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COLLECTIVE LEVELS IN LIGHT EVEN CERIUM ISOTOPES

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May 1968

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Nuclear reactions $^{116,118,120,122,124}Sn(^{16}O,4n\gamma)^{128,130,132,134,136}Ce$, $^{110,112,114,116}Cd(^{20}Ne,4n\gamma)^{128,130,132}Ce$, E = 4-5 MeV/nucleon; measured E_γ, I_γ, anisotropy. $^{128,130,132,134,136}Ce$, deduced levels, J, π, σ_γ.

COLLECTIVE LEVELS IN LIGHT EVEN CERIUM ISOTOPES†

David Ward, R. M. Diamond, and F. S. Stephens

Lawrence Radiation Laboratory
University of California
Berkeley, California

May 1968

ABSTRACT

Heavy ion reactions, (^{16}O,4n) and (^{20}Ne,4n), have been used to populate levels in the neutron-deficient even cerium isotopes ^{136}Ce - ^{128}Ce. Prominent γ-rays in the "in-beam" spectra have been assigned to transitions between the members of the ground-state quasi-rotational bands. The results show that as the number of neutrons decreases these isotopes tend towards rotational behaviour. The cross-sections for the neutron evaporation reactions used are considerably reduced for the most neutron-deficient systems due to competition from charged-particle emission. Such competition prevents us from studying Ce isotopes lighter than ^{128}Ce by this method.

†This work performed under the auspices of the U. S. Atomic Energy Commission.

Introduction

It has been suggested that some neutron-deficient nuclei having both proton and neutron numbers between 50 and 82 might be deformed and exhibit rotational behaviour[1]). The experimental studies by Sheline et al.[1]) and by Clarkson et al.[2]) have shown that the neutron-deficient isotopes of xenon (Z=54; N=66, 68) and barium (Z=56; N=68, 70, 72, 74) do show increasingly collective behaviour as the neutron number decreases. This is evidenced by the systematic decrease in the energy of the first 2^+ level, together with an increase in the ratio of the energies of the 4^+ to 2^+ levels. However, it is apparent that this trend is unlikely to continue much further in either the xenon or barium isotopes, since the ratio $E_4:E_2$ appears to reach its maximum value with ^{122}Xe and probably with ^{124}Ba. The first 2^+ level in ^{134}Ce is at 409 keV[2]), but it seems probable that for the lighter cerium isotopes the energy of this level will fall considerably. To examine this possibility we have made a study of the cerium isotopes ^{136}Ce through ^{128}Ce; the energy levels were populated in heavy-ion reactions in which these cerium isotopes were the final products of the (HI,xn) reactions. The "in-beam" technique of studying collective levels in neutron-deficient nuclei has been used by several authors, and has been discussed in the literature, e.g., refs.[2-4]). In addition to taking spectra with a single lithium-drifted germanium counter, we have in some cases used a γ-γ coincidence technique with two Li/Ge counters. In all cases we have measured the anisotropy in the angular distribution of the gamma rays with respect to the beam direction. Knowledge of these anisotropies has proved useful in the analysis of the spectra[5]).

Experimental Procedure

The heavy-ion accelerator, Hilac, at Berkeley has been used to provide the beams of ^{16}O and ^{20}Ne used in this work. We have utilized the reactions $^{A}Sn(^{16}O,4n)^{A+12}Ce$, A = 116-124, and $^{A}Cd(^{20}Ne,4n)^{A+16}Ce$, A = 110-116; separated isotopes of tin and cadmium were employed. The best bombarding energies were approximately 80 MeV for ^{16}O and 90 MeV for ^{20}Ne. Both the tin and cadmium targets were prepared by evaporating the material onto lead foil. The evaporated material was about 700 μg cm^{-2}; the lead foil was 0.05 mm thick, which was sufficient to stop the heavy-ion beams. We have found that the lead backing gave very little background in these experiments, whilst it considerably improved the quality of the spectra by stopping the recoiling compound nuclei, thus eliminating Doppler effects.

Gamma rays were detected in lithium-drifted germanium counters measuring 0.8 cm × 6 cm^2 and 1.3 cm × 6 cm^2. The counter was usually positioned at 90° to the beam direction, and at a distance of about 2 cm from the target. In the angular distribution measurements this distance was increased to 6 cm, and measurements were made at 0° and 90°. Details of the experimental arrangement have been given previously[2,5]). For the coincidence work, the two germanium counters were each positioned at 90° with respect to the beam, on opposite sides of the target, and were each about 2 cm from the target. Pulses from the germanium counter were passed to a pre-amplifier and amplifier designed to preserve a high resolution to moderately high counting rates[6]). The amplifier comprised three separate systems: (i) a low noise amplifier with pole-zero compensation; (ii) a pulse pile-up rejector with pre-set inspection time; and (iii) a linear-gate. An amplified pulse was passed by the linear-

gate only in the event there was no pulse falling within the inspection time. In conjunction with the germanium counter this system gave a typical performance of 2.5 keV resolution for the ^{60}Co γ rays at a total counting rate of 2×10^4 counts per second. The spectra were analyzed by a 2048-channel ADC and were stored using a PDP-7 computer operating on-line. The ADC was gated so that spectra taken during the beam burst and between beam bursts could be stored separately. During this work the Hilac was operating at a repetition rate of 40 pulses per second, each of 5 milliseconds duration. Spectra were taken at several bombarding energies, and from the excitation functions of the gamma-rays we were able to pick out those corresponding to the (HI,4n) reaction.

