PHYSICAL REVIEW C VOLUME 8, NUMBER 6 DECEMBER 1973

Nuclear Spectroscopy of ^{109}Ag from the ^{108}Pd(^{3}He, d) Reaction*

R. L. Auble, F. E. Bertrand, Y. A. Ellis, and D. J. Horen
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 27 July 1973)

The energy levels of ^{109}Ag are studied by means of the ^{108}Pd(^{3}He, d) reaction at 27-MeV bombarding energy. Deuteron angular distributions are compared with distorted-wave Born-approximation predictions to extract l transfers and spectroscopic strengths. Several previously unreported or poorly established levels are excited including a low-lying $\frac{1}{2}^+$ state at 706 keV. The available data are summarized and compared with previous studies of odd-mass silver and indium nuclei.

NUCLEAR REACTIONS ^{108}Pd(^{3}He, d), $E=27$; measured $\sigma(E_d, \theta)$; ^{109}Ag deduced levels, l_p, S, J, π.

I. INTRODUCTION

Examination of the recently published Nuclear Data Sheets for $A=109$ nuclei[1] shows a dearth of nuclear structure information for $^{109}_{47}$Ag, particularly for excitation energies greater than 1 MeV and for positive-parity states. The (^{3}He, d) reaction is particularly well suited for studying the positive-parity states associated with the $3s_{1/2}$, $2d_{3/2}$, $2d_{5/2}$, and $1g_{7/2}$ orbitals, which belong to the next major shell.

Further interest in the present study was provided by the suggestion of possible rotational structure in silver nuclei.[2-4] A similar interpretation had been suggested earlier[5] for low-lying positive-parity states in ^{115}In and ^{117}In, and a recent study[6] of the ^{116}Cd(^{3}He, d) reaction, in which possible $\frac{1}{2}^+$, $\frac{3}{2}^+$, $\frac{5}{2}^+$, and $\frac{7}{2}^+$ rotational band members were excited, appears to be consistent with such an interpretation in the case of ^{117}In. However, a similar low-lying $\frac{1}{2}^+$ state, on which this "band" is based, had not been previously reported in ^{109}Ag.

The present study was undertaken to fill some of the gaps in our knowledge of ^{109}Ag, to search for possible rotational structure, and to establish more firmly the characteristics of previously reported levels.

II. EXPERIMENTAL RESULTS

The measurements were made using 27-MeV ^{3}He ions from the Oak Ridge isochronous cyclotron. Deuteron spectra were recorded on Kodak NTB emulsions placed in the broad-range magnetic spectrograph. The 98% enriched ^{108}Pd target, approximately 170 μg/cm^2 in thickness, was prepared by evaporation onto ≈20-μg/cm^2 carbon foil. The thickness was deduced by comparison of the measured ^{3}He elastic scattering cross sections with optical-model predictions. A deuteron spectrum is shown in Fig. 1. The resolution in all spectra was approximately 25 keV full width at half maximum (FWHM).

The distorted-wave Born-approximation (DWBA) predictions used to extract l values and spectroscopic strengths were calculated with the code JULIE using the optical-model and bound-state parameters given in Table I. Experimental and predicted angular distributions are compared in Figs. 2 and 3. Those shown in Fig. 3 indicate that the deuteron groups involved include two or more levels excited by different l transfers. Spectroscopic factors were calculated using the relation, $C^2S'=\sigma_{\text{exp}}/4.42\sigma_{\text{DWBA}}$, and making a least-squares fit of one or more DWBA predictions to the experimental angular distributions. An estimate of the uncertainty in the absolute cross sections can be obtained from the sum of the spectroscopic factors for the ground-state ($\frac{1}{2}^-$) and 311-keV ($\frac{3}{2}^-$) levels, which essentially exhaust the $l=1$ strength, and the 131-keV ($\frac{9}{2}^+$) level which probably absorbs most of the $1g_{9/2}$ stripping strength (the next $l=4$ state with possible $J^\pi=\frac{9}{2}^+$ is at 1310 keV and is here assumed to be due to $1g_{7/2}$ stripping). The experimental value for this sum is 3.7 which is in good agreement with the value 4.0 expected for stripping on a $Z=46$ target. Thus, an uncertainty of approximately 10% is estimated for the strengths deduced for the more strongly excited levels, while proportionately larger uncertainties should be assigned to those for weaker levels and unresolved multiplets.

