COULOMB EXCITATION OF BROMINE ISOTOPES WITH PROTONS

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The $B(E2)$ values of the 217.3, 261.4, 306.4, 397.2, 522.8, 606.2 and 761.7 keV states of ^{79}Br and the 275.9, 538.2, 566.2, 650.0, 767.1, 828.5 and 836.5 keV states of ^{81}Br have been measured from Coulomb excitation with 2.5 MeV protons by observing the de-excited gamma-rays with a high resolution Ge(Li) detector. The low-energy protons have been used for the first time to Coulomb — excite the levels of bromine isotopes. The properties of the excited states of these nuclei have been discussed and compared with the results reported so far in the literature.

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1. *Introduction*

The Coulomb excitation technique has been proved to be a very good method to study the low-lying levels of the nuclei. This kind of study has provided a considerable amount of information on the energies, spins and transition moments of the low-lying excited states of the nuclei. The properties of the excited levels of ^{79}Br and ^{81}Br have been studied by various experimentalists and theoreticians. The experimental investigations have been carried out mainly by Coulomb excitation [1–6], radioactive decay [7–13] and the neutron inelastic scattering [14]. The theoretical studies of the energy levels of Br isotopes have been attempted using the weak and intermediate coupling models [2, 15–18]. It is also worth to re-investigate the Coulomb excitation of bromine nuclei with low-energy protons by using high resolution detector for detecting the de-excited gamma-rays. The possibility of multiple Coulomb excitation and nuclear scattering with the protons of energies much below the Coulomb barrier is negligible [19, 20], hence the $B(E2)$ of the excited states can be extracted from the first order perturbation theory of Alder et al. [21].

The survey of the available literature reveals that the transition probabilities of both

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the bromine isotopes have been measured in a few experimental studies and proton as a projectile has not been used so far to obtain electromagnetic properties of these nuclei. Hence in the present work, we report some of the results on reduced transition probabilities and other level properties obtained from the recent experiment conducted by us. We have Coulomb excited seven levels in each of the bromine isotopes using proton as projectile.

2. *Experiment*

The present experiment was carried out at Chandigarh Variable Energy Cyclotron, Chandigarh, India [22, 23]. Natural, thick target of KBr (99.9 percent) was bombarded with protons to produce sources of excited levels of ^{79}Br and ^{81}Br. The target was inclined at 45° with respect to the incident beam. The de-excited gamma-rays were detected by a Ge(Li) detector, which was placed at an angle of 55° to the direction of the beam in order to minimize the angular distribution effects. The resolution of the 50 cc Ge(Li) detector was 2.0 keV for 1.33 MeV line of ^{60}Co. Since the target was thick enough to the incident projectiles, the target chamber served as a Faraday cup for beam integration. The target current was integrated in a digital current integrator (ORTEC 439). The other experimental details are given elsewhere [26, 27].

The absolute efficiency of the Ge(Li) detector was measured with a set of standard calibrated gamma-ray sources (^{22}Na, ^{137}Cs, ^{60}Co, ^{57}Co, ^{54}Mn, ^{133}Ba, ^{152}Eu) obtained from New England Nuclear, U.K. The measurements for efficiency were made keeping the geometry same as used in the Coulomb excitation experiment.

3. *Experimental results*

Natural bromine contains two odd-mass nuclei. From the Coulomb excitation with protons, the de-excited gamma-rays from ^{79}Br and ^{81}Br have been identified. A typical pulse-height spectrum obtained with 2.5 MeV protons is shown in Fig. 1. The gamma-rays at 136, 208.8 217.3, 238.9, 261.4, 299.8, 306.4, 388.9, 397.2, 522.8, 544.4, 606.4 and 761.7 keV were assigned to the de-excitation of levels of ^{79}Br where as the lines at 275.9, 290.3, 491.2, 538.2, 552.6, 560.6, 566.2, 650, 767.1, 828.5 and 836.5 keV were identified to be associated with the transitions of nuclear levels of ^{81}Br. Our measured values of the gamma-ray energies are in good agreement with those reported in literature [24, 25]. A special care was taken to identify and separate all lines of interest from those belonging either to the background or the contaminants in the target. It was found that the unwanted gamma--rays did not interfere with those belonging to bromine isotopes. The level schemes for ^{79}Br and ^{81}Br are shown in Fig. 2 and Fig. 3, respectively.

The thick-target gamma-ray yields measured for various transitions from the total charge collected and the area under the peak were corrected for detector efficiency, gamma--ray absorption in the target and the target chamber, internal conversion and the cascade transitions feeding the level of interest from the higher levels. The integrated charge was corrected for the dead time of the electronic set-up. The measured yields were then compared with those obtained by integrating the theoretical excitation function along the path of

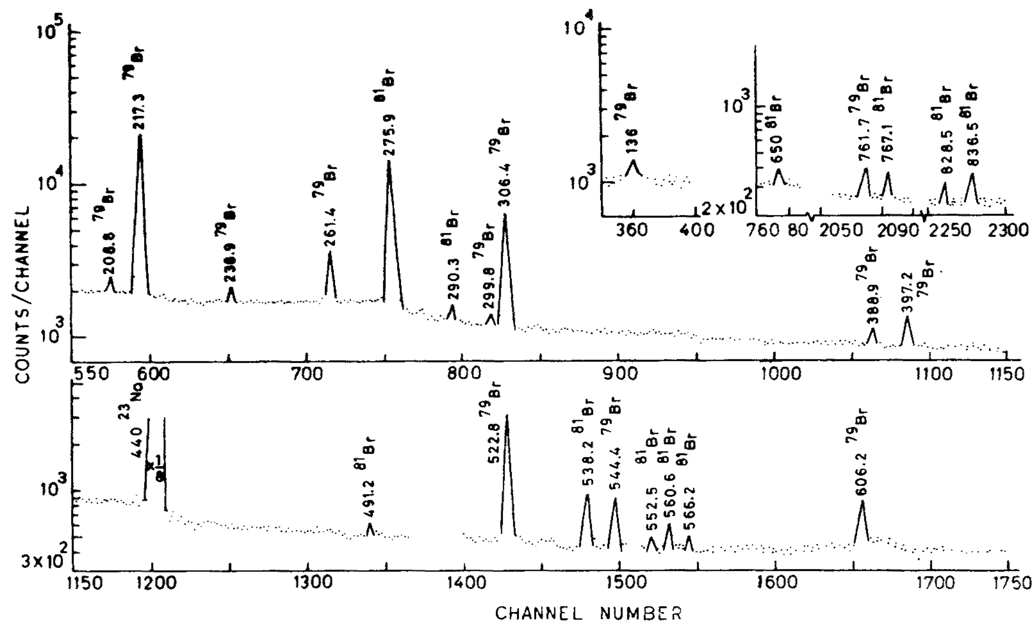

Fig. 1. Relevant portions of the gamma-ray spectrum from the bombardment of natural bromine target with 2.5 MeV protons

TABLE I

Summary of branching ratios and reduced transition probabilities for ^{79}Br levels

Level energy (keV)	Transition (keV)	Branching ratio (%)	$B(E2)\uparrow$ (e^2 cm$^4 \times 10^{-50}$)
217.3	217.3 → 0	100	2.60 ± 0.22
261.4	261.4 → 0	100	0.40 ± 0.04
306.4	306.4 → 0	100	1.15 ± 0.20
397.2	397.2 → 0	92 ± 3	0.32 ± 0.03
	397.2 → 261.4	8 ± 3	—
522.8	522.8 → 0	90 ± 1	8.8 ± 0.8
	522.8 → 217.3	10 ± 1	—
606.2	606.2 → 0	60 ± 4	1.7 ± 0.5
	606.2 → 217.3	15 ± 2	—
	606.2 → 306.4	13 ± 2	—
	606.2 → 397.2	12 ± 2	—
761.7	761.7 → 0	35 ± 2	11.4 ± 1.0
	761.7 → 217.3	58 ± 3	—
	761.7 → 522.8	7 ± 1	—

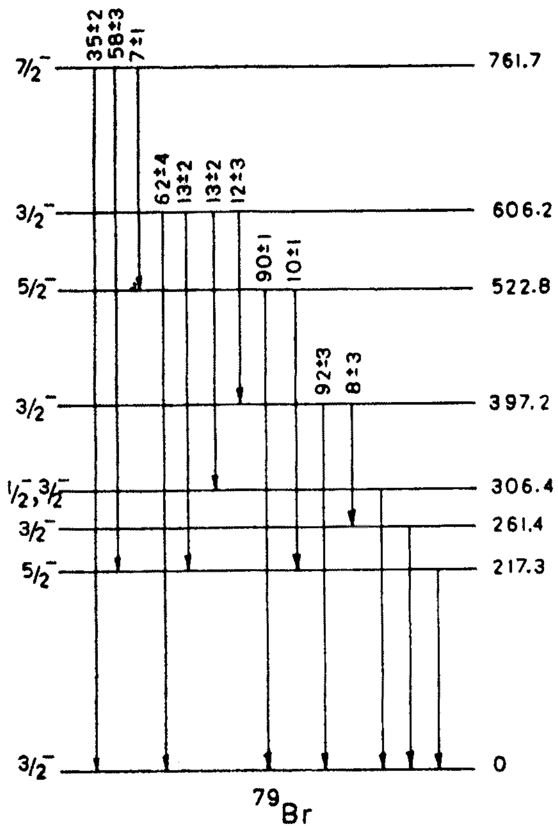

Fig. 2

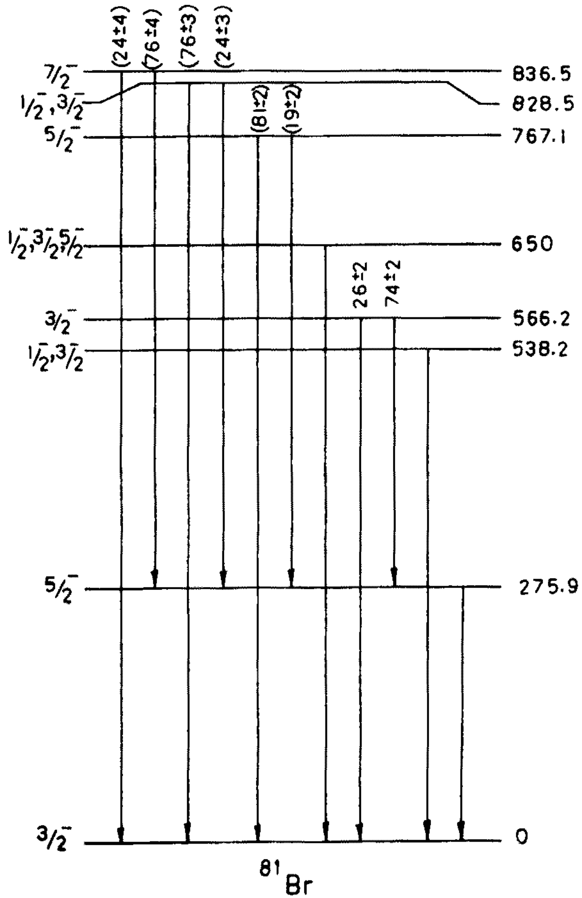

Fig. 3

Fig. 2. The level scheme of low-lying energy level of ^{79}Br

Fig. 3. The level scheme of low-lying energy levels of ^{81}Br

the proton in the target as described by Alder et al. [21]. The result of such calculation is given by

$$Y = \sigma(E_0)\frac{NE_0}{(dE/dx)_0}\left(\frac{\delta E_\lambda}{E_0}\right),$$

where Y is the fraction of the incoming particles which produce the nuclear excitation; N the density of target atom; $\sigma(E_0)$ the theoretical Coulomb excitation total cross-section; E_0 the maximum projectile energy; $(dE/dX)_0$ the atomic stopping power and $\delta(E_\lambda/E_0)$ the effective target thickness [21]. Since the cross section $\sigma(E_0)$ is directly proportional to the partial reduced upward transition probability, $\varepsilon B(E2)\uparrow$, so the latter parameter was extracted from the comparison of theoretical and experimental yields. The branching ratios shown in Fig. 2 and Fig. 3 are measured in the present work (Tables I and II).

TABLE II

Summary of branching ratios and reduced transition probabilities for ^{81}Br levels

Level energy (keV)	Transition (keV)	Branching ratio (%)	$B(E2)\uparrow$ (e^2 cm$^4\times10^{-50}$)
275.9	275.9 → 0	100	5.03±0.25
538.2	538.2 → 0	100	0.85±0.05
566.2	566.2 → 0	26±2	0.44±0.03
	566.2 → 275.9	74±2	—
650.0	650 → 0	100	0.23±0.02
767.1	767.1 → 0	81±2	3.40±0.23
	767.1 → 275.9	19±2	—
828.5	828.5 → 0	76±3	1.03±0.12
	828.5 → 275.9	24±3	—
836.5	836.5 → 0	24±4	5.8 ±0.5
	836.5 → 275.9	76±4	—

TABLE III

Comparison of $B(E2)\uparrow$ values with the previous Coulomb excitation studies of ^{79}Br

Level energy (keV)	Spin-parity[a) J^π	Measured $B(E2)\uparrow$ (e^2 cm$^4\times10^{-50}$)		
		Robinson et al. [2]	Andreev et al. [3]	Present work
217.3	5/2⁻	3.95±0.33	< 2.0	2.60±0.22
261.4	3/2⁻	0.70±0.06	0.46±0.15	0.40±0.04
306.4	1/2⁻, 3/2⁻	2.11±0.18	1.1±0.2	1.15±0.20
397.2	3/2⁻	0.33±0.05	< 0.2	0.32±0.03
522.8	5/2⁻	9.5 ±0.9	9.6±1.9	8.8 ±0.8
606.2	3/2⁻	1.52±0.23	1.8±0.5	1.7 ±0.5
761.7	7/2⁻	12.8±2.2	12±3	11.4 ±1.0

a) Ref. [24, 28].

TABLE IV

Comparison of $B(E2)\uparrow$ values with the previous Coulomb excitation studies of ^{81}Br

Level energy (keV)	Spin-parity[b] J^π	Measured $B(E2)$ ($e^2\,cm^4 \times 10^{-50}$)		
		Andreev et al. [3]	Robinson et al. [5]	Present work
275.9	5/2⁻	4.9±1.0	5.14±0.27	5.03±0.25
538.2	1/2⁻, 3/2⁻	—	0.85±0.05	0.85±0.05
566.2	3/2⁻	3.1±0.7	0.25±0.02	0.44±0.03
650.0	1/2⁻, 3/2⁻	—	0.224±0.013	0.23±0.02
767.1	5/2⁻	4±1	3.01±0.16	3.40±0.23
828.5	1/2⁻, 3/2⁻	—	0.87±0.10	1.03±0.12
836.5	7/2⁻	5.0±1.7	5.5±0.4	5.8±0.5
1322.7	*J*	—	1.23±0.16	—

[b] Ref. [25, 28].

TABLE V

Mixing ratios obtained from previously measured lifetimes and present $B(E2)$ values for the levels of ^{79}Br

Level energy (keV)	Transition (keV)	Half-life[b] (ps)	$J_f \to J_i$	Mixing ratios
217.3	217.3 → *gs*	34.0	5/2⁻ → 3/2⁻	0.08
261.4	261.4 → *gs*	0.13	3/2⁻ → 3/2⁻	0.0033
306.4	306.4 → *gs*	8.3	1/2⁻ → 3/2⁻	0.094
			3/2⁻ → 3/2⁻	0.067
397.2	397.2 → *gs*	13.0	3/2⁻ → 3/2⁻	0.084
522.8	522.8 → *gs*	1.3	5/2⁻ → 3/2⁻	0.23
606.2	606.2 → *gs*	2.0	3/2⁻ → 3/2⁻	0.22

[b] Ref. [24, 28].

TABLE VI

Properties of the excited states of ^{79}Br

Level energy (keV)	J^π	$B(E2)\downarrow$ $e^2\,cm^4 \times 10^{-50}$	$\frac{B(E2)\downarrow}{B(E2)_{S.P.}}$	Mixing ratio δ	$\frac{B(M1) \times 10^2}{(e\hbar/2MC)^2}$
217.3	5/2⁻	1.73±0.15	8.3 ±0.7	0.08	8.9
261.4	3/2⁻	0.40±0.04	1.92±0.19	0.0033	—
306.4	1/2⁻	2.30±0.4	11.1 ±2.0	0.94	17.0
	3/2⁻	1.15±0.2	5.5 ±1.5	0.067	
397.2	3/2⁻	0.32±0.03	1.54±0.15	0.084	5.0
522.8	5/2⁻	5.9 ±0.5	28.4 ±2.4	0.23	21.3
606.2	3/2⁻	1.7 ±0.5	8.2 ±2.4	0.22	9.0
761.7	7/2⁻	6.57±0.50	27.3 ±2.4	—	—

TABLE VII

Properties of the excited states of ^{81}Br

Level energy (keV)	J^{π}	$B(E2)\downarrow$ e^2 cm^4 $\times 10^{-50}$	$\frac{B(E2)\downarrow}{B(E2)_{S.P.}}$	Mixing ratio δ*	$\frac{B(M1)\times 10^2}{(e\hbar/2MC)^2}$	$T_{1/2}$ (ps)
275.9	5/2⁻	3.35±0.17	16.1±0.82	+0.085±0.022	$24.7^{+20.2}_{-9.1}$	$7.6^{+4.4}_{-3.4}$
538.2	1/2⁻	0.70±0.10	8.2 ±0.5	±0.090±0.011	$42.4^{+12.6}_{-8.8}$	0.61±0.14
	3/2⁻	0.85±0.05	4.1 ±0.2	±0.064±0.008		
566.2	3/2⁻	0.44±0.03	2.12±0.14	—	—	—
650.0	1/2⁻	0.46±0.04	2.22±0.15	$\pm 0.19^{+0.19}_{-0.06}$	1–8	3.8^{+10}_{-2}
	3/2⁻	0.23±0.036	1.11±0.08	$\pm 0.13^{+0.13}_{-0.04}$		
767.1	5/2⁻	2.27±0.15	10.9±0.7	0.19 ±0.03	$25.8^{+10.6}_{-6.5}$	0.34±0.10
828.5	1/2⁻	2.06±0.24	9.90±1.15	±0.21 ±0.04	23^{+11}_{-7}	0.31±0.8
	3/2⁻	1.03±0.12	4.95±0.58	±0.15 ±0.03		
836.5	7/2⁻	2.90±0.25	13.95±1.20	—	—	4.9 ±0.5

* Ref. [5].

The present results on $B(E2)$ along with the previous Coulomb excitation results [2, 3, 5] are given in Tables III and IV. In calculating the δ values for the 217.3, 261.4, 306.4, 397.2, 522.8 and 606.4 keV transitions in ^{79}Br, the previously measured lifetimes [24] and the values of $B(E2)$ found in the present work were used. These results are presented in Table V. The properties of the excited states of ^{79}Br and ^{81}Br are given in Tables VI and VII, respectively.

4. *Discussion*

Since the Coulomb excitation is via the $E2$ mode and the ground states of bromine isotopes have $J^{\pi} = 3/2^-$, the spins and parities of all the excited states are restricted to $1/2^-$, $3/2^-$, $5/2^-$ or $7/2^-$. The spins shown in Table III and IV are taken from the existing literature [24, 25].

There is a general agreement of our values with the values of other authors [2, 3, 5] for both the isotopes, however, the $B(E2)$ values for 217.3 and 261.4 keV transitions in ^{79}Br differ from those determined by Robinson et al. [2]. The reduced $M1$ transition probabilities (Table VI) for five transitions are calculated by us for the first time using the present $B(E2)$ and the mixing ratio obtained from the half lives reported in the literature [24, 28]. The column 4 of Table VI shows the comparison of $B(E2)$ values with the single particle estimates. From this comparison it has been found that the levels at 522.8 and 761.7 keV are more collective in nature.

The reduced $E2$ transition probabilities for all the levels in ^{81}Br are comparable with the previous results [3,5] except the level at 566.2 keV. Our value for this level is larger than that of Robinson et al. [5]. The level at 1322.7 keV [5] of ^{81}Br has not been excited in the present experiment. The Table VII shows the electro-magnetic properties for the levels of ^{81}Br. The comparison with single particle estimates shows that the levels at 275.9, 767.1, 828.5 (for spin $1/2^-$) and 836.5 keV are more collective in nature while other levels show the weak $E2$ enhancement. The $B(M1)$ and $T_{1/2}$ values are given in the columns 6 and 7 of the Table VII.

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