Results

Examples of the spectra obtained are shown in figs. 1 and 2. The results for the energies, anisotropies, and relative yields of the gamma rays are given in table 1. The individual transition energies are considered accurate to about 0.15% in all cases. The relative yields have been corrected for conversion-electron emission, counter efficiency, and the effect of absorbers. These yields are probably good to 15% for the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions, and 25% for higher transitions.

The present angular distribution measurements give only the relative yields at 0° and 90° which is not sufficient to determine the parameters A_2 and A_4. We have therefore quoted the anisotropies, which we have defined as $(I_0-I_{90})/I_{90}$. However, if the values of A_4 are small, comparable to those previously found in similar reactions[5]), A_4 may be neglected and the anisotropy

can be readily related to A_2 with an error which is small compared with the experimental error.

Coincidence experiments were performed for ^{128}Ce, ^{132}Ce, and ^{136}Ce. The statistical accuracy of the points in the coincidence spectra was rather poor, and it was not possible to draw any definite conclusions other than that the results were compatible with the proposed schemes.

We were not able to identify unambiguously the levels in ^{126}Ce from the system ^{110}Cd + ^{20}Ne. The prominent lines in the spectrum could be assigned to $^{124,126}Ba$ and some tentatively to ^{127}Ce.

Discussion

Level Schemes.

In assigning a transition to the ground-state quasi-rotational band of a particular even-even nucleus we have been guided by considerations of the excitation functions, relative transition intensities, angular distributions, and where measured, the coincidence spectra. From the excitation functions it was found that the xn reaction, for x=3-5, peaked at an excitation energy corresponding to (15-17) MeV per evaporated neutron.

From the work of Newton et al.[5]) the range of values found for the anisotropy in the angular distribution of stretched E2 gamma rays following a HI,xn reaction is +0.33 to +0.75. With the exception of the nucleus ^{136}Ce it will be seen from table 1 that the present assignments of ground-band transitions fall into this range. The fact that the anisotropy lies within the above range is generally a necessary condition for a stretched E2 transition.

(But this is not always sufficient; for example, a mixed M1-E2 transition could have an anisotropy in this range for certain values of the mixing ratio.) However, it is possible that the anisotropy could be lower than 0.33 and the transition still be a stretched E2. This could occur if the alignment of the parent state is reduced because: a) its half-life, or the half-life of a substantial feeding transition, is sufficiently long to allow external perturbations to have an effect; or b) the state is populated mainly by non-stretched transitions between levels of low spin[7]). An example of the first situation was pointed out in ref. 5 where it was shown that the values of A_2 for the $2 \rightarrow 0$ transitions, the longest-lived members of the ground-band cascade, were sometimes considerably smaller than those of the other, faster transitions. It also seems plausible to us that reductions in the values of the anisotropies due to b) above may be correlated to the entrance point in the feeding of the band (e.g., refs. 4 and 10). In a rotational nucleus where the ground-band energy spacings are low, entrance into the ground band usually occurs at reasonably high spins (12-20). It is then clear that any non-stretched transitions preceding the ground band must be between states of high spin and therefore cannot cause very much misalignment of the state. On the other hand, if the energy spacings are large, as in vibrational-type nuclei such as ^{136}Ce, the ground-band will be entered at a relatively low spin ($J = 4$ for ^{136}Ce), and now a non-stretched transition feeding that (4^+) level could seriously affect the alignment of that state and of succeeding members.

In the present experiments, the energy of the ground-band transitions always exceeded 200 keV, and the half-life should be short enough to rule out the first part of possibility a). Only in the case of ^{132}Ce was an isomeric

level detected: this lies at 2344 keV and decays with a half-life of 8.4 ± 1 milliseconds to the 6^+ level. (We will discuss this isomer in more detail in connection with other N = 74 nuclei in a later publication.) However, in the recorded spectra, the feeding of the ground-band from the isomer was not large compared to the prompt feeding, and so there would be little effect on the measured anisotropies. The anisotropies for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in ^{136}Ce are considerably lower than the range defined above. This probably is due to the 664.8 keV transition, which carries most of the population to the 4^+ level, (75% ± 10%). This transition, with A = -0.05 ± 0.04, is either non-stretched, case (b) above, or some level preceeding it has a relatively long half-life as in case (a) above.

In view of the systematic behaviour of the energy levels, and the results of the angular distribution and coincidence measurements, we feel that the proposed level schemes for the ground bands shown in Fig. 3 are reasonably well established. The present results for the only previously studied nucleus, ^{134}Ce, are in agreement with the earlier work with the exception of the $8^+ \rightarrow 6^+$ transition which was previously given tentatively as 871 keV by Clarkson et al.[2]).

Amongst the existing models for rotational energy spacings, it seems to us that the expressions of Harris[11]) best reproduce the experimental values over the whole range from strongly deformed nuclei to near-spherical ones. We have therefore used the two-parameter Harris equations:

$$E_J = \frac{1}{2}\omega^2(\Im_o + 3\,\alpha\omega^2)$$

$$J(J+1) = \omega^2(\Im_o + 2\,\alpha\omega^2)^2$$

to fit the cerium levels. A least squares computer program was used for this purpose. The energy levels were weighted in proportion to their inverse squares, so that the rms percentage deviations in the energy levels would be a minimum. The results from this program are shown in table 3. The differences between the experimental and the fitted values are in general somewhat outside the experimental errors. The moment of inertia increases very rapidly with increasing spin for these nuclei. This is presumably due both to centrifugal stretching[4]), and to other effects such as Coriolis anti-pairing[12]). Calculations including these effects have been performed in the rare-earth[13]) region, and an extension of this type of calculation to the barium region should be of interest. The quality of the fits to the Harris expressions in this region is comparable to that obtained in the rare earth region.