III. DISCUSSION

The experimental excitation energies, l transfers, and spectroscopic strengths are listed in

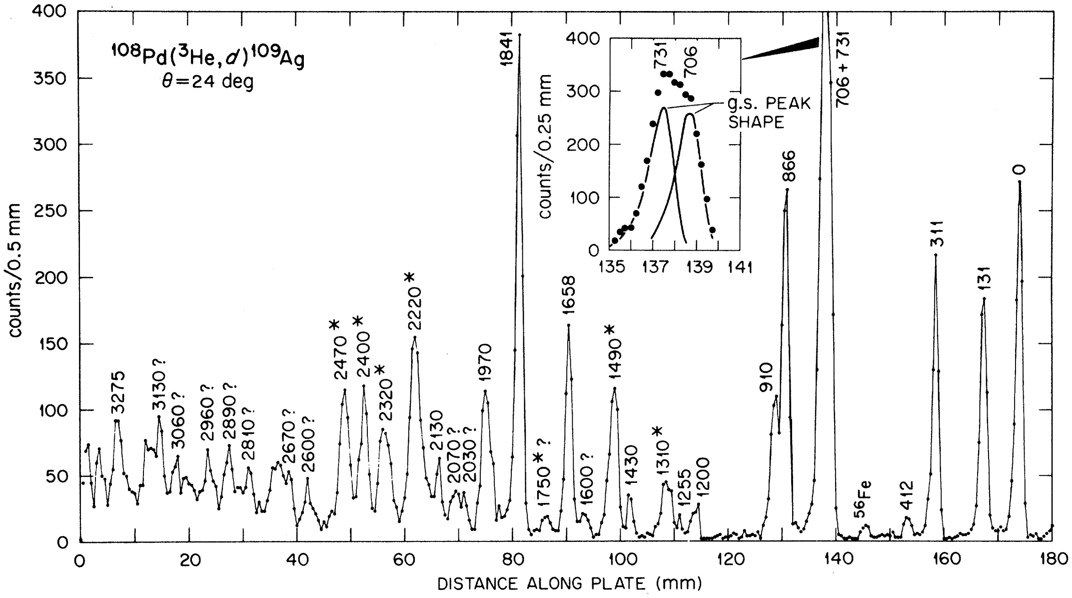

FIG. 1. Deuteron spectrum from the ^{108}Pd(^{3}He,d)^{109}Ag reaction. Asterisk denote unresolved multiplets.

Table II. In addition to those listed, there are at least seven deuteron groups between 2470 and 3275 keV, all of which appear to be unresolved multiplets excited predominantly by $l=2$ transfers. The total $l=2$ strength in this region is approximately the same as that for the 1841-keV level. At higher excitation energies, the deuteron spectrum becomes essentially flat, and no strong resolved groups were observed up to approximately 7 MeV of excitation.

Included in Table II is a summary of previous level and J^{π} assignments. In general, the present data are consistent with previous measurements except for a possible discrepancy in the 700-keV region. In view of our observance of a $\frac{1}{2}^{+}$ level at 706 keV, we have reexamined the available literature pertaining to the decay of ^{109}Pd from which most of the previous information was derived. Upon doing so, we noted a number of inconsistencies therein as regards the possible feeding of a level at 707 keV. Graeffe and Gordon[7] claim to

TABLE I. Optical-model parameters used in the DWBA calculations.

