Coulomb Excitation of Sb, Cs, and Ba

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Coulomb excitation of several nuclei in the region between $A=123$ and 137 has resulted in observation of the following gamma rays: Sb^{123}, 161 and 376 kev; Cs^{133}, 82, 163, 302, and 385 kev; Ba^{130}, 359 kev; Ba^{132}, 470 kev; Ba^{135}, 218 kev; and Ba^{137}, 281 kev. Values of reduced transition probability for excitation are given for most of the above gamma rays. In the case of Cs^{133}, absolute intensities and branching ratios are given for the gamma rays in the decay of the upper excited states. Level schemes are proposed based on coincidence studies and excitation curves.

I. INTRODUCTION

WITH the possible exception of nuclei whose mass numbers are near $A=25$,[1] 75,[2] or 105,[3–5] none of the odd-A nuclei with $A<150$ have spectra which exhibit approximately rotational properties. These nuclei, which are in general subject to intermediate coupling, have complicated spectra which are not amenable to a vibrational or rotational interpretation. It is hoped that investigation by Coulomb excitation of the odd-A isotopes of Sb, Cs (monoisotopic), and Ba reported here will add to the information necessary to understand the nuclei subject to intermediate coupling. The results of the Coulomb excitation of two of the even isotopes of barium, Ba^{130} and Ba^{132}, are also included.

II. EXPERIMENTAL TECHNIQUE

The Coulomb excitation of the nuclei investigated here was produced by bombardment with alpha particles up to 5.6 Mev in energy from the NRL large Van de Graaff generator. Targets were made by compressing the powdered materials into small depressions in planchets of stainless steel or tin. All targets were in chloride form, except for the Sb, which was in metallic form. The chloride targets were baked at 120°C for several hours in order to rid the chloride of as much water of crystallization as possible. This caused the intensity of the 350-kev gamma ray from the $O^{18}(\alpha,n)Ne^{21}$ reaction to be at least low, if not negligible, in all cases. The target planchets were mounted at a 45° angle to the beam direction so that gamma rays from the front face of the target were observed at 90 degrees to the beam. The gamma rays emerging from the target surface passed through approximately 0.0025 inch of tin, 0.050 inch of aluminum, and 0.095 inch of magnesium oxide before reaching the detecting crystal. The isotopic enrichments of the targets used were the following: 97.7% Sb^{121}; 23.31% Ba^{130}; 12.01% Ba^{132}; 67.32% Ba^{135}; 43.56% Ba^{137}; 98.04% Ba^{138}.

The gamma-ray detector was a scintillation counter consisting of a NaI(Tl) crystal, $1\frac{3}{4}$ inches in diameter by 2 inches thick, and an RCA 6342 photomultiplier. Pulse-height spectra were obtained with a 100-channel pulse-height analyzer. Ba^{133}, Sb^{125}, Na^{22}, and Cs^{137} sources were used for energy calibration. Coincidence measurements were made with an arrangement having a single-channel pulse-height analyzer in one branch and a 100-channel pulse-height analyzer in the other.

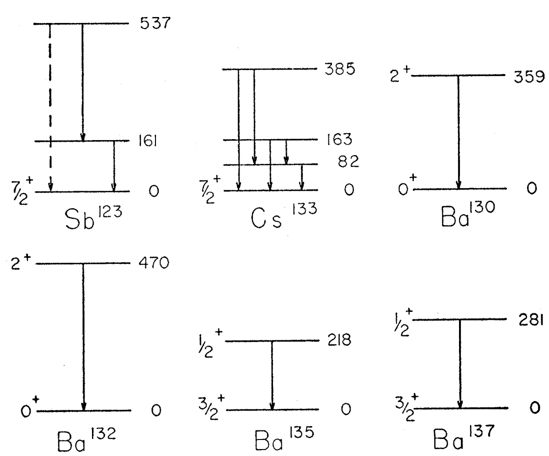

FIG. 1. Proposed energy level schemes for the nuclei studied. Energies are in kev. The broken line representing a 537-kev crossover gamma ray in Sb^{123} means that its existence is probable but has not been confirmed.

