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Beta Decay of ^{146}Ce†

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The γ-ray spectrum of 14-min ^{146}Ce has been reexamined with a high-resolution Ge(Li) detector, and the following previously unreported γ transitions were observed: 106.4, 351.9, 369.1, 415.6, 467.9, 491, and 503.0 keV. A previously observed peak at $\approx$99 keV was resolved into 98.3- and 100.9-keV photopeaks. More precise energies and additional conversion coefficients have been determined for many of the transitions. On the basis of energy differences a new level, believed to be 1+, has been placed at 503.0 keV. γ–x-ray and γ–electron coincidence measurements suggest that a previously postulated 35-keV level is de-excited by a 23–12-keV γ cascade.

I. INTRODUCTION

Although the main features of the β decay of ^{146}Ce, including β population of a 1+ level at 351 keV in ^{146}Pr, have been reported,[1] failure to find evidence for de-excitation of a postulated level at $\approx$35 keV, believed to be fed strongly by a 317-keV γ transition, was quite puzzling. In the present study, γ–x-ray and γ–e^- coincidence measurements were performed which suggest that the level is predominantly de-excited by a 23–12-keV γ cascade.

II. EXPERIMENTAL PROCEDURE

The ^{146}Ce sources were separated from the fission products of ^{235}U irradiated as uranyl nitrate for a few minutes in the rabbit port of the Los Alamos "Water Boiler" Reactor. The cerium was purified by a previously described procedure[2] involving liquid-liquid extractions and column partition chromatography using hydrogen di-(2-ethylhexyl)orthophosphoric acid (HDEHP). For the measurements of conversion electrons and x rays, the carrier-free cerium activity was eluted from the HDEHP column and evaporated on 0.5-mil Teflon film.

Our 7-mm×4-cm^2 Ge(Li) and 3-in.×3-in. NaI(Tl) detectors were used for observations of the γ-ray spectra. Both xenon- and krypton-filled Reuter-Stokes proportional counters having 5-mil beryllium windows were used in measuring low-energy γ transitions and x rays, and a cooled 2-mm×80-mm^2 Si(Li) detector was used in the electron measurements. Coincidence circuitry having a resolving time of $\approx$0.15–0.20 μsec was used.

III. RESULTS

A. γ-Ray Spectra

The γ-ray spectrum of 14-min ^{146}Ce was reexamined with a high-resolution Ge(Li) detector (Figs. 1 and 2) and the following previously undetected, low-intensity transitions were found: 106.4, 351.9, $\approx$360(?), 369.1, 415.6, 467.9, 491, and 503.0 keV. The cerium was subjected to a hexone extraction and back extraction following the usual chemical separation, but these photopeaks were still present in the same relative intensities and decayed with a 14-min half-life. A previously observed peak at $\approx$99 keV was resolved into 98.3- and 100.9-keV photopeaks. The contribution from 33-h ^{143}Ce, determined at later times, was subtracted before the calculation of photopeak intensities.

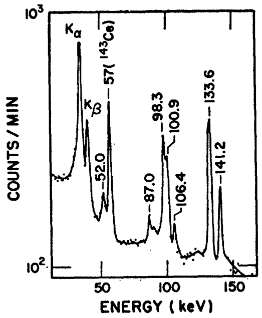

FIG. 1. Low-energy γ spectrum of ^{146}Ce (+^{143}Ce) measured with the Ge(Li) detector. 20-min count begun 65 min after end of bombardment.

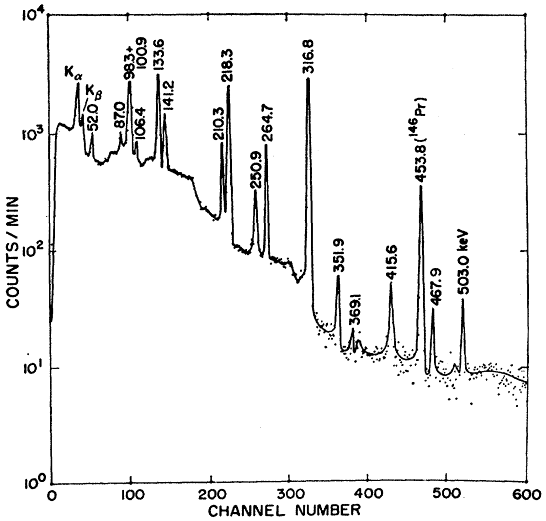

FIG. 2. Net high-energy γ spectrum of ^{146}Ce measured with the Ge(Li) detector covered with 1.48 g/cm^2 Be. (The contribution from 33-h ^{143}Ce has been subtracted.)