	^{3}He	d	Form factor
V (MeV)	172	101.4	
r_0 (fm)	1.14	1.085	1.20
a (fm)	0.70	0.857	0.65
W (MeV)	16	0	
$4W_D$ (MeV)	0	61	
r_0' (fm)	1.54	1.293	
a' (fm)	0.80	0.788	
V_s (MeV)	0	7.2	$\lambda=25$
r_s (fm)		1.085	
a_s (fm)		0.857	
r_c (fm)	1.40	1.30	1.25

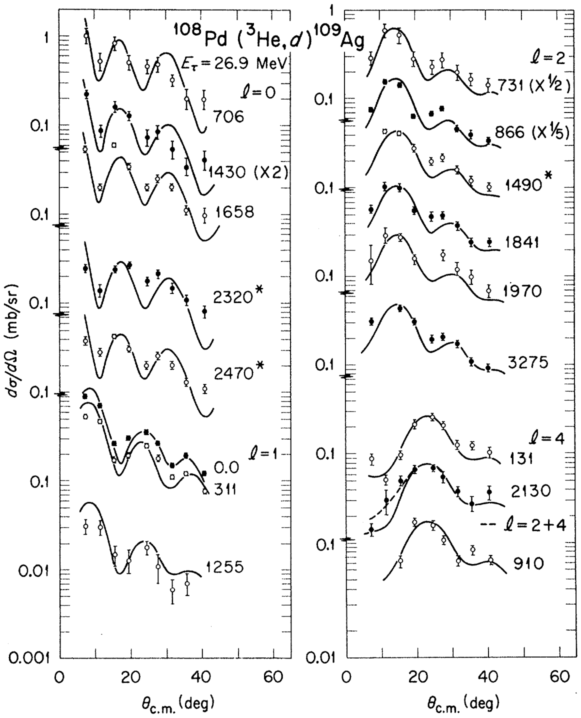

FIG. 2. Angular distributions for ^{109}Ag levels populated by the ^{108}Pd(^{3}He,d) reaction. The curves are DWBA predictions for the indicated l transfer.

TABLE II. Summary of known levels in ^{109}Ag.

Present studies				Previous assignments[a]	
E	l	j[b]	C^2S'	E	J^π
0.0	1	$\frac{1}{2}$	0.86	0.0	$\frac{1}{2}^-$
(88)	if 4	$\frac{7}{2}$	<0.2	88.03	$\frac{7}{2}^+$
131 2	4	$\frac{9}{2}$	2.4	132.8	$(\frac{9}{2})^+$
311 2	1	$\frac{3}{2}$	0.43	311.4	$\frac{3}{2}^-$
412 10	if 3	$\frac{5}{2}$	≈0.2	415.3	$\frac{5}{2}^-$
				701.9	$\frac{3}{2}^-$
706 5	0	$\frac{1}{2}$	0.29	707.0?[c]	
731 5	2	if $\frac{3}{2}$	1.9	724.4	$(\frac{3}{2})^+$
		if $\frac{5}{2}$	1.4	735.3	$(\frac{5}{2})^+$
				839.8?	
				862.7	$\frac{5}{2}^-$
866 7	2	$\frac{5}{2}$	0.75	869.5	$(\frac{5}{2}^+)$
910 10	4	$\frac{7}{2}$	2.7	911.0	$\frac{5}{2}^\pm, \frac{7}{2}^\pm, \frac{9}{2}^-$ [d]
				912.3	
				1090.6	
				1099?	
1200 10	2?	$\frac{5}{2}$	0.02		
	+4?	$\frac{9}{2}$	0.15		
1255 10	1?	$\frac{1}{2}$	0.02	1260	
1310[e]	1?	$\frac{3}{2}$	0.02	1324.2	$(\frac{3}{2}^-)$
	+2	$\frac{5}{2}$	0.06		
	+4	$\frac{7}{2}$	1.0		
1430 10	0	$\frac{1}{2}$	0.03		
1490[e]	2	$\frac{5}{2}$	0.36	1510	
1600?				1610	
1658 10	0	$\frac{1}{2}$	0.20		
1750?[e]					
1841 10	2	$\frac{5}{2}$	0.93		
1970 10	2	$\frac{5}{2}$	0.23		
2000?					
2030?					
2070?					
2130 10	4	$\frac{7}{2}$	1.1		
	+2?	$\frac{5}{2}$	0.007	2150	$\frac{5}{2}^+, \frac{7}{2}^+$
2220[e]	2?	$\frac{5}{2}$	0.66		
	+4?	$\frac{7}{2}$	3	2230	$\frac{5}{2}^+, \frac{7}{2}^+$
2320[e]	0	$\frac{1}{2}$	0.10		
2400[e]	2?	$\frac{5}{2}$	0.13		
	+5?	$\frac{11}{2}$	1.6		
2470[e]	0	$\frac{1}{2}$	0.15		
3275 10	2	$\frac{5}{2}$	0.10		

[a] From Ref. 1 except as noted.