TABLE I. Values are given for the gamma-ray energies observed and for some of the corresponding reduced transition probabilities for excitation. Since the multipole mixtures are not known in the decays, the internal conversion coefficients, α_T, have not been included in the calculation of the reduced transition probabilities.

Isotope	E_γ (kev)	$\left(\frac{B(E2)_{ex}}{e^2(\alpha_T+1)}\right)\times10^{50}$ (cm⁴)
Sb^{123}	161	0.39
	376	
Cs^{133}	82	0.87
	163	
	302	
	385	
Ba^{130}	359	73
Ba^{132}	470	72
Ba^{135}	218	0.48
Ba^{137}	281	1.3

[1] Litherland, Paul, Bartholomew, and Gove, Phys. Rev. **102**, 208 (1956).
[2] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. **28**, 432 (1956).
[3] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **95**, 861 (1954).
[4] Mark, McClelland, and Goodman, Phys. Rev. **98**, 1245 (1955).
[5] Fagg, Wolicki, Bondelid, Dunning, and Snyder, Phys. Rev. **100**, 1299 (1955).

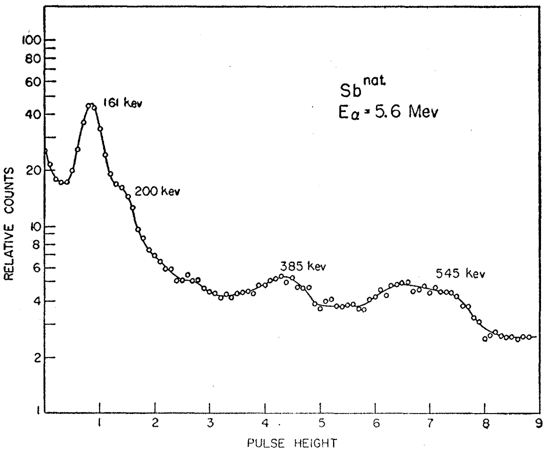

FIG. 2. Pulse-height spectrum obtained from natural Sb when bombarded with 5.6-Mev alpha particles.

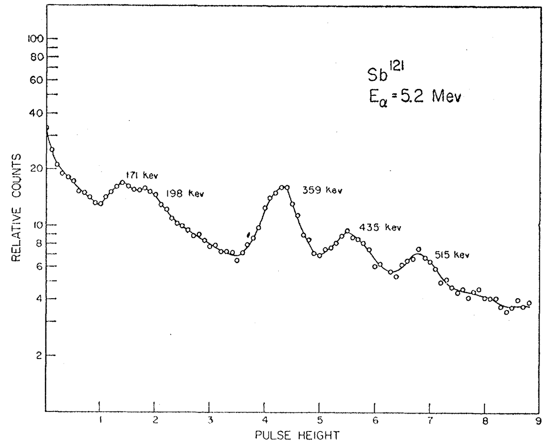

FIG. 3. Pulse-height spectrum obtained from Sb^{121} when bombarded with 5.2-Mev alpha particles.

When there was any chance of accepting false coincidences due to the Compton effect, the scintillation counters were separated by a 30° lead wedge.

The method used for obtaining the reduced transition probabilities for excitation has been described in an earlier article.[5] A vital part of the reduced transition probability measurement is the determination of the efficiency of the scintillation counter as a function of gamma-ray energy. This was done by using calculated values for the total gamma-ray absorption in NaI,[6] experimentally checked calculated values of absorption in the material between target and crystal, and experimentally determinated photopeak-to-total intensity ratios. This efficiency curve was checked at 511 kev against values of efficiency obtained using two different calibrated Na^{22} sources, and there was agreement to within 2%. Effects resulting from the angular distribution of the gamma rays produced by Coulomb excitation were estimated to be small enough to be neglected.

The gamma-ray energies were measured to an accuracy of $\pm 1.5\%$. Absolute values of $B(E2)_{ex}/e^2(\alpha_T+1)$ are considered accurate to about $\pm 25\%$.

III. RESULTS AND DISCUSSION

Most of the results obtained in this investigation are summarized in Table I. The energies of the gamma rays that were detected are given, along with the corresponding values of the reduced transition probabilities where measurement was possible. The energy level schemes proposed as a result of the study of each of the nuclei listed in Table I are given in Fig. 1.