Reaction Mechanism

The spectra become progressively worse for the lighter ceriums, in that the peak-to-background ratios are poorer, and more transitions are present. We interpret this as being due to the increasing competition from charged-particle evaporation. This would be expected in view of the decrease in proton and alpha binding energies with decreasing neutron number, whilst the neutron binding energies become larger. Some of the stronger extraneous lines can be identified from their energies to be transitions in light barium nuclei, as established by Clarkson et al.[2]). For the system $^{112}Cd + ^{20}Ne$ at 92 MeV there is the $2^+ \rightarrow 0^+$ transition in ^{126}Ba at 256.0 ± 0.3 keV (256.1 ± 0.8)[2]). This product would be made by evaporation of an alpha particle and two neutrons

from the compound nucleus. Similarly in the system $^{110}Cd + ^{20}Ne$ the set of lines 229.6 ± 0.3, 421.6 ± 0.5, and 576.1 ± 0.7 keV may be identified with the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, $6^+ \rightarrow 4^+$ transitions in ^{124}Ba (229.5 ± 0.7, 420.6 ± 1.3, and 573 ± 2 keV)[2]). Again this would be an α2n evaporation. For this system the evaporation of two protons and two neutrons may be identified from the corresponding transitions in ^{126}Ba, 256.0 ± 0.3, 455.5 ± 0.6 and 621.0 ± 0.9 keV (256.1 ± 0.8, 455.5 ± 1.4, 621 ± 2 keV)[2]). The presence of these charged-particle evaporations must reduce the cross section available for neutron evaporation.

The cross section for production of a particular γ ray may be estimated by comparing its yield to that of the Coulomb-excited $2^+ \rightarrow 0^+$ transition in the target nucleus. We find that the cross sections for the $2^+ \rightarrow 0^+$ transitions in ^{130}Ce and ^{128}Ce from the 4n reactions using ^{20}Ne as projectile were 310 and 215 mb., respectively, at the peak of their excitation functions. There was no detectable α2n competition (as evidenced by production of ^{128}Ba) in the system $^{114}Cd + ^{20}Ne$ (to make ^{130}Ce). However, at the peak of the 4n reaction for the system $^{112}Cd + ^{20}Ne$, the cross section for α2n evaporation was 45 mb. For the system $^{110}Cd + ^{20}Ne$ we were not able to identify unambiguously the 4n product, ^{126}Ce; however, at the bombarding energy at which the peak of the 4n reaction would be expected in this case, namely 100 MeV, the cross-section for α2n evaporation was 125 mb. and for 2p2n evaporation, 105 mb. The uncertainty in these quoted cross sections should be taken as 25%; this is composed partly of the uncertainty in the B(E2) values in the cadmium nuclei (taken from ref. [14]) and partly from the possible systematic error in calculation of the cross section for Coulomb excitation at bombarding energies which exceed the Coulomb

barrier height. In evaluating these cross sections we have integrated the differential cross section for Coulomb excitation over the range $\theta = 0$ to θ_c, where θ_c is defined by the grazing collision. A radius parameter $R_0 = 1.45$ F. was assumed. The differential cross sections were obtained from the deBoer-Winther computer program[15]. The conclusion to be drawn from these measurements seems to be that charged-particle evaporation begins to compete with neutron evaporation for very neutron-deficient systems. The present data imply that this competition begins to lower the 4n reaction cross section considerably for the initial compound nucleus ^{132}Ce (final product ^{128}Ce). It therefore becomes difficult to use the present techniques for the study of nuclei in this region which are more neutron-deficient than ^{128}Ce. Further study in this region could probably be carried out using reactions such as ^{100}Ru(^{32}S,α2n)^{126}Ce. Such reactions should be quite feasible since it has recently been shown by Ward et al.[10]) that with systems such as ^{120}Sn + ^{40}A at around 160 MeV, the dominant process is formation of a compound nucleus with evaporation of particles. In such cases one could discriminate against the competing reactions by observing the γ-ray spectrum in coincidence with alpha particles.

Energy Level Systematics

A knowledge of only the energies of the ground-state band members is not sufficient to determine whether or not a nucleus has a stable ground-state deformation, except in cases where the 2^+ level lies exceptionally low and the ratios of the energies of the band members are quite close to those of a (rigid) rotor. Examples are the stable erbium and ytterbium isotopes. As was anticipated, the lowest lying 2^+ level in these cerium nuclei (^{128}Ce) is lower than

that in any presently known xenon or barium isotope, viz. fig. 4, but is not low enough to be comparable to the rare earth nuclei just mentioned.