[b] Spin assumed in extracting spectroscopic factors. Most probable value of J^π based on l transfer and previous data.

[c] Level proposed in Refs. 2 and 4 but not adopted in Ref. 1.

[d] From logft value and γ-decay properties.

[e] Unresolved multiplet indicated by deuteron peak width.

have observed 707-γ-45-γ coincidences requiring placement of a level at 839.8 keV, while Berzins, Bunker, and Starner[2] indicate that these transitions are not in coincidence and assign the 707-keV photon to the deexcitation of a level at 707 or 795 keV in ^{109}Ag. Schick and Talbert[4] adopted the latter conclusion and favored the 707-keV level assignment since they detected a weak 396-keV photon which energetically could be placed between levels at 707 and 311 keV. If one accepts this interpretation of the data and tries to associate such a level with that observed in this work, two problems arise. The first is how the level would be populated in the ^{109}Pd decay. Since the latter has $J^\pi = \frac{5}{2}^+$, a direct β transition would be second forbidden (i.e., $\frac{5}{2}^+ \rightarrow \frac{1}{2}^+$) and could account for only ≈0.1% of the reported γ intensity (if logft $\gtrsim 11$). However, examination of the coincidence spectrum gated with the 145-keV γ ray in the work of Berzins, Bunker, and Starner[2] seems to indicate the presence of more than just a 724 γ; i.e., the relative intensities of the peaks at 636 and ≈724 keV are apparently not the same as observed in the singles spectrum, whereas they should be if they arise from the same level. A possible explanation could be that there is a low-energy (≈17-keV) transition between the level at 724 keV and the level at 707 keV, and that a large fraction of the coincidence counts observed[2] above ≈680 keV are due to the 707-keV γ ray.

Although it appears as though the first problem might be rationalized, a second would exist if one accepts the validity of the conversion-coefficient measurement of Bashandy.[8] The latter assigns a multipolarity $M1$, $E2$, or admixture thereof to the 707-keV transition, which if correct would require the 707-keV level to have negative parity. Unfortunately, the author does not show the spectrometer data for transitions in the vicinity of 700 keV, so we are unable to further evaluate his results. We conclude that the questions raised above can only be resolved by further experiments.

The excitation of the $\frac{1}{2}^+$ state at 706 keV is most interesting since the low-spin positive-parity states found in the indium isotopes have been suggested as possible members of $\frac{1}{2}^+$ [431] rotational bands. This interpretation was suggested[5] by the large $E2$ transition probability connecting the $\frac{3}{2}^+$ and $\frac{1}{2}^+$ levels at 829 and 864 keV in ^{115}In and at 660 and 749 keV in ^{117}In. Supporting evidence in the case of ^{117}In is found in the measured magnetic dipole[9] and electric quadrupole[10] moments for the 660-keV level, the consistency between experimental and theoretical (^{3}He, d) strengths,[6] and the reasonable band parameters obtained in fitting[11] experimental energies of $J^{\pi}=\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$, and ($\frac{9}{2}^+$) levels to the $K=\frac{1}{2}$ rotational band formula. Similar evidence available for ^{115}In levels[10,12,13] and recent calculations by Sen[14] lend additional support for the inclusion of deformed states in describing the excited levels of indium nuclei.

