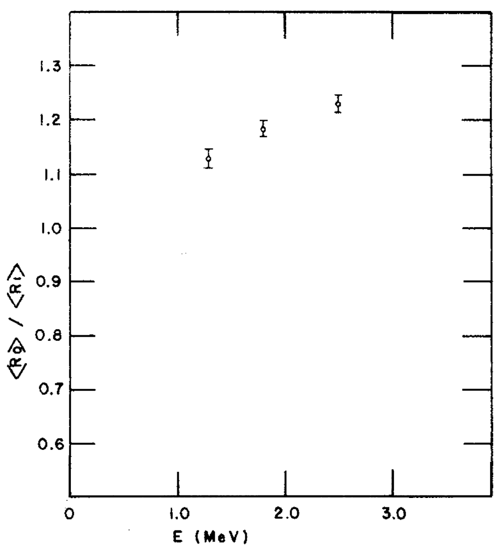


Fig. 4 - Variation of the ratio $\langle R_0\rangle/\langle R_1\rangle$ as a function of the threshold, E,. for the single spectra.

value. the ratio $\langle R_0 \rangle / \langle R_1 \rangle$ has a well-marked spin effect. Although intensity considerations would favour a coincidence energy threshold as low as possible. its value must be such as to prevent severa1 low energy effects which tend to increase the random coincidence counting rate.

Background measurements under comparable conditions were obtained and subtracted from the spectra.

The radiative background caused by a small superposition of the wings of close resonances was also subtracted and areas were calculated using only a narrow region near the peak of the resonances.

Figs. 5 and 6 show the typical time-of-flight neutron resolution obtained.

The neutron energy range was 7-440 eV. However, in the coincidence spectrum. it was only possible to analyse the peak resonances up to 210 eV, due to insufficient statistics in the high energy region of this spectrum.

4. Results and Discussion

The results of the quantitative analysis of spectra and spin assignments are listed in Table 1. The first two columns exhibit the resonance energies and the respective isotopes. The normalized ratios R, are shown in the third column, while the fourth shows the deviation from the third column value $(R,)$ or (R,). Our results are shown in the last colurnn, spin 0 being assigned to the 139.7 $\pm$ 0.2 eV level.

In order to facilitate resonance identification. Table 2 shows energy values obtained in this experiment and those compiled from Ref. 20.

In Table 3. the results of the present work are compared to those of previous measurements. Resonances marked by (*) are p-wave levels and hence were not analysed in the present work. The 40.1 $\pm$ 0.1, 41.5 $\pm$ 0.1 and 173.1 $\pm$ 0.2 eV resonances could not be analysed. The first two resonances were not sufficiently resolved in the coincidence count spectrum, while the third one overlaps with the one at 169.8 $\pm$ 0.2 eV. The 83.5 $\pm$ 0.2 eV resonance, which is extremely weak, was not observed in our spectra. As can be seen from this table. there is an encouraging agreement between our results and the current experimental information.

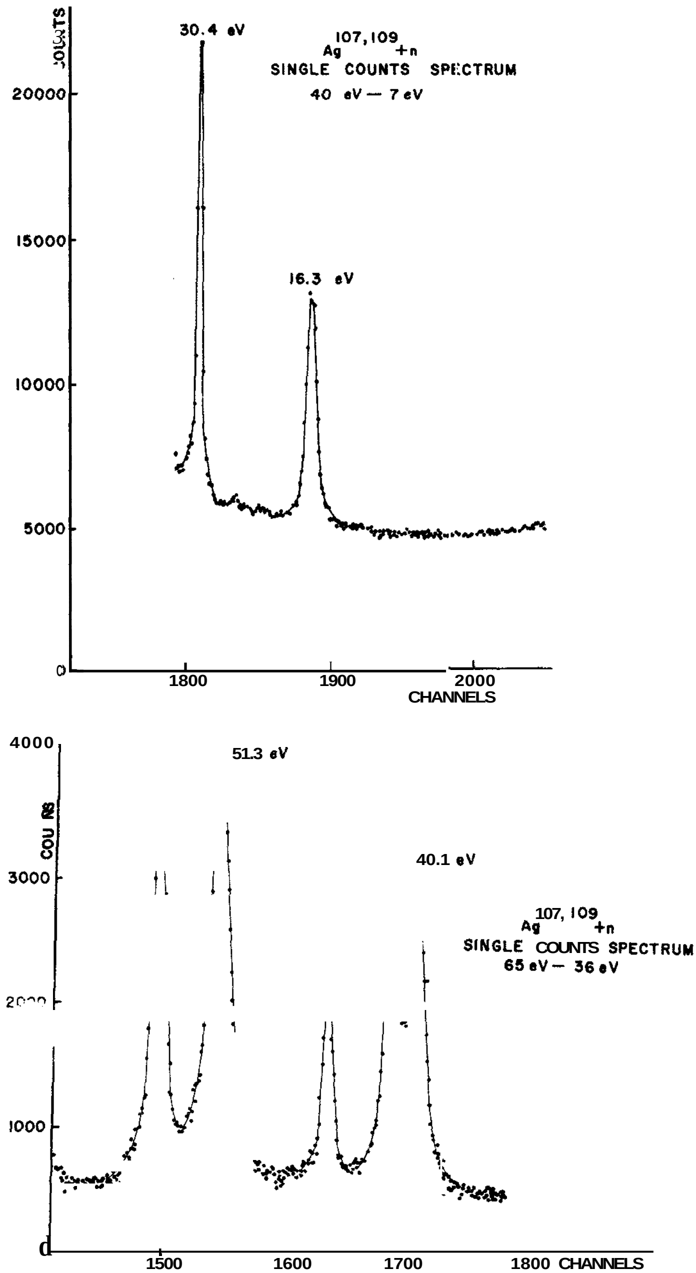
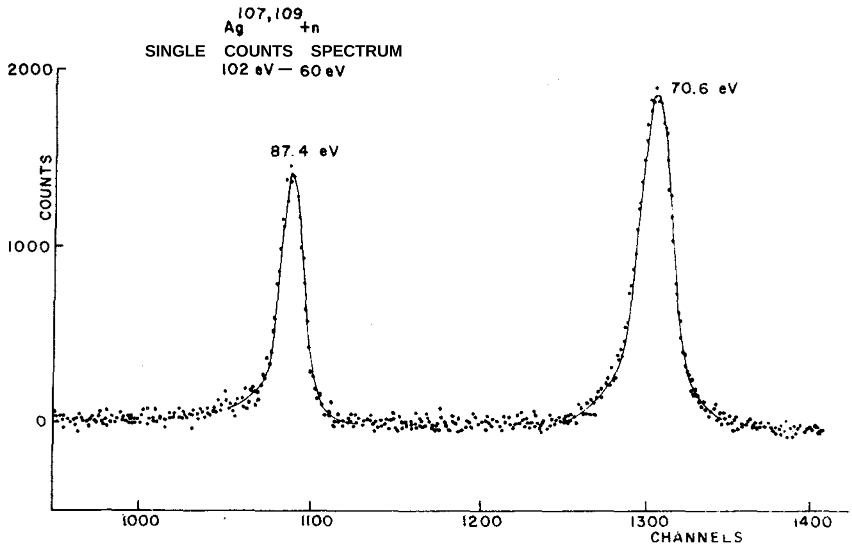


Fig. 5 - Coincidence spectra (cont.)


107,109
Ag +n
SINGLE COUNTS SPECTRUM
102 eV — 60 eV
2000
1000
0
COUNTS
87.4 eV
70.6 eV
1000
1100
1200
1300
1400
CHANNELS

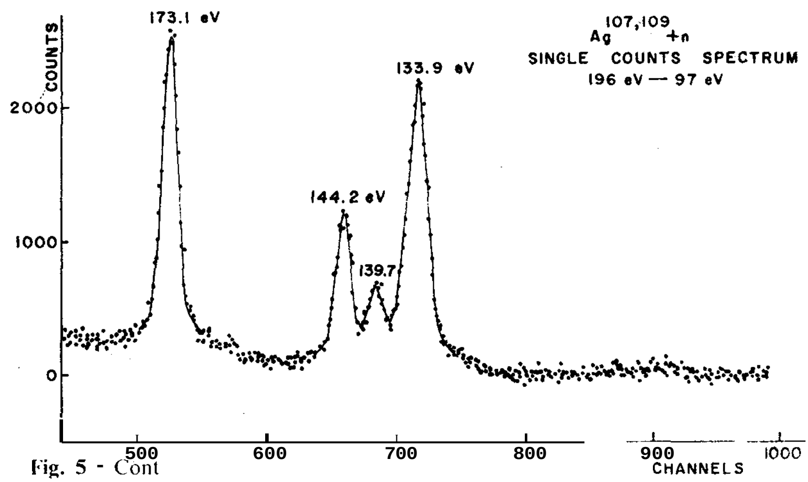

173.1 eV
107,109
Ag +n
SINGLE COUNTS SPECTRUM
196 eV — 97 eV
133.9 eV
COUNTS
2000
1000
0
144.2 eV
139.7
500
600
700
800
900
1000
CHANNELS

Fig. 5 - Cont

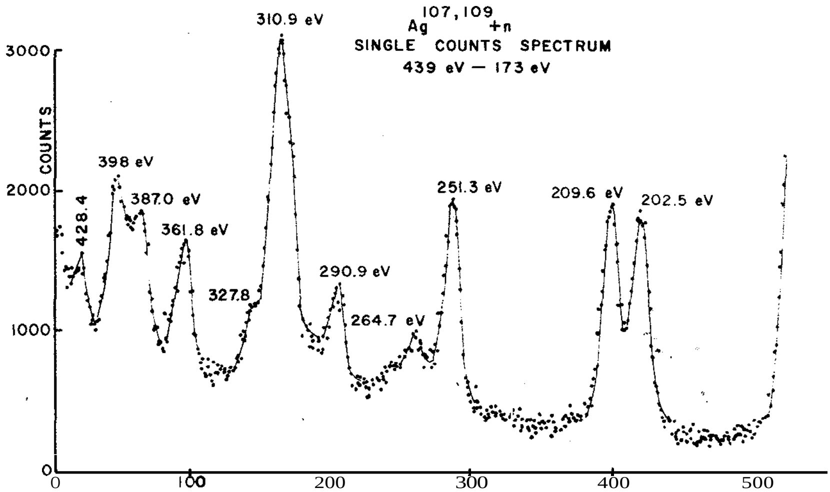


Fig. 5 - Cont.

It is worthwhile noticing that a large number of different gamma-rays were collected from each resonance even using our experimental conditions. Thus, Porter and Thomas fluctuations of $\Gamma_{\lambda i}$ (Ref. 17) are negligible. There was no marked isotope effect in $^{108,110}Ag$ radiation widths[18] and the characteristic parameters of each one are the same[19].

The R, values for different resonances are grouped around two values (Fig. 7) with a dispersion probably due to statistical fluctuations in the partial radiative widths. The relative separations of the two resonance groups is about 23%.

5. Conclusion

For silver odd-odd compound nuclei, the clear separation between the two R,-value groups and the agreement of our results with those of other authors show the successful application of the method. Spin 0 was assigned to the 139.7 ± 0.2 eV resonance. Such assignment could be made in this paper since the y-ray cascade multiplicity method only needs capture measurements and, also, since this resonance has a large Γ_γ value ($\Gamma_\gamma = 133 \pm 46$ MeV) [Ref. 20]. Besides that, its extremely small Γ_n value ($2g\Gamma_n = 2.2 \pm 0.3$ MeV) [Ref. 20] makes the application of methods based on transmission measurements extremely difficult.