The systematic behaviour of the energy levels between isotopes of a given element or between isotones is also of little help in deciding this question, except in cases where an abrupt change in $E2^+$ and in the ratio $E4^+:E2^+$ occurs, as for example between N = 88 and N = 90 in isotopes of dysprosium, gadolinium and samarium. It seems reasonable to suppose that there is a sudden onset of deformation in these nuclei at N = 90. However, this behaviour seems perculiar to a limited region; there is no corresponding discontinuity between N = 88 and N = 90 for the isotopes of erbium and ytterbium. A comparison of the ratio of the energy of the 4^+, and higher levels to that of the first 2^+ state in the cerium nuclei studied is also ambiguous. For the 4^+ and 6^+ levels the rigid rotor model gives ratios of 3.33 and 7.0 respectively; ^{128}Ce has values of 2.93 and 5.6. These are quite far from the harmonic oscillator values of 2 and 3, and are larger than those for any of the xenon or barium isotopes observed so far, but they are still considerably below the rotational values.

Another way of comparing the energy level data is to plot the transition rotational constant, $A_I = (E_I - E_{I-2})/(4I - 2)$, (corrected by a factor of $A^{5/3}$ to approximately remove the mass dependence of the moment of inertia) versus the spin of the upper level I. Such a plot is shown in fig. 5 for the measured cerium nuclei. The similarity between the three lightest cerium nuclei, ^{128,130,132}Ce, and the 90-neutron nuclei, ^{156}Dy, ^{158}Er and ^{160}Yb, is rather striking. Not only are the individual patterns very similar, but also the addition or removal of pairs of protons in these 90-neutron nuclei has

very much the same effect as pairs of neutrons do in these cerium nuclei. The light platinum isotopes comprise another set that is obviously quite similar. It should be noted that some other nuclei show quite different properties when plotted in this manner, we have included ^{184}Os in the figure to illustrate a dissimilar case. The curves in fig. 5 seem to indicate that the cerium, platinum and 90-neutron nuclei are similar in some way. However, since it is not clear whether the platinum and these 90-neutron nuclei are deformed or not, this similarity is of little help in settling the question of deformation in the cerium nuclei. However, since a low-lying $K = 0^+$ band (quasi β-vibrational band) is known in the case of ^{156}Dy,[16]) and ^{184}Pt,[17]) the similarity does suggest that such a band may be low-lying in the cerium nuclei, and it will be of interest to try to observe it.

It is clear that more information is needed to determine whether the light cerium nuclei are deformed. Perhaps the most direct evidence would be measurement of the static quadrupole moments of some of the 2^+ levels excited. However, this would not be an easy measurement on these short-lived nuclei, and furthermore would not necessarily indicate the shape of these nuclei in their ground states. Other information that would bear (less directly) on these nuclear shapes would be: 1) the transition quadrupole moments (half-lives) of members of the band; 2) the energies of the second 2^+ and 0^+ levels (quasi γ- and β-vibrational bands) in these nuclei; 3) the energies of levels in still lighter even cerium nuclei; and 4), as has been recently suggested[18]), the identification of levels in some odd-mass cerium (or barium) isotopes. We plan to pursue the question of deformation in this region of the periodic table, probably along lines 2) and 3) above.

Acknowledgments

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Table 1. Transitions assigned to the quasi-rotational bands. The energies in keV are denoted, E, the relative intensities, I, and the anisotropies, A. The reactions used are indicated in column 1.

		2 → 0	4 → 2	6 → 4	8 → 6
^{136}Ce	E	552.0	761.6	(899.0)	
^{124}Sn(^{16}O,4n)	I	100	99	19	
	A	0.25±0.04	0.19±0.06	0.05±0.2	
^{134}Ce	E	409.2	639.3	813.9	946.5
^{122}Sn(^{16}O,4n)	I	100	89	62	40
	A	0.42±0.04	0.47±0.08	0.63±0.15	0.45±0.15
^{132}Ce	E	325.4	533.5	683.8	787.8
^{120}Sn(^{16}O,4n)	I	100	97	73	52
^{116}Cd(^{20}Ne,4n)	A	0.61±0.03	0.53±0.07	0.43±0.1	0.72±0.15
^{130}Ce	E	254.1	456.7	613.4	729.0
^{118}Sn(^{16}O,4n)	I	100	86	82	61
^{114}Cd(^{20}Ne,4n)	A	0.40±0.04	0.49±0.07	0.57±0.1	0.87±0.15
^{128}Ce	E	207.3	399.9	550.6	662.5
^{116}Sn(^{16}O,4n)	I	100	73	72	59.0
^{112}Cd(^{20}Ne,4n)	A	0.41±0.03	0.60±0.1	0.59±0.15	0.59±0.15
^{111}Cd(^{20}Ne,3n)					

Table 2. Prominent γ-rays not assigned to the quasi-rotational bands. Relative intensities refer to the intensity of the $2^+ \rightarrow 0^+$ in the corresponding nucleus.

Nucleus	Energy (keV)	Relative Intensity	Anisotropy
^{136}Ce	664.8	75	-0.05±0.04
^{134}Ce	907.0	24	0.9±0.2
^{132}Ce	570.5	28	0.79±0.16
	802.0	16	0.44±0.15
	828.7	28	1.2±0.3
^{130}Ce	503.3	29	0.53±0.1
	756.3	30	0.50±0.12

Table 3

Harris Model fits

Nucleus		Energy levels (keV)						Parameters		
		2^+	4^+	6^+	8^+	10^+	12^+	$\mathfrak{J}_o$ $\times 10^3$	c $\times 10^8$	rms deviation %
^{136}Ce	Expt.	552.0	1313.6	2213						
	Theory	552.1	1312.6	2214.0	3224	4325	5503	1.947	2.533	0.17
^{134}Ce	Expt.	409.2	1048.6	1862.4	2808.9					
	Theory	407.2	1060.1	1864.0	2783	3796	4889	5.018	2.682	0.92
^{132}Ce	Expt.	325.4	858.9	1542.7	2331					
	Theory	324.1	866.0	1542.6	2321	3182	4114	6.898	4.095	0.51
^{130}Ce	Expt.	254.1	710.7	1324.1	2053.1					
	Theory	252.7	719.4	1325.0	2035	2830	3699	10.25	4.311	0.81
^{128}Ce	Expt.	207.3	607.3	1157.8	1820.3					
	Theory	205.7	613.8	1162.3	1818	2561	3379	13.43	4.389	0.64

Figure Captions

Fig. 1. Gamma-ray spectra for ^{136}Ce, ^{134}Ce, ^{132}Ce, and ^{130}Ce. The reactions used to produce these spectra are indicated on the figure and all the spectra were taken at 0 deg. to the beam direction.

Fig. 2. Gamma-ray spectra for ^{128}Ce from the reactions $^{112}Cd(^{20}Ne,4n)$ and $^{111}Cd(^{20}Ne,3n)$. These spectra were also taken at 0 deg. to the beam direction.

Fig. 3. Ground-band energy levels in the light even cerium nuclei.

Fig. 4. Comparison of the energy of the first 2^+ levels in even isotopes of Xe, Ba, and Ce. The dashed line represents the value of $(E2+)_{crit}$ which indicates the general region of transition between spherical and spheroidal nuclei.

Fig. 5. Values of the rotational constant A_I as a function of spin I for ground-band levels in the cerium nuclei compared with other nuclei.

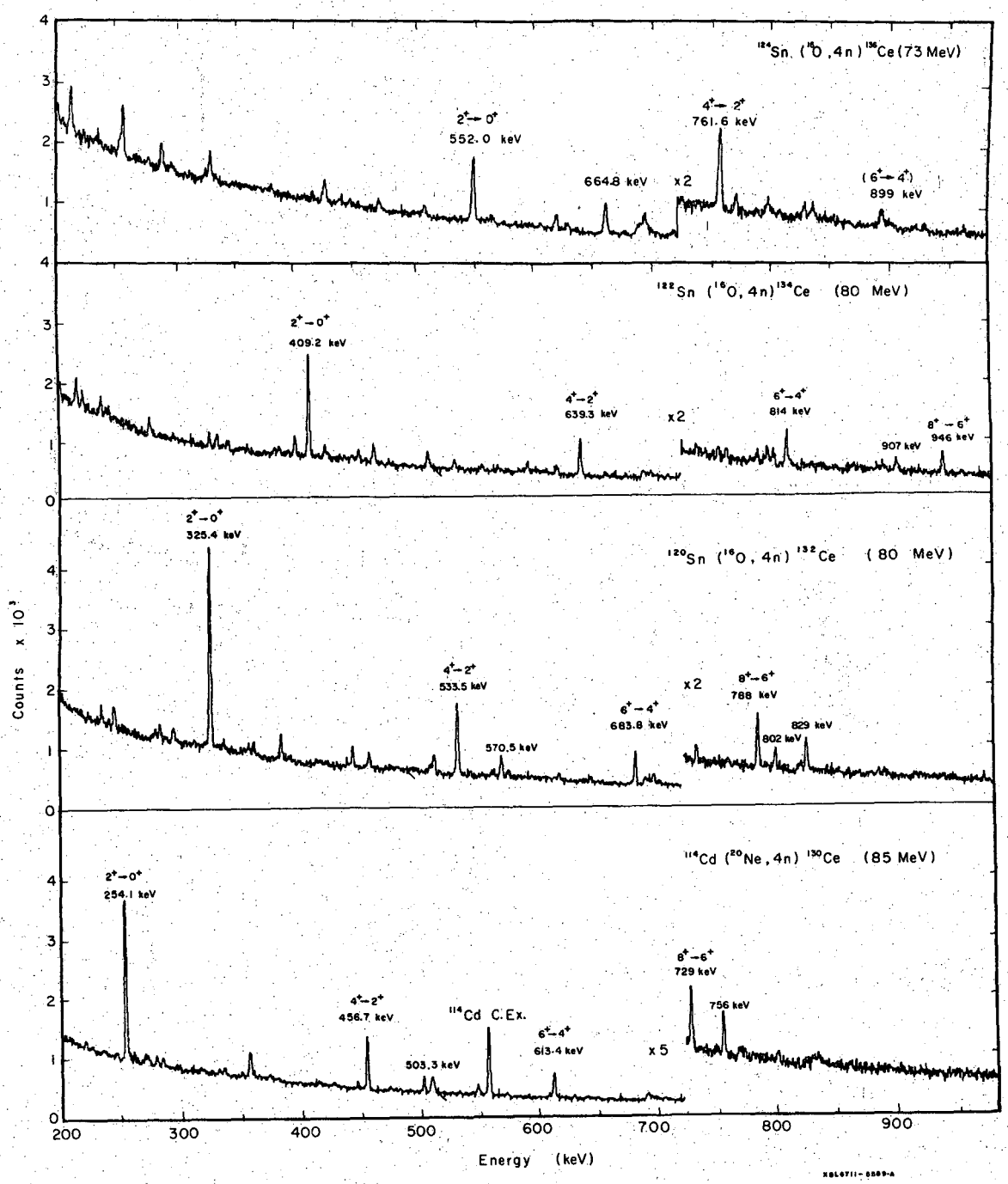

124Sn (16O, 4n) 136Ce (73 MeV)
2+→0+
552.0 keV
664.8 keV
x2
4+→2+
761.6 keV
(6+→4+)
899 keV
122Sn (16O, 4n) 134Ce (80 MeV)
2+→0+
409.2 keV
4+→2+
639.3 keV
x2
6+→4+
814 keV
907 keV
8+→6+
946 keV
120Sn (16O, 4n) 132Ce (80 MeV)
2+→0+
325.4 keV
4+→2+
533.5 keV
570.5 keV
6+→4+
683.8 keV
x2
8+→6+
788 keV
802 keV
829 keV
114Cd (20Ne, 4n) 130Ce (85 MeV)
2+→0+
254.1 keV
4+→2+
456.7 keV
503.3 keV
114Cd C.Ex.
6+→4+
613.4 keV
x5
8+→6+
729 keV
756 keV
Counts x 10³
Energy (keV)

Fig. 1

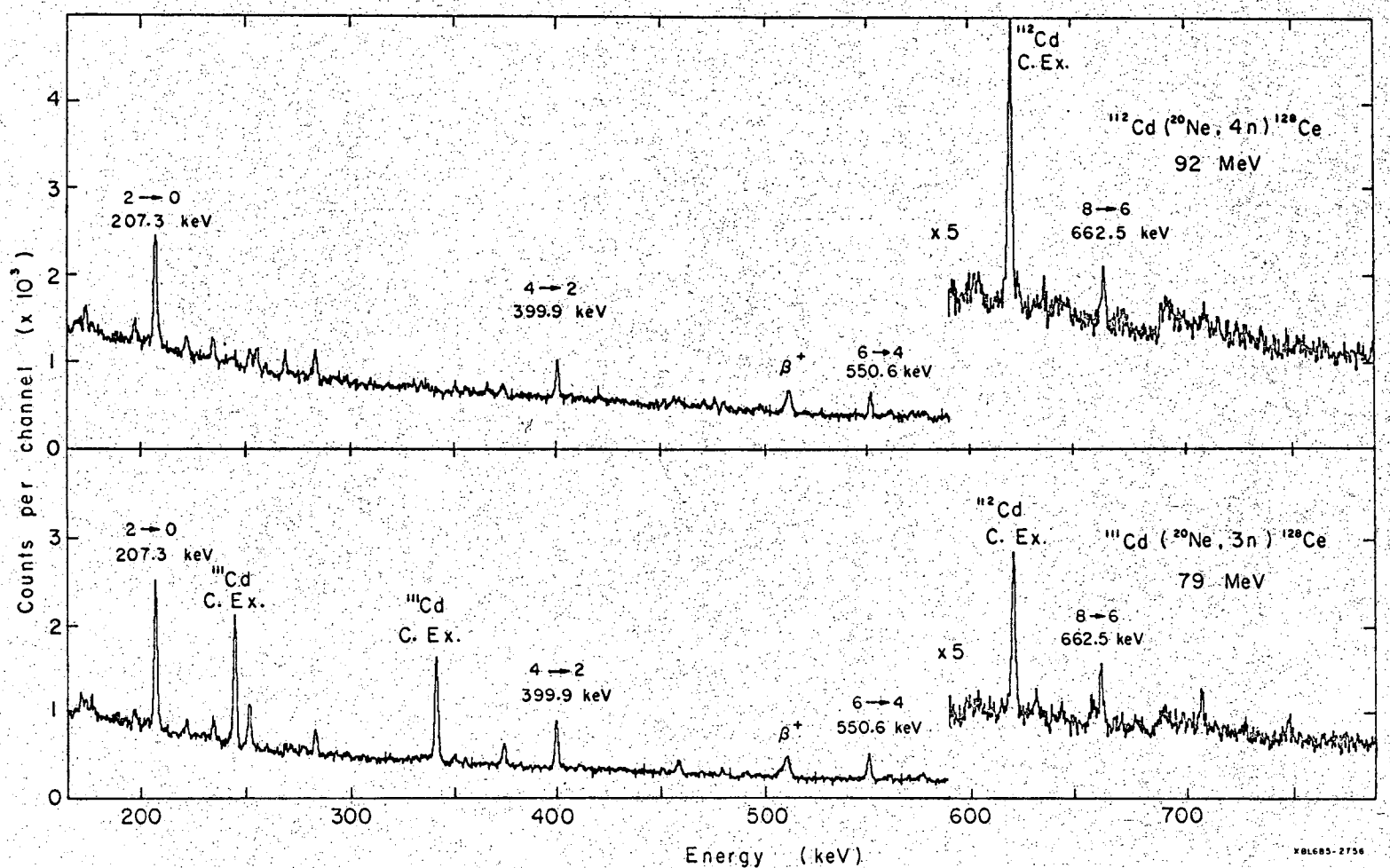
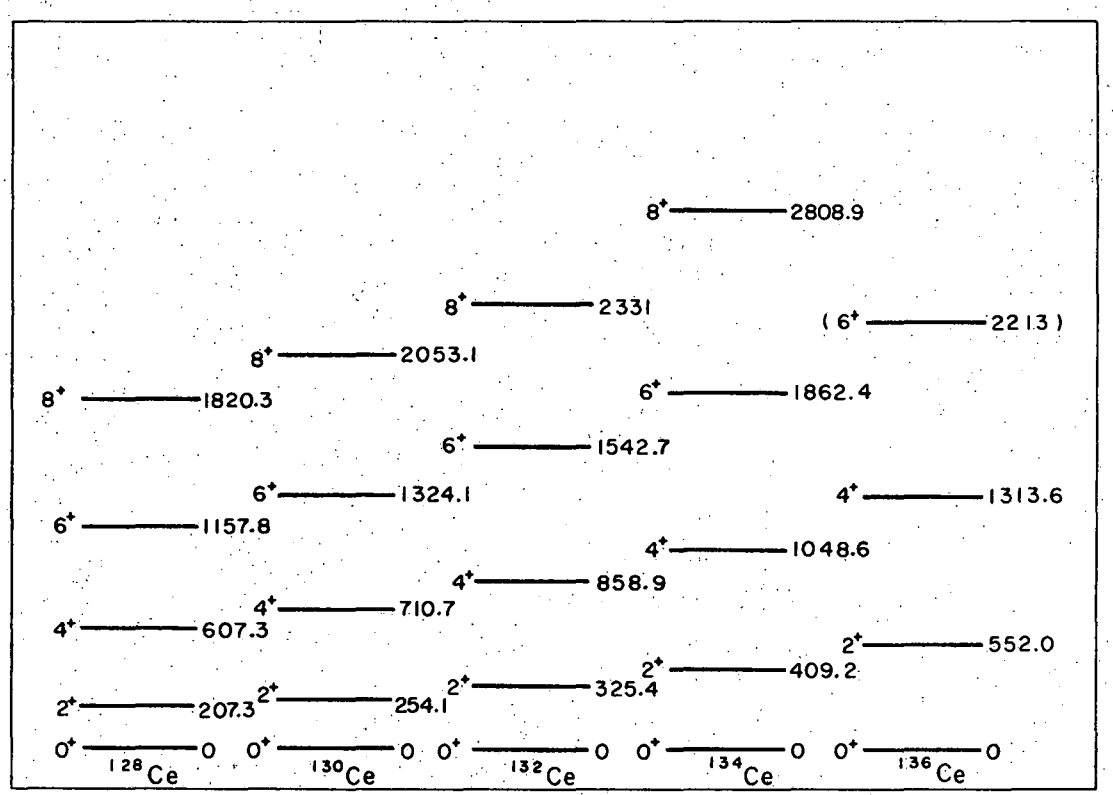

Counts per channel (x 10³)
Energy (keV)
2 → 0
207.3 keV
4 → 2
399.9 keV
β⁺
6 → 4
550.6 keV
x 5
¹¹²Cd
C. Ex.
¹¹²Cd (²⁰Ne, 4n) ¹²⁸Ce
92 MeV
8 → 6
662.5 keV
¹¹¹Cd
C. Ex.
¹¹¹Cd (²⁰Ne, 3n) ¹²⁸Ce
79 MeV
XBL683-2756

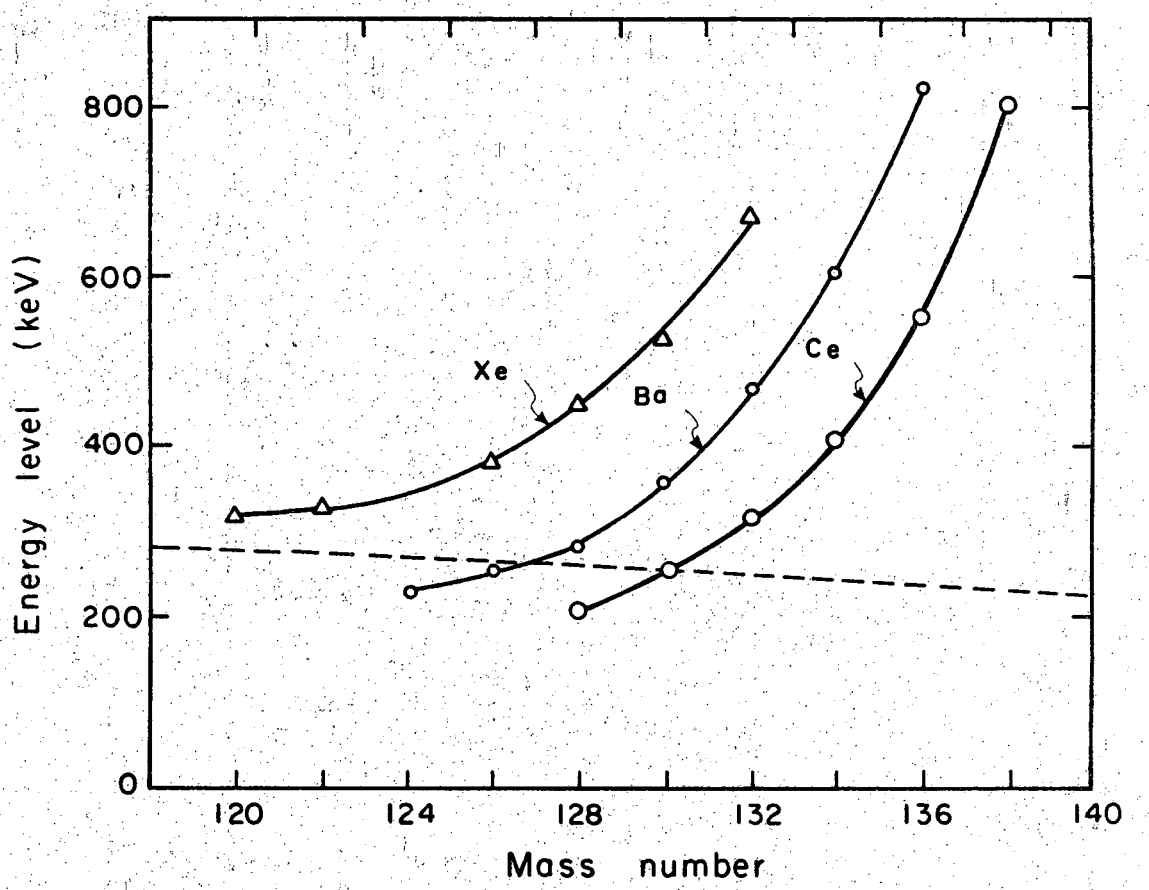
Fig. 2



Energy levels in light Cerium nuclei

XBL6711-5587-A

Fig. 3



MU-35638

Fig. 4

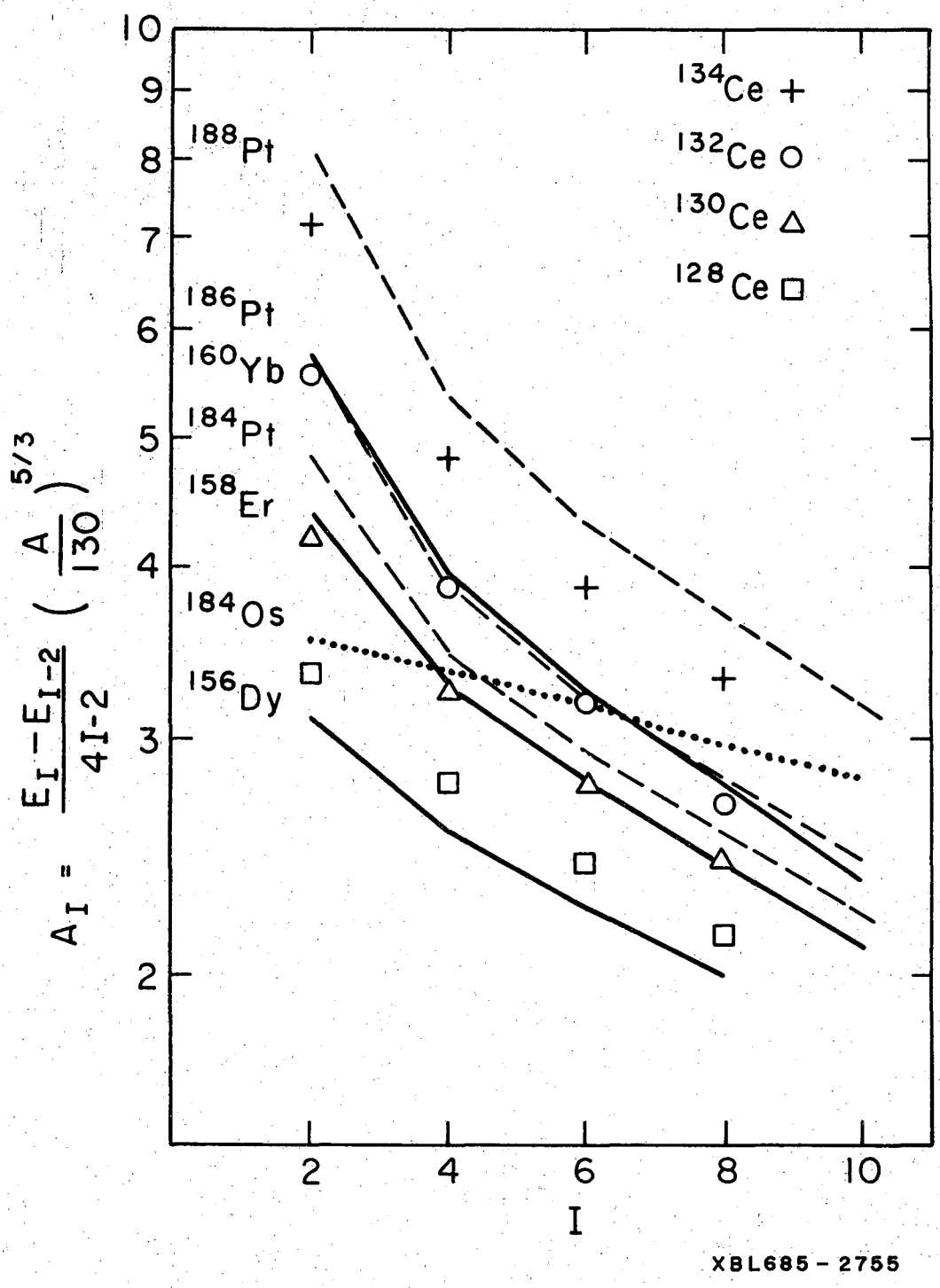

$A_I = \frac{E_I - E_{I-2}}{4I-2} \left(\frac{A}{130}\right)^{5/3}$
I
^{188}Pt
^{186}Pt
^{160}Yb
^{184}Pt
^{158}Er
^{184}Os
^{156}Dy
^{134}Ce +
^{132}Ce ○
^{130}Ce △
^{128}Ce □
XBL685-2755

Fig. 5

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