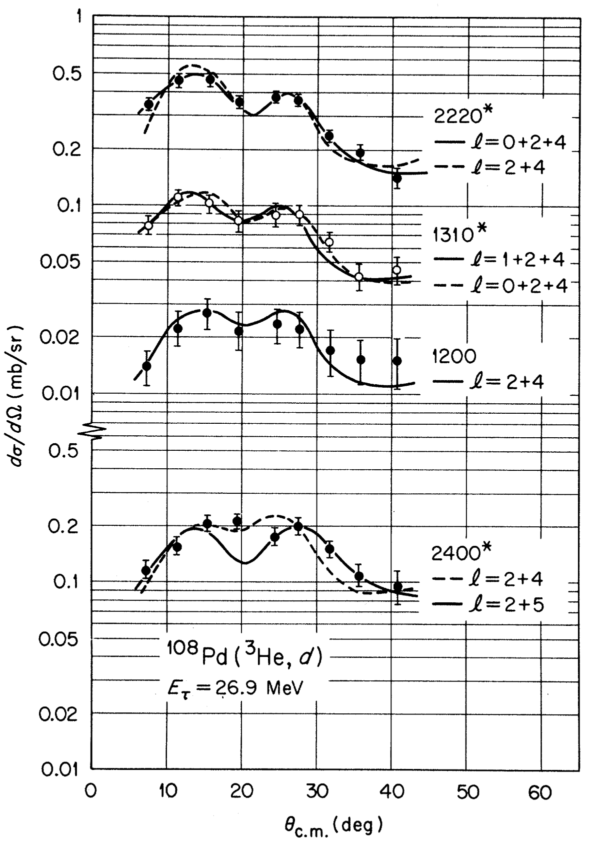

FIG. 3. Angular distributions for probable unresolved multiplets in ^{109}Ag populated in the (^{3}He,d) reaction. The curves are linear combinations of DWBA predictions for two or more different l transfers.

TABLE III. The C_{jl} coefficients characterizing the $\frac{1}{2}^+$ [431] Nilsson orbit.

J^{π}	C_{jl}^2 (experimental) [a]		C_{jl}^2 (calculated) Chi [d]	Faessler and Sheline [e]	
	^{109}Ag [b]	^{117}In [c]	$\beta=0.2$	$\beta=0.1$	$\beta=0.2$
$\frac{1}{2}^+$	0.050	0.037	0.050	0.038	0.14
$\frac{3}{2}^+$	$\leq$0.33 [f]	0.14	0.20	0.084	0.20
$\frac{5}{2}^+$	0.13	0.37	0.06	0.20	0.25
$\frac{7}{2}^+$	0.47	0.45	0.66	0.66	0.36
$\frac{9}{2}^+$	(0.026)	0	0.03	0.01	0.05

[a] From $C_{jl}^2 = C^2S'_{jl} / \sum_{jl} C^2S'_{jl}$.

[b] From present work, assuming the levels observed at 706, 724.4, 869.5, 911.0, and 1200 keV are the members of the $\frac{1}{2}^+$ [431] Nilsson orbit.

[c] From Ref. 6.

[d] From Ref. 18. Harmonic-oscillator potential was used.

[e] From Ref. 17. Woods-Saxon potential was used (calculated for $A=185$).

[f] Peak at 731 keV probably includes known 724- ($\frac{3}{2}^+$) and 735- ($\frac{5}{2}^+$) keV levels.

(Meyer, Struble, and Smith[15] have recently suggested that the $E2$ enhancement for the 35-keV transition in ^{115}In was overestimated in Ref. 5. However, their smaller value is based on the absolute L-conversion coefficient which, in this case, is inherently less reliable than the L-subshell ratios used in Ref. 5.)

There have been previous speculations[2-4] regarding possible rotational bands in silver nuclei involving both negative- and positive-parity states. However, most of these levels could also be explained by alternative models, for example three

TABLE IV. Band parameters for the $\frac{1}{2}^+$ [431] orbit.

			a	$\hbar^2/2I$ (keV)
Experimental	^{109}Ag [a]		−0.65	17.6
	^{117}In [b]		−2.7	14
	^{115}In [c]		−2.2	20
	^{111}Ag [d]		−1.5?	19?
Calculated	Chi [e]	$\beta=0.1$	−3.6	
		$\beta=0.2$	−2.6	
	Faessler and Sheline [f]	$\beta=0.1$	−2.1	
		$\beta=0.2$	−0.68	

[a] From present work, assuming the levels observed at 706, 724.4, 869.5, 911.0, and 1200 keV are the members of the $\frac{1}{2}^+$ [431] Nilsson orbit.

[b] From Ref. 11.

[c] From Ref. 5.

[d] From Refs. 3 and 4.

[e] From Ref. 18. Harmonic-oscillator potential was used.