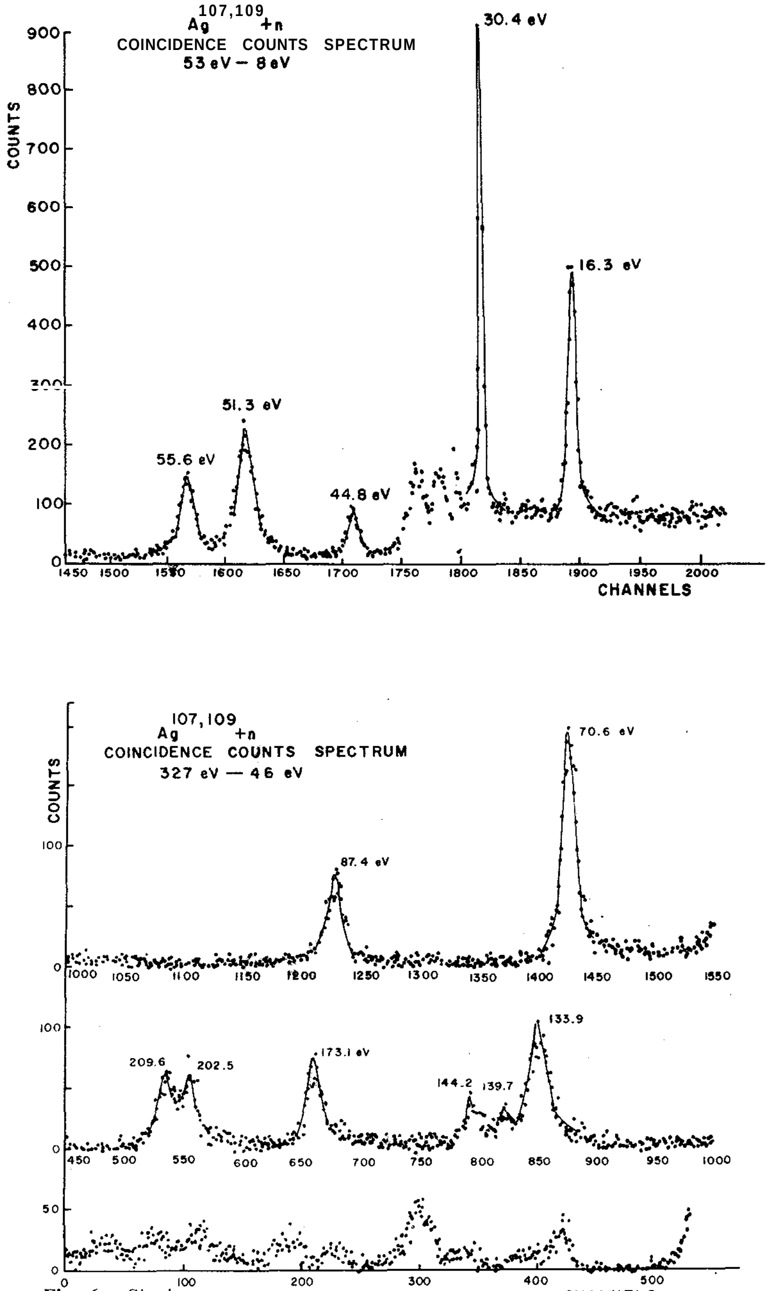


Fig. 6 - Single spectra.

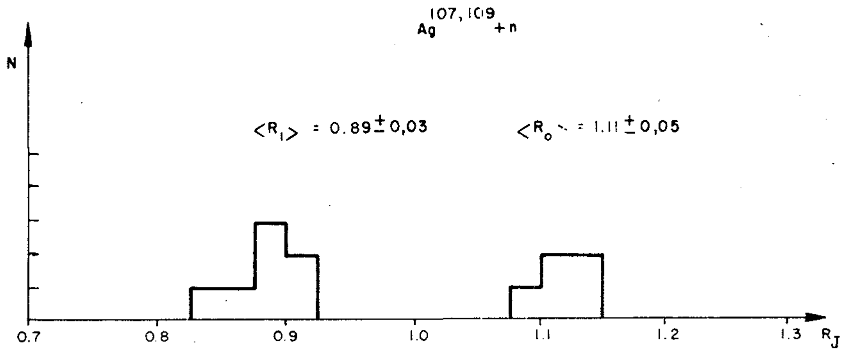


Fig. 7 - Frequency distribution of measured R_J-values.

The excellent results obtained in the present experiment stimulate future applications of the method. Also. it would be desirable that more experimental information could be made available in order to obtain a definitive conclusion as to the validity of the extension of the method. If it shows applicability to all nuclei. it will probably be the most effective tool (up to now) for spin assignments of low energy neutron resonances[1] . This method has also been applied to other odd-odd compound nuclei such as ^{76}As and ^{134}Cs. and these results will be published in a later paper.

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