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† Work done under the auspices of the U. S. Atomic Energy Commission.

[1] D. C. Hoffman, O. B. Michelsen, and W. R. Daniels, Arkiv Fysik **36**, 211 (1967).

[2] O. B. Michelsen and D. C. Hoffman, Radiochim. Acta **6**, 165 (1966).

The intensity of the 352-keV photopeak was determined from a spectrum observed through 1.48-g/cm^2 beryllium and 0.574-g/cm^2 lead to minimize coincidence summing. A correction for coincidence summing (≈20% of the observed peak) was calculated and subtracted from the intensity of the 352-keV photopeak. A summary of the γ-ray data is given in Table I.

B. Electron Measurements

The low-energy portion of the electron spectrum of ^{146}Ce is shown in Fig. 3(a). The praseodymium K x radiation is also clearly visible. (The efficiency of our detector for praseodymium K x radiation relative to that for 91-keV electrons was found to be ≈40%. The ratio of the intensities of the K x radiation and the 91-keV K-conversion electron line from a ^{144}Ce source was determined for our detector and compared with a "true" ratio based on the data of Geiger *et al.*[3]) The conversion coefficients given in Table II were then obtained by comparing the intensities of the electron lines normalized to the intensity of the K x rays with the γ-ray intensities given in Table I, also normalized through the K x-ray intensity. It was assumed that all of the electron lines except the very low-energy lines from the 23-keV transition were detected with equal efficiencies. The relative detection efficiency for the L- and M-conversion electrons of the 23-keV transition was estimated to be ≈70%. [The ratio of the K-(≈15 keV) and L-(≈51 keV) conversion electrons from the 57-keV γ transition of 33-h ^{143}Ce measured in the same source was measured at later times and compared with the theoretical ratio of ≈6.6 estimated from the tables of Sliv and Band[4] for an $M1$ transition.[5]] The transition multipolarities deduced from our experimentally determined conversion coefficients are given in Table III.

TABLE I. Summary of γ-ray intensity data.

γ-ray energy (keV)	Relative γ intensity	Transition intensity[a] (%)
23 ±2	(0.11 ±0.004)[b]	≈70
K x rays	0.35 ±0.05	...
52.0±0.2	0.0185±0.004	7.8
87.0±0.2	0.011 ±0.003	2.1
98.3±0.3	0.071 ±0.010	8.4
100.9±0.4	0.049 ±0.010	3.2
106.4±0.3	0.011 ±0.002	1.3
133.6±0.2	0.192 ±0.030	15.7
141.2±0.3	0.085 ±0.030	6.2
210.3±0.3	0.119 ±0.025	6.4
218.3±0.3	0.391 ±0.040	20.9
250.9±0.3	0.062 ±0.015	3.5
264.7±0.3	0.187 ±0.020	9.9
316.8±0.3	1.000 ±0.100	52.8
351.9±0.5	0.005 ±0.002	0.3
≈360(?)	$\lesssim$0.0008	$\lesssim$0.04
369.1±0.4	0.004 ±0.001	0.2
415.6±0.3	0.025 ±0.003	1.3
467.9±0.4	0.014 ±0.002	0.7
491 ±1	≈0.0006	≈0.03
503.0±0.3	0.022 ±0.003	1.2

[a] Transition intensities were calculated on the basis of the multipolarities given in Table III (above 316.8 keV no corrections for conversion were made), and normalized so that an intensity balance was obtained using the decay scheme shown in Fig. 4.

[b] This intensity was calculated from the conversion electron data assuming the transition is $M1$.