[f] From Ref. 17. Woods-Saxon potential was used (calculated for $A=185$).

proton holes coupled to quadrupole vibrations.[16] Such is not the case for $\frac{1}{2}^{+}$ states which, in the spherical shell model, would require excitation of a proton into the $3s_{1/2}$ orbit (a one-particle–four-hole state in the case of $Z = 47$) or coupling of the proton to higher-order or multiple-phonon excitations. Thus, the presence of a low-lying $\frac{1}{2}^{+}$ state is believed to be a more unique indicator of deformed states. With the exception of a tentative assignment[3] for the 405-keV level in ^{111}Ag, no $\frac{1}{2}^{+}$ states had been previously reported in the silver isotopes.

Considering the 706-keV level as the $\frac{1}{2}^{+}$ [431] Nilsson state, it becomes interesting to search for possible rotational band members and to compare the results with those reported in ^{117}In and with theoretical predictions. Unlike the indium isotopes, where the lowest $\frac{1}{2}^{+}$ and $\frac{3}{2}^{+}$ states are inverted, one finds that the most likely candidate for the $\frac{3}{2}^{+}$ level is at 724.4 keV (see Table II). Examination of the remaining known positive-parity states suggests that 869.5- and 911.0-keV levels as $\frac{5}{2}^{+}$ and $\frac{7}{2}^{+}$ band members. Fitting the first three energies to the $K = \frac{1}{2}$ rotational band formula, one obtains $\hbar^2/2I = 17.6$ keV and $a = -0.65$. The predicted energies for the $\frac{7}{2}^{+}$ and $\frac{9}{2}^{+}$ levels are 912 and 1174 keV. The first value is in good agreement with the experimental value of 911 keV, and the angular distribution for the 1200-keV level, apparently an unresolved multiplet, suggests an $l = 2 + 4$ assignment. Tables III and IV compare the present results with the ^{117}In data[6,11] and with theoretical predictions.[17,18]

The present studies, while clearly inconclusive, add some support to the possibility of deformations in the silver nuclei. More data in the form of γ-transition rates and nuclear moments will be required to establish the character of these levels.

---

[*] Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

[1] F. E. Bertrand, Nucl. Data B6, 1 (1972).

[2] G. Berzins, M. E. Bunker, and J. W. Starner, Nucl. Phys. A114, 512 (1968).

[3] G Berzins, M. E. Bunker, and J. W. Starner, Nucl. Phys. A126, 273 (1969).

[4] W. C. Schick, Jr., and W. L. Talbert, Jr., Nucl. Phys. A128, 353 (1969).

[5] A. Bäcklin, B. Fogelberg, and S. G. Malmskog, Nucl. Phys. A96, 539 (1967).

[6] S. Harar and R. N. Horoshko, Nucl. Phys. A183, 161 (1972).

[7] G. Graeffe and G. E. Gordon, Nucl. Phys. A107, 67 (1968).

[8] E. Bashandy, Z. Phys. 236, 130 (1970).

[9] V. R. Pandharipande, K. G. Prasad, and R. P. Sharma, Nucl. Phys. A104, 525 (1967).

[10] H. Haas and D. A. Shirley, UCRL Report No. UCRL-20426, 1970 (unpublished), p. 208.

[11] P. R. Gregory and M. W. Johns, Can. J. Phys. 50, 2012 (1972).

[12] V. Sergeev, J. Becker, L. Eriksson, L. Gidefeldt, and L. Holmberg, Nucl. Phys. A202, 385 (1973).

[13] E. Thuriere, thesis, University of Paris, 1970 (unpublished).

[14] S. Sen, Nucl. Phys. A191, 29 (1972).

[15] R. A. Meyer, G. L. Struble, and N. Smith, Bull. Am. Phys. Soc. 17, 467 (1972); R. A. Meyer and G. L. Struble, International Conference on Nuclear Moments and Nuclear Structure, Osaka, 1972 (unpublished), p. 211.

[16] V. Paar, Phys. Lett. 39B, 587 (1972).

[17] A. Faessler and R. K. Sheline, Phys. Rev. 148, 1003 (1966).

[18] B. E. Chi, in *Collective Models of the Nucleus*, edited by J. P. Davison (Academic, New York, 1968), Appendix D.