LEVEL STUDIES IN $^{107,\,109}$Ag FROM COULOMB EXCITATION MEASUREMENTS

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Low-lying negative parity levels of isotopes in natural silver were Coulomb excited by 3.0—4.2 MeV protons. Five levels in each of the ^{107,109}Ag isotopes up to 1464.7 and 1324.2 keV excitation energies, respectively, were excited. De-excitation gamma-rays were observed with a high resolution 50 cc Ge(Li) detector. Low-energy protons have been used for the first time to Coulomb excite the levels at 1464.7 keV in ^{107}Ag, and 1324.2 keV excitation energies in ^{109}Ag. Level energies, branching ratios, multipole mixing ratios, B(E2) and B(M1) transition probabilities were deduced. Experimental thick-target gamma-ray yields for various transitions have been compared with the theoretical Coulomb and compound contributions. Also the results have been compared with those reported so far in literature.

I. INTRODUCTION

It was suggested several years ago by de-Shalit [1] that the low-lying negative parity states of ^{107}Ag and ^{109}Ag may arise from the coupling of an odd $2P_{1/2}$ proton or protonhole to the collective vibrational states of the doubly envencore. Level energies, spins and reduced quadrupole transition probabilities, have been reported earlier [2, 3], which is quite consistent with this weak coupling model. In cases where the core state is expected to correspond to a highly collective level of a neighbouring even-mass nucleus, the core excitation model has been successful. It should be interesting to study the silver odd-mass isotopes in relation to the core excitation model because these isotopes not only have even-mass neighbours with strong collective properties, they also have ground state spins of 1/2 and, therefore, the least possible number of states in a given multiplet. However, the positive parity states to silver isotopes cannot be explained by this simple model [1]. A detailed description of the odd-mass silver nuclei is given by Paar [5] who has shown that the coupling of a cluster of three proton holes in the $P_{1/2}$, $P_{3/2}$ and $g_{9/2}$ subshells to vibrational motions of the Sn core could explain the low-spin states either with negative or positive parity.

The excited states of ^{107}Ag and ^{109}Ag have been earlier studied by the inelastic scattering of protons [4, 6] and alpha-particles [7, 8] and Coulomb excitation with heavy ions [12—14], and β-decay [13, 20—29]. Also only the first few states in each isotope have been studied through Coulomb excitation by protons [2, 3, 9—12].

In the present investigations, we report the results on B(E2), branching ratios, δ and B(M1) values from a Coulomb excitation study as effected with protons in the energy range of 3.0 to 4.2 MeV. With this projectile the multiple E2 Coulomb excitation is negligible. Thus, the gamma-ray yields can straightforwadly be used to extract the B(E2) values of the ground state transitions. The transition rates for intermediate transitions were obtained from gamma-ray branching, multipole mixing ratios, and the B(E2) for ground state transitions. The measured excitation functions are also compared with the theoretical Coulomb and compound cross-sections; and we have found that at these energies the contribution from compound nucleus formation is very small. This is the first time that a proton induced Coulomb excitation study has been undertaken in detail for the excited levels of ^{107}Ag and ^{109}Ag, above the first-few excited states.

II. EXPERIMENTAL PROCEDURE

The experimental procedure followed has been described in detail elsewhere [30, 31]. A thick-foil of 99.9% spectroscopically pure natural silver was bombarded with protons in the energy range from 3.0 to 4.2 MeV, available from the Variable Energy Cyclotron at Panjab University, Chandigarh [32]. The beam current on the target was maintained around 150 nA to avoid large dead-time correction for the multichannel analyser. The deexcitation gamma-rays were detected at a distance of 8.8 cm from the target, with a 50 cc Ge(Li) detector having an energy resolution of about 2.0 keV for the 1.332 MeV line from the ^{60}Co source. The spectra were recorded at the angles of 0°, 55° and 90° to the beam direction, to produce the data for the anisotropy treatment. The data at 55°, being independent of angular distribution effects, were used to extract reduced quadrupole transition probabilities.

III. EXPERIMENTAL RESULTS

III.1. Gamma-ray yields

De-excitation gamma-rays from the Coulomb excitation of ^{107}Ag and ^{109}Ag with protons have been identified. A typical gamma-ray spectrum recorded at

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55° to the beam direction and displaying the well-resolved peaks, is shown in Fig. 1. Ten gamma-rays of 98, 324.8, 364, 423.1, 462, 526.5, 624.9, 786.5, 949.8 and 1140 keV energies were assigned to the deexcitation of the levels of ^{107}Ag, whereas the lines at 103, 311.3, 391, 415.1, 447.3, 551.1, 702, 862.5 and 1013 keV were identified to be associated with the transitions of nuclear levels of ^{109}Ag, on the basis of their well-known energies [33, 34]. The remaining gamma-ray peaks in the spectrum arise from the background and other contaminants. Figs. 2 and 3 show the level diagrams for ^{107}Ag and ^{109}Ag, respectively.

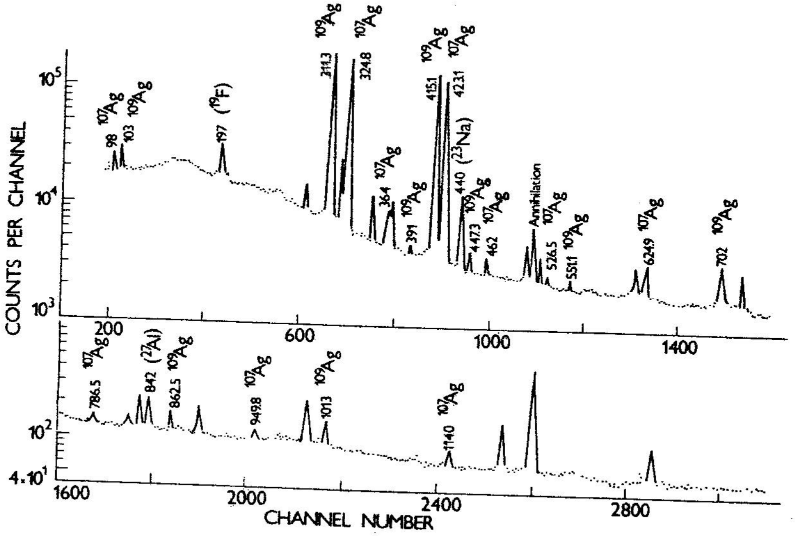
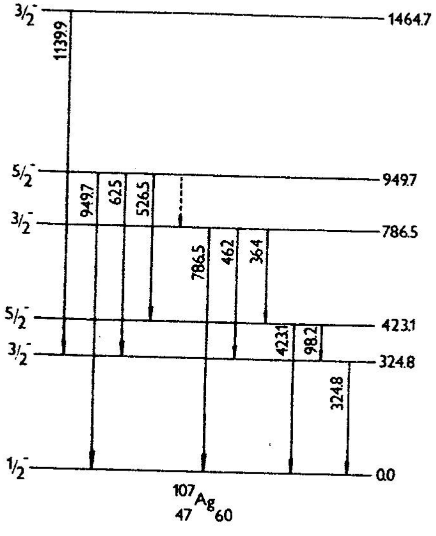


Fig. 1. Relevant portion of the gamma-ray spectrum obtained from the bombardment of a natural silver target with 3.7 MeV protons.

As discussed in our previous papers [30, 31], the experimental thick-target gamma-ray yield per incident proton, for each transition, was compared with the theoretical gamma-ray yield obtained by integrating the theoretical excitation function [11] along the path of the proton in the target. The reduced quadrupole transition probabilities were obtained from the comparison of theoretical and experimental gamma-ray yields for various transitions.

Fig. 4 displays the energy dependence of the experimental gamma-ray yields for the 311.3, 415.1, 862.5 keV levels of ^{109}Ag, and the 786.5 keV level of ^{107}Ag. A comparison of these yields has been made with the compound nucleus contribution, computed with the code CINDY [35], and with the first-order perturbation theory of Alder et al. [11] for the direct-E2 mode of excitation. From this comparison it is clear that the experimental gamma-ray yields follow the predictions of the Coulomb excitation theory of the E2 mode while the curve for the compound formation is much below the Coulomb cross section. The present B(E2) values along with their comparison with previous results are shown in Table 1. The errors assigned to the B(E2) values result from



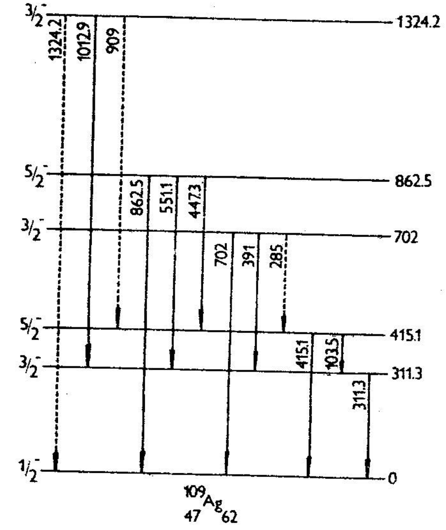


Fig. 2. The level scheme of low-lying states of ^{107}Ag.

Fig. 3. The level scheme of low-lying states of ^{109}Ag.

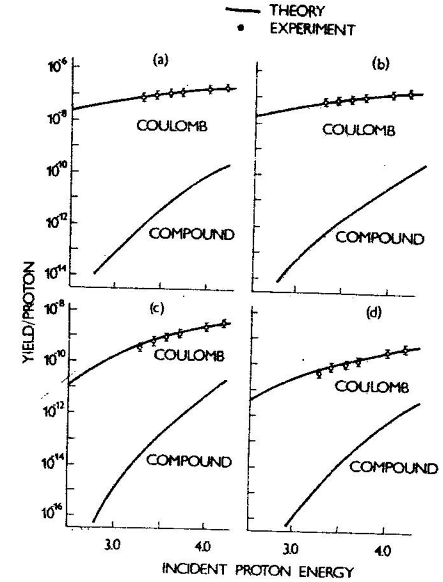


Fig. 4. Excitation functions of the levels at (a) 311.3 keV of ^{109}Ag (b) 415.1 keV of ^{109}Ag (c) 862.5 keV of ^{109}Ag and (d) 786.5 keV of ^{107}Ag.

Table 1

B(E2) values of the levels of ^{107,109}Ag.

Level energy	Measured B(E2)↑ ($e^2cm^4 \times 10^{-50}$)			
	Present work	Robinson et al. [15]	Black and Gruhle [13]	McGowan and Stelson [3]
		^{107}Ag		
324.8	19.7 ± 1.9	20.2 ± 1.8	21.9	21.9 ± 1.5
423.1	28.1 ± 2.9	28.7 ± 2.4	28.2	33.4 ± 2.4
786.5	0.29 ± 0.04	0.28 ± 0.05	0.32	—
949.7	2.29 ± 0.24	2.03 ± 0.22	2.5	—
1464.7	3.60 ± 0.28/	0.85 ± 0.12/	—	—
		^{109}Ag		
311.3	21.9 ± 1.8	22.2 ± 1.9	24.9	24.9 ± 1.7
415.1	32.7 ± 2.8	32.0 ± 2.6	36.3	37.7 ± 2.6
702	0.10 ± 0.02	0.087 ± 0.019	0.24	—
862.5	1.78 ± 0.15	1.73 ± 0.17	2.24	—
1324.2	1.25 ± 0.20	1.23 ± 0.18	1.44	—

uncertainties in the peak areas, the calibrated efficiency of the Ge(Li) detector, and the stopping power of Ag for protons.

III.2. Angular distribution

The angular distributions of the gamma-rays were determined from spectra with 4.0 MeV protons at 0° and 90° relative to the beam direction. The results were fitted to the equation

$$W(\Theta) = 1 + a_2 g_2 A_2 P_2(\cos\Theta) + a_4 g_4 A_4 P_4(\cos\Theta)$$

where a_2 and a_4 are the thick-target particle parameters [11], g_2 and g_4 are the finite solid angle correction factors. The coefficients A_2 and A_4 are a function of the spin sequence and the multiple mixing ratios. The last term in the above equation has been neglected since the parameter a_4 is very small. The measurement of the ratio $R = W(0°)/W(90°)$ determines A_2 uniquely and thereby the multiple mixing ration [36] allowed for a particular transition. The summary of the anisotropy results obtained in the present work is shown in Tables 2, 3 and 4. The errors quoted in the δ values were estimated from the uncertainties in the coefficients A_2 resulting from the measured gamma-ray yields.

Table 2

Summary of gamma-ray anisotropy results from the Coulomb excitation of ^{107,109}Ag by 4.8 MeV protons.

Level (keV)	$E\gamma$ (keV)	$R = W(0°)/W(90°)$	a_2	A_2
		^{107}Ag		
324.8	324.8	0.745 ± 0.05	0.518	−0.378 ± 0.009
423.1	423.1	1.226 ± 0.002	0.632	+0.232 ± 0.002
	98	0.802 ± 0.037	0.632	−0.236 ± 0.047
786.5	786.5	0.654 ± 0.014	0.872	−0.309 ± 0.015
	462	1.218 ± 0.077	0.872	+0.163 ± 0.054
949.7	949.8	1.495 ± 0.060	0.939	+0.311 ± 0.032
	624.9	0.480 ± 0.033	0.939	−0.465 ± 0.037
	526.5	1.151 ± 0.082	0.939	+0.107 ± 0.055
1464.7	1140	1.290 ± 0.065	1.106	+0.164 ± 0.034
		^{109}Ag		
311.3	311.3	0.736 ± 0.008	0.503	−0.403 ± 0.013
415.1	103	0.794 ± 0.054	0.624	−0.249 ± 0.070
702	702	0.651 ± 0.062	0.833	−0.327 ± 0.055
	391	0.816 ± 0.096	0.833	−0.165 ± 0.115
862.5	862.5	1.389 ± 0.099	0.905	+0.263 ± 0.059
	551.1	0.520 ± 0.045	0.905	−0.438 ± 0.048
	447.3	1.178 ± 0.030	0.905	+0.130 ± 0.020
1324.2	1013	1.395 ± 0.096	1.066	+0.225 ± 0.047

IV. DISCUSSION

Since the Coulomb excitation is via the E2 mode and the ground states of the Ag-isotopes have $J^\pi = 1/2^-$, the spins and partities of all the excited states are restricted either to $3/2^-$ or $5/2^-$. Our angular distribution results fully support the reported [33, 34] spin values of all the excited levels as shown in Figs. 2 and 3. The mixing ratios in the present work are, in general, in agreement with the values obtained by Robinson et al. [15]. They, however, differ significantly from some of the values given in literature [33, 34]. A comparison of the mixing ratios with previous values is shown in Table 5. The δ value for the 391 keV transition in ^{109}Ag is, however, the new value extracted from the present angular distribution data.

There is a general agreement of our B(E2) values with the values given by Robinson et al. [15] for both isotopes except that the present B(E2) for the excited level at 1464.7 keV of ^{107}Ag is much larger in comparison with the erlier reported value [15]. The B(E2) values reported by Black and Gruhle [13] for the $3/2_1^-$ and $5/2_1^-$ levels in both isotopes are also in good agreement, but the values

Table 3

Summary of the level properties of ^{107}Ag

Level (keV)	$E\gamma$ (keV)	$I\gamma$ (%)	B(E2)↓ ($e^2 cm^4 \times 10^{-50}$)	$\frac{B(E2)\downarrow}{B(E2)_{s.p.}}$	δ	$B(M1) \times 10^{-2}$ $(e\hbar/2MC)^2$
324.8	324.8	—	9.85 ± 0.95	32.64 ± 3.15	−0.171 ± 0.089	24.8 ± 4.2
423.1	423.1	96.1 ± 1.3	9.37 ± 0.97	31.05 ± 3.21	—	—
	98.2	3.9 ± 0.2	0.77 ± 0.23	2.55 ± 0.76	−0.045 ± 0.014	4.0 ± 1.5
786.5	786.5	61.2 ± 1.4	0.145 ± 0.020	0.48 ± 0.07	−0.072 ± 0.019	12.09 ± 3.45
	461.9	31.3 ± 1.3	0.50 ± 0.70	1.65 ± 2.32	−0.049 ± 0.068	$31.0^{+39.8}_{-18.8}$
	365.1	7.5 ± 0.9	—	—	—	—
949.7	949.7	13.5 ± 0.14	0.733 ± 0.080	2.43 ± 0.27	—	—
	624.9	37.6 ± 1.2	1.52 ± 0.22	5.04 ± 0.73	−0.32 ± 0.06	4.1 ± 1.3
	526.5	46.9 ± 1.2	2.02 ± 0.65	6.70 ± 2.15	−0.21 ± 0.09	9.0 ± 2.9
1464.7	1464.7*	—	1.80 ± 0.14/	5.80 ± 0.5/	—	—
	1139.9	—	—	—	−0.043 ± 0.013	—
	1042*	—	—	—	—	—

* Not observed

Table 4

Summary of the level properties of ^{109}Ag

Level (keV)	$E\gamma$ (keV)	$I\gamma$ (%)	B(E2)↓ ($e^2 cm^4 \times 10^{-50}$)	$\frac{B(E2)\downarrow}{B(E2)_{s.p.}}$	δ	$B(M1) \times 10^{-2}$ $(e\hbar/2MC)^2$
311.3	311.3	—	10.95 ± 0.90	35.40 ± 2.91	−0.211 ± 0.024	16.50 ± 2.37
415.1	415.1	94.2 ± 1.2	10.90 ± 0.93	35.20 ± 3.00	—	—
	103.5	5.8 ± 0.2	1.67 ± 1.09	5.40 ± 3.52	−0.049 ± 0.020	5.2 ± 2.5
702	702	83.4 ± 1.3	0.05 ± 0.01	0.16 ± 0.03	−0.095 ± 0.022	1.63 ± 0.62
	391	16.6 ± 1.0	3.93 ± 1.62	12.71 ± 5.24	−0.53 ± 0.20	1.5 ± 1.0
862.5	862.5	10.0 ± 1.3	0.59 ± 0.05	1.91 ± 0.16	—	—
	551.1	40.0 ± 1.2	1.64 ± 0.30	5.04 ± 0.95	−0.283 ± 0.076	4.35 ± 1.80
	447.3	50.0 ± 1.2	2.18 ± 0.40	5.60 ± 1.26	−0.17 ± 0.04	10.68 ± 3.10
1424.2	1324.2*	13†	0.63 ± 0.07	2.04 ± 0.23	—	—
	1012.9	81†	0.016 ± 0.004	0.052 ± 0.013	−0.033 ± 0.012	10.5 ± 4.6
	909*	6†	—	—	—	—

* Not observed
† from ref. 32.

Table 5

Comparison of the mixing ratios (E2/M1) with the previously reported results for the transitions in ^{107,109}Ag.

$E\gamma$ (keV	Mixing ratios (δ)		
	Present	Robinson et al. [14]	Others [33, 34]
		^{107}Ag	
98	-0.035 ± 0.014	-0.059 ± 0.018	—
324.8	-0.171 ± 0.089	-0.189 ± 0.014	-0.21 ± 0.01
462	-0.049 ± 0.068	-0.01 ± 0.08	—
526.5	-0.208 ± 0.092	-0.24 ± 0.03	$-0.17^{+0.07}_{-0.10}$
624.9	-0.318 ± 0.062	-0.28 ± 0.02	-0.09 ± 0.06
786.5	-0.072 ± 0.011	-0.057 ± 0.010	-0.3 or -1.4
1140	-0.043 ± 0.013	-0.12 ± 0.03	—
		^{109}Ag	
103	-0.049 ± 0.020	-0.039 ± 0.017	—
311.3	-0.211 ± 0.024	-0.196 ± 0.027	-0.19 ± 0.01
391	-0.53 ± 0.20		
447.3	-0.17 ± 0.04	-0.16 ± 0.04	—
551.1	-0.283 ± 0.076	-0.28 ± 0.04	—
702	-0.095 ± 0.022	-0.09 ± 0.08	—
1013	$+0.033 \pm 0.014$	$+0.09 \pm 0.03$	—

for the higher excited levels are somewhat larger (in magnitude). The branching ratios measured in this experiment are also in reasonable agreement with literature [33, 34].

Recently Chatterjee et al. [12] have reported measurements of B(E2) up to the $5/2_2^-$ states of ^{107,109}Ag from a Coulomb excitation with 4—5.0 MeV proton energies. The proton energies used by them are quite high for a direct Coulomb excitation. At these high energies, there is expected a fair contribution (up to 50 %) from Compound nucleus formation. Surprisingly the results of Chatterjee et al. [12] for B(E2) are in good agreement with previously reported data [13, 15]. As they have not taken into account the compound nucleus contribution, this agreement seems to be fortuitous. Our results on B(E2) are obtained by using 3.7 MeV protons at which the compound nucleus formation is negligible according to our calculations.

The weak coupling model of de-Shalit [1] has been successful in explaining the properties of the first two excited odd-parity states (two in each nucleus). In this model the excited levels of odd-A nuclei are described by the

coupling of a single particle (or hole) to the adjacent doubly even core nucleus. The single particle is considered to remain in its ground state and the properties of the odd-A nucleus are attributed to the excitation of the core nucleus. The Ag isotopes have $J = 1/2^-$ ground states and may be described either as a $p_{1/2}$ proton coupled to a Pd core or as a $P_{1/2}$ proton hole coupled to a Cd core. The first $3/2^-$, $5/2^-$ doublet in the two nuclei is then described as the coupling of the single particle (or hole) to the first 2^+ excited state of the core nucleus. According to the core excitation model, the B(E2) for the transitions to the ground state from each member of the multiplet should be the same as the B(E2) for the corresponding transition in the associated core nucleus. In the present investigations, the values of B(E2) for the $3/2 \to 1/2$ and $5/2 \to 1/2$ transitions are nearly equal, and are found similar to the B(E2; $2_1 \to 0$) of the even mass core [37, 38].

The 786.5 and 949.7 keV states in ^{107}Ag and the analogous states at 702 and 862.5 keV in ^{109}Ag are attributed to the coupling of the odd $P_{1/2}$ proton to the second 2^+ state of the core [15]. Also from comparison of the shapes and magnitudes of the differential cross sections for scattering in the neighbouring even-mass nuclei, Ford et al. [6] have suggested that the 786.5 and 949.7 keV states of ^{107}Ag, and the analogous states at 702 and 862.5 keV of ^{109}Ag arise from the coupling of the odd $P_{1/2}$ proton with the second 2^+ core state. But the second doublet has not been explained by the simple core excitation model since the $3/2_2^-$ and the $5/2_2^-$ states violate the core excitation intensity rule.

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REFERENCES

[1] de-Shalit, A.: Phys. Rev., *122* (1961), 1530.
[2] McGowan, F. K., Stelson, P. H.: Phys. Rev., *99* (1955), 127.
[3] McGowan, F. K., Stelson, P. H.: Phys. Rev., *109* (1958), 901.
[4] Ford, J. L. C., et al., Stelson, P. H.: Phys. Rev., *158* (1967), 1194.
[5] Paar, V.: Nucl. Phys., *A211* (1973), 29.
[6] Ford, J. L. C., et al.: Phys. Rev., *158* (1967), 1194; Nucl. Phys., *A142* (1970), 525.
[7] Stewart, W. M.: Phys. Rev., *171* (1962), 1316.
[8] Crut, M., et al.: Nucl. Phys., *16* (1960), 655.
[9] Fagg, L. W., et al.: Phys. Rev., *100* (1955), 1299.
[10] Temmer, G. M., Hyydenberg, M. P.: Phys. Rev., *104* (1956), 967.
[11] Alder, K., et al.: Rev. Mod. Phys., *28* (1956), 432.
[12] Chatterjee, M. B., et al.: Acta Phys. Slovaca, *33* (1983), 65.
[13] Black, J. L., Gruhle, W.: Nucl. Phys., *A93* (1967), 1.

[14] Robinson, R. L., et al.: Nucl. Phys., *A123* (1969), 193.
[15] Robinson, R. L., et al.: Nucl. Phys., *A150* (1970), 225.
[16] Throop, M. J., et al.: Phys. Lett., *41B* (1972), 585.
[17] Cottrell, C. W.: Nucl. Phys., *A204* (1973), 161.
[18] Erokhina, K. I., et al.: Bull. Acad. Sci. USSR (Phys. Ser). *38* (1974), P102.
[19] Milner, T. R., Takeda, M.: Nucl. Phys., *A221* (1974), 392.
[20] Lark, N. L., et al.: Nucl. Phys., *35* (1962), 582.
[21] Graeffe, G., Gordon, G. E.: Nucl. Phys., *A107* (1967), 67.
[22] Berzins, G., et al.: Nucl. Phys., *A114* (1968), 512.
[23] Schick, W. C., et al.: Nucl. Phys. *A128* (1969), 353.
[24] Burmistrova, V. R., et al.: Bull. Acad. Sci. USSR (Phys. Ser.) *32* (1969), 210.
[25] Bashandy, E.: Z. Phys., *236* (1970), 130.
[26] Brenner, D. S., Perlman, M. L.: Nucl. Phys., *A181* (1972), 207.
[27] Jain, H. C., et al.: Nucl. Phys., *A178* (1972), 437.
[28] Paradellis, T., Kalfas, C. A.: Z. Phys., *271* (1974), 79.
[29] Bosch, H. C., et al.: Can. J. Phys., *55* (1977), 175.
[30] Singh, K. P., et al.: Phys. Rev., *C31* (1985), 79.
[31] Singh, K. P., et al.: Can. J. Phys., *63* (1985), 432.
[32] Govil, I. M., Hans, H. S.: Proc. Indian Acad. Sci. (Engg. Sci.) *3* (1980), 237.
[33] Bertrand, F. E., Horen, D. H.: Nucl. Data Sheets *34* (1981), 643.
[34] Bertrand, F. E.: Nucl. Data Sheets, *23* (1978), 229.
[35] Sheldon, E., Rogers, V. C.: Comput. Phys. Commun., *6* (1973), 99.
[36] Krane, K. S., Steffen, R. M.: Phys. Rev., *C4* (1971), 1419.
[37] Stelson, P. H., Grodzins, L.: Nucl. Data, *A1* (1965), 21.
[38] Robinson, R. L., et al.: Nucl. Phys., *A124* (1969), 553.

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ИССЛЕДОВАНИЕ УРОВНЕЙ В ЯДРАХ ^{107}Ag И ^{109}Ag НА ОСНОВЕ ИЗМЕРЕНИЙ КУЛОНОВСКОГО ВОЗБУЖДЕНИЯ

Низколежащие уровни изотопов в природном серебре, имеющие отрицательную четность, подвергались кулоновскому возбуждению при помощи протонов с энергиями из интервала 3,0—4,2 МэВ. В каждом из изотопов ^{107}Ag и ^{109}Ag были возбуждены по пять уровней вплоть до энергий возбуждения 1464,7 кэВ и 1324,2 кэВ соответственно. Гамма-лучи, снимающие возбуждение, наблюдались при помощи Ge(Li) детектора высокого разрешения объёмом 50 см^3. Впервые использовались низкоэнергетические протоны для кулоновского возбуждения уровней при энергии 1464,7 кэВ в ряде ^{107}Ag и уровней при энергии 1324,2 кэВ в ядре ^{109}Ag. Определены уровни энергии, относительные вероятности распада, коэффициенты мультипольного смешивания и вероятности переходов B(E2) и B(M1). Проведено сравнение экспериментального выхода гамма-лучей для толстой мишени в случае различных переходов с теоретическими вкладами от кулоновского возбуждения и образования составного ядра. Кроме того, результаты сравниваются с данными, опубликованными в настоящее время в научной литературе.