Figure 3(b) shows the electron spectrum gated by 300- to 360-keV pulses from the 317-keV photopeak detected in a 3-in.×3-in. NaI(Tl) detector at ≈180° to the Si(Li) detector. (A very small contribution, <2%, from ^{143}Ce was determined at later times and subtracted.) There appear to be electron peaks at ≈16 and 22 keV, corresponding to the L- and M-conversion lines of a 23-keV transition. There also is some evidence for a peak on the high side of the M line which would be the proper position for a 23-keV γ ray. If this is assumed to represent a 23-keV photopeak, α_{L+M} can

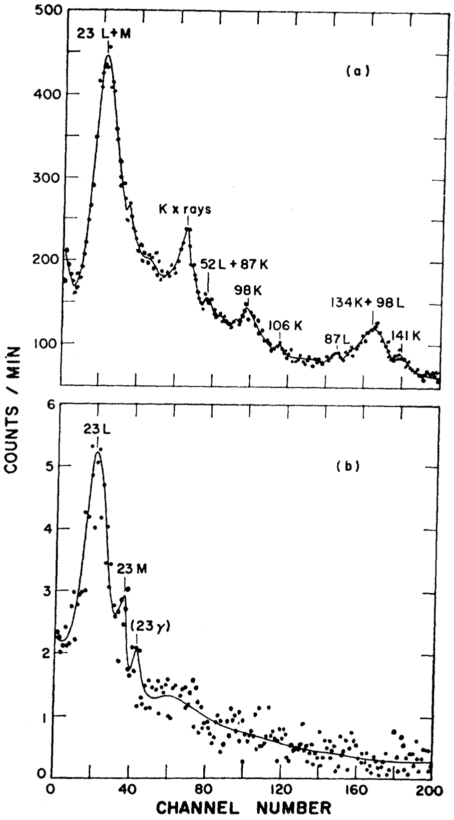

FIG. 3. (a) Ungated, low-energy electron spectrum of ^{146}Ce. (b) Electron spectrum of ^{146}Ce gated by 300- to 360-keV photopeak region. ^{143}Ce contribution has been subtracted from both spectra.

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[3] J. S. Geiger, R. L. Graham, and G. T. Ewan, Nucl. Phys. **16**, 1 (1960).

[4] L. A. Sliv and I. M. Band, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), Vol. 2, p. 1639.

[5] R. L. Graham, J. M. Hollander, and P. Kleinheinz, Nucl. Phys. **49**, 641 (1963).

be estimated to be 11±4. However, there is no evidence for a 28-keV L-conversion line from a possible 35-keV transition. A 35-keV photopeak would, of course, be masked by the K x radiation. The ratio of the L- to M-conversion lines from the 23-keV transition was estimated to be 4.8±1. Theoretical values of 4.5, 5.5, 3.1, and 4.2 for $M1$, $M2$, $E1$, and $E2$ transitions, respectively, have been estimated from the tables of Rose[6] after correcting the M-subshell values for screening according to the empirical method of Chu and Perlman.[7] However, observation of the weak 23-keV γ ray would rule out $E2$ and $M2$ multipolarity since their conversion coefficients are so high. ($\alpha_{L+M} > 900$ for $E2$ and >1500 for $M2$ multipolarity.) The experimentally observed L/M ratio of ≈ 4.8 and the estimated α_{L+M} of ≈ 11 seem more consistent with $M1$ than $E1$ multipolarity, since α_{L+M} is ≈ 11.4 for an $M1$ and ≈ 2.3 for an $E1$ transition. Therefore, the 23-keV transition has been assumed to be $M1$ and its intensity was calculated from the singles electron spectrum to be ≈ 1.36 times that of the 317-keV transition.

TABLE II. Electron lines associated with the decay of ^{146}Ce.

Electron energy (keV)	Assignment	Relative intensity[a]	Conversion coefficient[b]
≈ 16	$23L$	0.8	...
≈ 22	$23M$		
45	$52L+87K$	0.033	$(\alpha_{87K} \approx 1.7)$[c]; $\alpha_{52L} = 0.8$
57	$98K$[d]	0.071	1.0
64	$106K$	0.011	1.0
80	$87L$	0.011	1.0
≈ 91	$134K+98L$	0.10	$(\alpha_{134K} = 0.5)$[e]; $\alpha_{98L} \approx 0.11$
99	$141K$	0.026	0.3
127	$134L$	0.011	0.06
134	$141L$	0.006	0.07
169	$210K$	0.0046	0.039
176	$218K$	0.010	0.026
210	$251K$	≈ 0.005	≈ 0.08
222	$265K$	≤ 0.005	≤ 0.03
275	$317K$	0.008	0.008

[a] