Coulomb Excitation of Bromine and Rhenium

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(Received October 2, 1956)

Separated isotopes of bromine and rhenium have been studied by means of Coulomb excitation with 2- to 4.2-Mev protons and alpha particles. Gamma rays were observed with a NaI crystal spectrometer at the following energies: Br^{79}, 219 kev; Br^{81}, 278 kev; Re^{185}, 126, 160, and 286 kev; Re^{187}, 135, 168, and 303 kev. Probable level schemes are given which are based on coincidence measurements and, in some cases, on excitation curves. The results from data on Ta^{181} taken in the course of this study are also included. The reduced transition probabilities for excitation of all relevant nuclear levels have been measured. In the case of Ta and the Re isotopes the cascade to crossover intensity ratio in the decay of the second excited state has also been measured.

INTRODUCTION

COULOMB excitation of nuclei has proven to be particularly useful in the study of various aspects of the unified model of Bohr and Mottelson.[1] While the many successes of this model have been most encouraging, continued investigations are needed to determine the extent to which it applies. In the present work, results of interest to this theory are reported for isotopes of bromine and rhenium.

EXPERIMENTAL TECHNIQUES

Proton and alpha particle beams from the Naval Research Laboratory 5-Mv Van de Graaff accelerator[2] were used to bombard isotopically enriched thick targets. The targets were made by compressing powders into depressions in disks of pure tin. The bromine targets were in the form of KBr and the rhenium targets were of pure metal. The isotopic enrichments were as follows: 86.98% Br^{79}(13.02% Br^{81}), 96.81% Br^{81}(3.19% Br^{79}), 85.38% Re^{185}(14.62% Re^{187}), and 98.22% Re^{187}(1.78% Re^{185}).* Targets were placed at 45 degrees to the beam and the resulting gamma rays were observed from the front face of the target at 90 degrees in order to avoid the absorption due to the thickness of the target and target backing.

The scintillation spectrometer consisted of $1\frac{3}{4}$-inch diameter by 2-inch thick commercially potted NaI(Tl) crystal and an RCA 6342 photomultiplier tube. Pulse-height spectra were obtained with a 20-channel pulse-height analyzer. Radioactive sources of Ba^{133}, Sb^{125}, and Na^{22} were used for energy calibration. Gamma-ray energies are accurate to approximately $\pm 1\%$. Coincidence spectra were observed with an arrangement consisting of two NaI(Tl) scintillation counters separated by a 30-degree lead wedge which prevented coincidences due to Compton scattering.

Absolute gamma-ray efficiencies were determined by two methods. In the first, the efficiency was measured directly as a function of gamma-ray energy by using calibrated radioactive sources of I^{131} and Na^{22}. In the second, radioactive sources were used to determine the photopeak-to-total area ratio as a function of gamma-ray energy and to measure the gamma ray absorption of materials between the target and the NaI crystal container. The absorption measurements agreed with calculations.[3] However, the absorption due to the aluminum container and the MgO powder surrounding the crystal could only be calculated. These results were

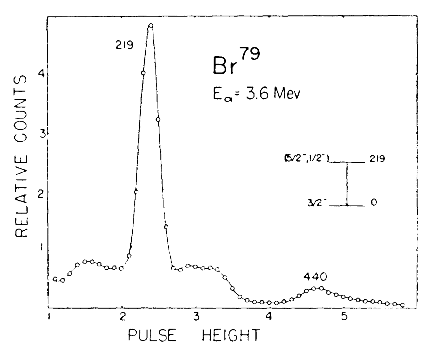

FIG. 1. Pulse-height spectrum from 3.6-Mev alpha-particle bombardment of Br^{79}.

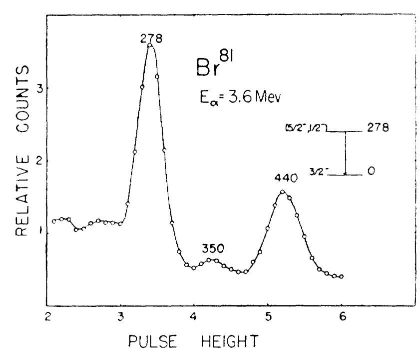

FIG. 2. Pulse-height spectrum from 3.6-Mev alpha-particle bombardment of Br^{81}.

[1] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat-fys. Medd. **27**, No. 16 (1953).
[2] Dunning, Bondelid, Fagg, Kennedy, and Wolicki, Naval Research Laboratory Progress Report, May 1955 (unpublished), p. 8.
* Enriched isotopes were obtained from Oak Ridge National Laboratory.
[3] Absorption coefficients were taken from G. R. White, National Bureau of Standards Report No. 1003 (unpublished).

TABLE I. Gamma-ray energies and reduced transition probabilities observed in the Coulomb excitation of Br^{79} and Br^{81}.

Isotope	E_γ (kev)	$\frac{B(E2)_{ex}}{e^2(\alpha_T+1)}$ (cm⁴)
Br^{79}	219	0.023×10^{-48}
Br^{81}	278	0.029×10^{-48}

then combined with a calculated total efficiency of the NaI(Tl) crystal for point isotropic sources[4] to give the desired absolute photopeak efficiency. All efficiencies obtained from these two methods were in agreement within 8%. In the case of the rhenium a target-to-crystal distance of 3.88 cm was used and a slight correction to the efficiencies should be made when gamma-ray angular distributions are known. The bromine spectra were taken at 1.77 cm and angular distribution corrections can be neglected. Furthermore, preliminary measurements showed the bromine angular distributions to be isotropic within 5%.

The internal conversion coefficients used in the rhenium and tantalum calculations were obtained from the Oak Ridge tables[5] by double interpolation. The logarithm of the internal conversion coefficient for most cases studied is a nearly linear function of atomic number for constant energy. From such curves, graphs of log α_2 and log β_1 against log E for a particular Z could be constructed. α_2 and β_1 are the electric quadrupole and magnetic dipole internal conversion coefficients, respectively. This procedure was used for the K- and L-shell coefficients; a small correction was made for the M-shell contribution.

The manner of obtaining $B_{ex}(E2)$, the reduced transition probabilities for excitation, from a given spectrum has been described in a previous article.[6] Absolute values of $B_{ex}(E2)$, excluding uncertainties in the gamma-ray internal conversion coefficients used, are considered accurate to $\pm20\%$.

RESULTS AND DISCUSSION

The spectrum resulting from alpha-particle bombardment of Br^{79} is shown in Fig. 1. Gamma rays were observed at 219 and 440 kev. The 440-kev radiation is due to inelastic scattering from a sodium impurity. Since there is a known[7] level at 263 kev in Br^{79}, an attempt was made to detect a 44-kev gamma ray, which would probably be highly converted, arising from cascade emission through a 219-kev level. No radiation of this energy was observed, and in addition, no gamma rays were found to be in coincidence with the 219-kev radiation. Furthermore, an excitation curve obtained for the 219-kev gamma ray fits a theoretical curve calculated for the excitation of an energy level at 219 kev. The spectrum also showed some evidence for the presence of a 310-kev gamma ray which can perhaps be associated with a known level in Br^{79} at 307 kev.[8] Additional evidence will be required to test this possibility. The level scheme proposed on the basis of these results is included in Fig. 1. The spins shown for the first excited state are consistent with either the single-particle or unified model. The angular distribution measurements mentioned previously do not in themselves permit a spin assignment to be made.

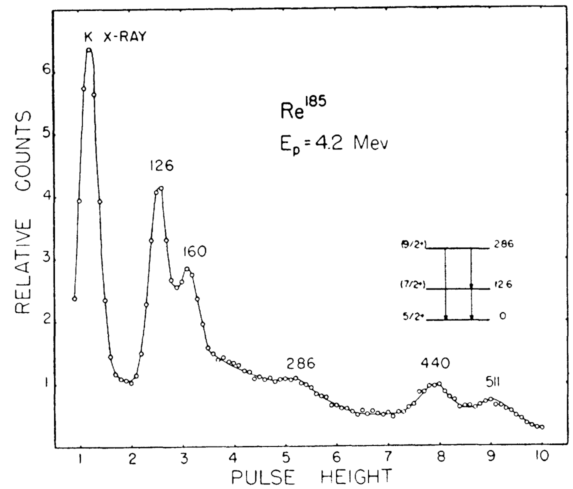

FIG. 3. Pulse-height spectrum from 4.2-Mev proton bombardment of Re^{185}.

The spectrum obtained for Br^{81} is shown in Fig. 2. Gamma rays were observed at 278, 350, and 440 kev. The 350- and 440-kev lines are probably due to oxygen and sodium impurities, respectively. The 278-kev gamma ray excitation curve was found to agree with a theoretical calculation for an excitation energy of 278 kev. No coincidences with this gamma ray were found. The level scheme included in Fig. 2 is proposed for this nucleus. These results modify those reported previously by other investigators using natural bromine.[9] The energy levels and reduced transition probabilities for excitation in the bromine isotopes are presented in Table I. The internal conversion coefficients, α_T, have not been included in the calculation of the bromine reduced transition probabilities.

Spectra from Re^{185} and Re^{187} targets bombarded by 4.2-Mev protons are shown in Figs. 3 and 4. Bremsstrahlung spectra obtained using lead targets were subtracted from all rhenium spectra. The gamma rays at 440 kev are again due to a sodium impurity and the 511-kev line is due to induced positron activity. In the case of Re^{185}, gamma rays were observed at 126, 160,

[4] Wolicki, Jastrow, and Brooks, Naval Research Laboratory Report No. 4833.
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[9] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **93**, 906 (1954).

TABLE II. Observed and derived quantities in the Coulomb excitation of Ta^{181}, Re^{185}, and RE^{187}.

Isotope	E (kev)	α_T	$B(E2)_{ex}\div e^2$ (10^{-48} cm^4)	Q_0 (10^{-24} cm^2)	Cascade / crossover	$1/\delta_{21}^2$	$\frac{B_{21}(M1)_d}{(e\hbar/2mc)^2}$	(g_K-g_R)	μ (nm)	g_K	g_R
Ta^{181}	137	1.93	1.74	6.4					2.1		
	166	1.11			1.45	5.1	0.13×10^{-48}	±0.40		{0.51 0.69	{0.91 0.28
	303	0.083	0.47	6.6							
Re^{185}	126	3.28	1.41	5.5					3.14		
	160	1.60			4.24	23.8	0.36×10^{-48}	±0.88		{1.01 1.51	{1.88 0.63
	286	0.104	0.56	5.8							
Re^{187}	135	2.66	1.28	5.2					3.17		
	168	1.30			3.99	22.4	0.34×10^{-48}	±0.86		{1.03 1.51	{1.88 0.66
	303	0.089	0.54	5.7							

and 286 kev. Coincidences between the 126- and 160-kev gamma rays were observed, indicating that the 286-kev level decays partly by cascade gamma-ray emission through the 126-kev state. A ratio of the intensity of the 160- to the 286-kev gamma ray was measured at a proton bombarding energy of 4.2 Mev. A similar situation was found for Re^{187} with gamma rays observed at 135, 168, and 303 kev. Coincidences between the 135- and 168-kev gamma rays were observed, and the ratio of intensities of the 168- and 303-kev gamma rays was also measured. The reduced transition probabilities for excitation to the first excited state were measured at a proton energy of 2 Mev and for the second excited state at 4.2 Mev. Coulomb excitation of rhenium nuclei has been reported by several other investigators.[10–13] The gamma-ray intensity measurements reported here are in agreement with these results, with the possible exception of the Re^{185} measurements reported by Davis *et al.*[13] The ratio of the Re^{185} and Re^{187} quadrupole moments obtained in the present work agrees closely with that expected from spectroscopic measurements. Measurements made on the Ta^{181} nucleus in the course of the investigation of the rhenium isotopes are summarized in Table II along with the rhenium measurements.

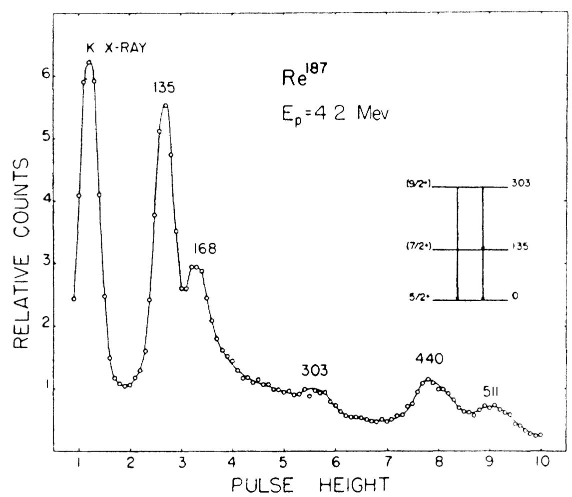

FIG. 4. Pulse-height spectrum from 4.2-Mev proton bombardment of Re^{187}.

In this table values of $B_{ex}(E2)$, the internal conversion coefficients, α_T, and quadrupole moments, Q_0, for the nuclei studied are given. Quadrupole moments have been obtained from the reduced transition probabilities by using relations of Bohr and Mottelson applying to well-deformed nuclei. Shown also are values obtained for the cascade-to-crossover gamma-ray intensity ratios and for $1/\delta_{21}^2$, where δ_{21}^2 is the ratio of the number of $E2$ quanta to the number of $M1$ quanta emitted in the decay of the second to the first excited state. δ_{21}^2 is calculated using the measured cascade-to-crossover ratio together with relations which apply to states in a rotational band. From the values of Q_0^2, δ_{21}^2 and the ground state nuclear magnetic moment, it is possible to calculate two gyromagnetic ratios g_K and g_R. The quantity g_K is associated with the intrinsic angular momentum K of the deformed nucleus and g_R with the rotational motion. The possible solutions for these quantities are shown in Table II together with the magnetic moments used. In addition, values for the quantity

$$\frac{B_{21}(M1)_d}{(e\hbar/2mc)^2}$$

are given, where $B_{21}(M1)_d$ is the reduced transition probability for magnetic dipole radiation in the cascade transition.

ACKNOWLEDGMENTS

We wish to thank Dr. H. H. Seliger of National Bureau of Standards for calibrating solutions of I^{131} and Na^{22}. We are greatly indebted to Dr. Conrad Cheek for preparing sources from these solutions.

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[13] Davis, Divatia, Moffat, and Lind, Phys. Rev. **103**, 1801 (1956).