Sb^{123}

Figure 2 shows the gamma-ray spectrum obtained from the alpha-particle bombardment of a natural metallic Sb target. Gamma rays are observed at 161 kev[7] and 200 kev, with two broad peaks centered at about 385 kev and 545 kev. Comparison of this spectrum with one similar to that given in Fig. 3, obtained from a target enriched in Sb^{121}, shows that the 161-kev radiation must come from Sb^{123}. The thick-target experimental excitation curve for the 161-kev gamma ray matches the theoretically calculated curve for the Coulomb excitation of a level at 161 kev. The natural Sb spectrum was also examined by using the coincidence arrangement mentioned in Part II. Although the coincidence counting rate was very low, the 161-kev gamma ray was found to be in coincidence with a gamma ray of 376 kev, which implies the existence of a state at 537 kev. The bombarding energy used in the coincidence experiment was about 5.3 Mev, considerably higher than the energy range over which the 161-kev excitation curve was studied. Consequently, the excitation of the 537-kev state in this energy range was low enough that the contribution due to cascade radiation from this state did not noticeably affect the shape of the 161-kev excitation curve. The 376-kev gamma ray probably contributes to the broad peak centered at 385 kev. Although crossover radiation from the 537-kev state probably contributes to the broad peak centered at 545 kev, with the spectra obtained in this experiment it was not possible to confirm this supposition. Excitation curves were impractical in this case because of the low intensity and the mixture of neighboring gamma radiation.

The fact that the radiation at about 200 kev from natural Sb (Fig. 2) appears with greater intensity in the spectrum from Sb^{121} (measured at 198 kev in Fig. 3) suggests that the 200-kev radiation might be associated with Sb^{121}. However, the thick-target excitation curve for the 200-kev gamma ray does not match the theoretically calculated curve for the Coulomb excitation of a level at 200 kev. The possibility that the

[6] E. A. Wolicki *et al.*, Naval Research Laboratory Report NRL-4833, October 5, 1956 (unpublished).

[7] A gamma ray at 160 kev has also been observed by G. M. Temmer and N. P. Heydenburg, Phys. Rev. **93**, 351 (1954).

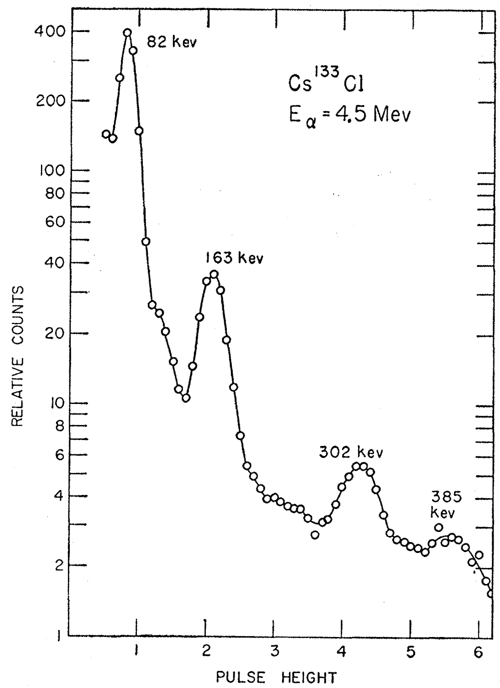

FIG. 4. Pulse-height spectrum obtained from Cs^{133}Cl when bombarded with 4.5-Mev alpha particles.

200-kev radiation is cascade radiation to a state corresponding to other gamma radiation, perhaps that at 171 kev, in the Sb^{121} spectrum was also explored. No coincidences were found. Considerable difficulty was encountered in obtaining a reliable spectrum from the Sb^{121}, because after the target material available was compressed, it cracked under bombardment. Consequently, some of the radiation represented by the five peaks marked in Fig. 3 could be due not only to a Zn contamination, but also to the stainless steel backing. There is also the possibility that a small contamination of molecular deuterium in the beam may have been present and produced nuclear reactions in the target. Nevertheless, no radiation was observed that could be conclusively attributed to the Coulomb excitaiton of Sb^{121}.

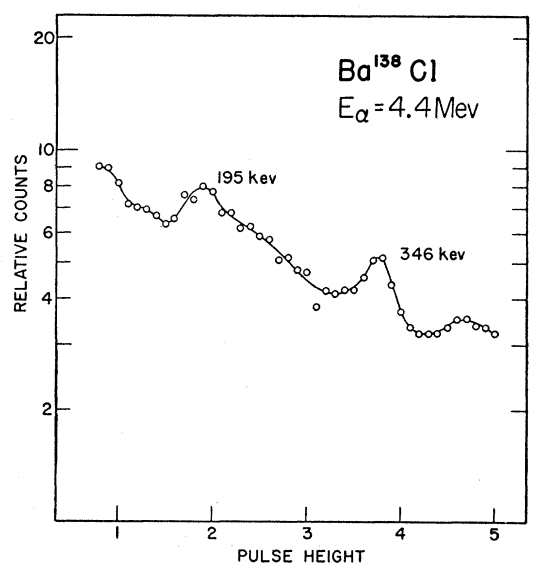

FIG. 5. Pulse-height spectrum obtained from Ba^{138}Cl when bombarded with 4.4-Mev alpha particles.

Cs^{133}

Shown in Fig. 4 is the gamma-ray spectrum obtained from the alpha-particle bombardment of a CsCl target. Gamma rays were observed at 82, 163, 302, and 385 kev.[8] In order to verify that all these gamma rays are associated with Cs, this spectrum was compared, as were all other spectra obtained from chloride targets, with that obtained from a target of Ba^{138} Cl$_2$ (enriched 98.04% in Ba^{138}), given in Fig. 5. This is a closed shell nucleus for neutrons and should not yield any gamma rays due to Coulomb excitation at the bombarding energies used in these experiments. The small peak at 195 kev is apparently due to an alpha-particle reaction in the chlorine, whereas the 346-kev peak is due to a small amount of water of crystallization. The comparison with the CsCl spectrum indicated that all four gamma rays are from Cs. The Cs spectrum was also examined using the coincidence arrangement mentioned in Part II. It was found that two gamma rays of about 80-kev energy are in coincidence, apparently resulting from the cascade from a 163-kev state through the 82-kev state. The existence of the 163-kev state is confirmed by the fact that the thick-target excitation curve for the 163-kev gamma ray matches the theoretically calculated curve for the Coulomb excitation of a level at 163 kev. Consistent also with the excitation-curve result is the fact that no gamma rays were observed in coincidence with the 163-kev gamma ray.

Furthermore, the 302-kev and 82-kev gamma rays were found to be in coincidence. This result is supported by the fact that the thick-target excitation curve for the 302-kev gamma ray matches the calculated theoretical curve for the excitation of a level at 385 kev. The resulting conclusion that the level at 385-kev decays by cascade through the 82-kev level is in agreement with studies of the Ba^{133} β decay.[9] It is felt that the above coincidence and excitation-curve results justify the level and decay scheme shown in Fig. 1 for Cs^{133}.

Only for the 82-kev level has a value of the reduced transition probability for excitation been given. Since such a measurement for the upper two levels would involve knowledge of more than one internal conversion coefficient, it was considered simpler and clearer to give only the absolute gamma-ray intensities involved

[8] Gamma rays at 81 kev and 163 kev have also been observed by G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).

[9] M. Langevin, Compt. rend. **240**, 289 (1955).

in the decay of each of these two levels, as presented in Table II. These intensities were not immediately obtainable in the case of the decay of the 163-kev level, since the 80-kev cascade radiation from the 163-kev level could not be distinguished from the radiation from the 82-kev level. Therefore, at the given bombarding energy, the intensity of the cascade radiation was obtained by subtracting from the total 80-kev intensity the amount given by the theoretical 82-kev excitation curve normalized by experimental points at the lower bombarding energies.

Ba^{130} and Ba^{132}

The spectra obtained from the alpha-particle bombardment of targets of $Ba^{130}Cl_2$ and $Ba^{132}Cl_2$ are presented in Figs. 6 and 7, indicating gamma rays at 359 kev and 470 kev, respectively. This conclusion is supported by comparison with the $Ba^{138}Cl_2$ spectrum. The thick-target excitation curves for the 359-kev and 470-kev gamma rays match the calculated theoretical curves for the excitation of levels at 359 kev and 470 kev in Ba^{130} and Ba^{132}, respectively. The 2^+ character assigned to the first excited states in Ba^{130} and Ba^{132} in Fig. 1 is based on the fact that virtually all first excited states of even-even nuclei amenable to Coulomb excitation have a 2^+ character. An attempt was also made to excite the first excited state in Ba^{134}, but its intensity was too low to be observed above the background produced by nuclear reactions in the chlorine.

TABLE II. Values of the absolute thick-target gamma-ray yields at the given bombarding energy are presented for the cascade and the crossover radiation in the decay of the 163-kev and 385-kev states in Cs^{133}, along with the corresponding cascade-to-crossover ratios.

E_α (Mev)	E_γ (kev)	(γ's/α) $\times 10^{12}$	Cascade/crossover
4.70	302	21	2.5
	385	8.6	
2.68	81	16	4.3
	163	3.7	

Ba^{130} and Ba^{132} are even-even nuclei and, as such, certain properties would be expected to conform to trends known to exist among the even isotopes of elements with even Z.[10] Namely, the first excited state energy increases and the reduced transition probability decreases as a closed shell is approached. The energies of the first excited states in Ba^{130} and Ba^{132} obviously conform to such a trend. This is further supported by the fact that the first excited state in Ba^{134} is at 604 kev known from β-decay studies.[11] Nevertheless, the values of the reduced transition probabilities given in Table I for Ba^{130} and Ba^{132} do not conform strikingly to the above-mentioned trend. However, it must be pointed out that the value of $B(E2)$ for Ba^{132} is probably the least accurate of those given in Table I because of its low intensity and the presence of the 511-kev radiation.

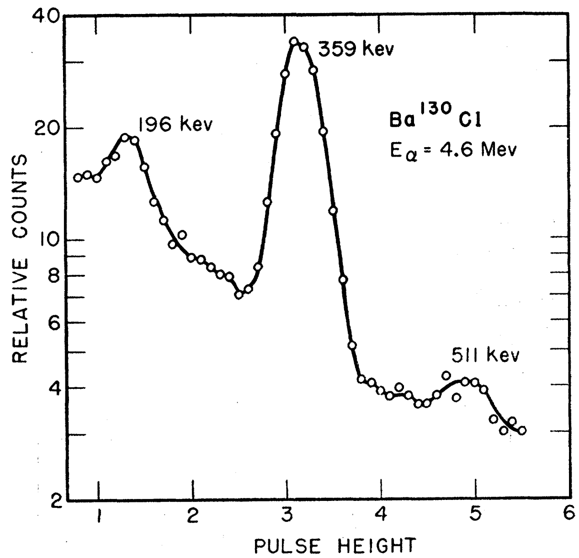

FIG. 6. Pulse-height spectrum obtained from $Ba^{130}Cl$ when bombarded with 4.6-Mev alpha particles.

Ba^{135} and Ba^{137}

In Figs. 8 and 9 are presented the spectra resulting from the alpha-particle bombardment of $Ba^{135}Cl_2$ and $Ba^{137}Cl_2$, showing the presence of gamma rays at 218 kev and 281 kev, respectively. This conclusion is evident by comparison with the $Ba^{138}Cl_2$ spectrum. Furthermore, the experimental excitation curves for the 218-kev and 281-kev gamma rays in Ba^{135} and

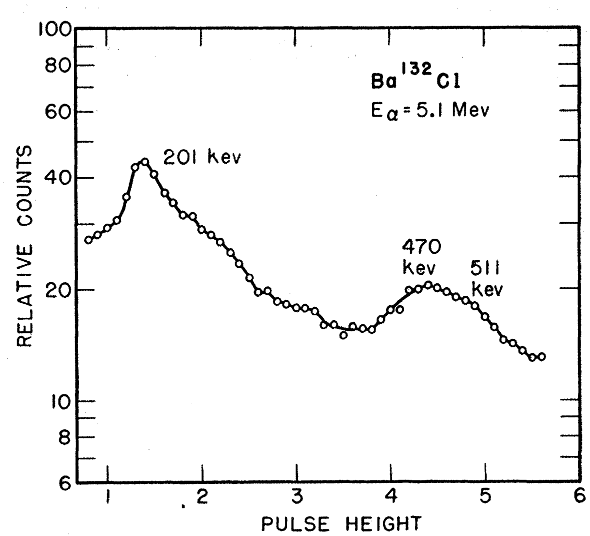

FIG. 7. Pulse-height spectrum obtained from $Ba^{132}Cl$ when bombarded with 5.1-Mev alpha particles.

[10] G. M. Temmer and N. P. Heydenburg, Phys. Rev. 98, 1308 (1955).
[11] A. Chandra, Proc. Indian Acad. Sci. 44A, No. 4, 194 (1956).

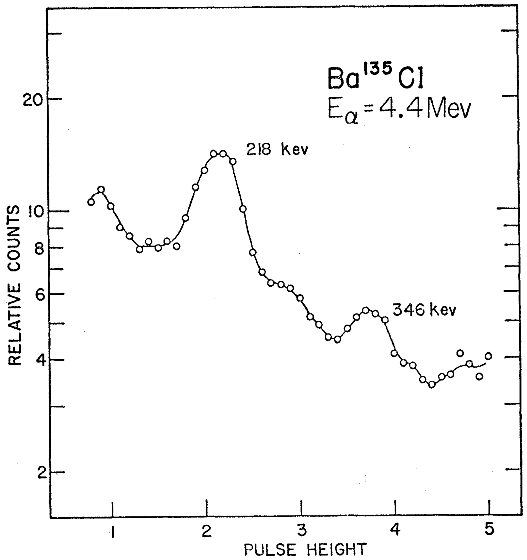

FIG. 8. Pulse-height spectrum obtained from Ba^{135}Cl when bombarded with 4.4-Mev alpha particles.

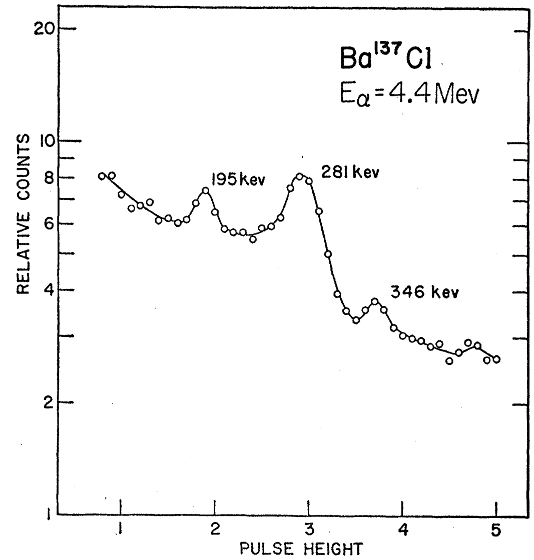

FIG. 9. Pulse-height spectrum obtained from Ba^{137}Cl when bombarded with 4.4-Mev alpha particles.

Ba^{137} match the calculated theoretical curves for the excitation of levels at 218 kev and 281 kev, respectively.

The excitation of these levels is interesting since in the case of both isotopes no β decay to these levels is observed, and no cascade radiation has been observed in the decay of the known isomeric levels, which lie at a higher energy. These facts lead to the conclusion that these levels probably have a character of $\frac{1}{2}+$. Consider, for example, Ba^{137}: there is no observable β decay from the $\frac{7}{2}+$ state in Cs^{137} to a 281-kev state, but only to the $11/2^-$ metastable state at 661 kev and the $\frac{3}{2}+$ ground state.[12] The considerably lower transition probability for the β radiation of higher forbiddenness that would be required in a transition to a state of character $\frac{1}{2}+$, would explain the fact that no β radiation has been observed to the 281-kev state. The same conclusion is also reached by analogous reasoning applied to the possible decay by cascade of the 661-kev metastable state through the 281-kev state. Identical arguments apply to the 218-kev state in Ba^{135}.

[12] Hollander, Perlman, and Seaborg, Revs. Modern Phys. 25, 469 (1953).

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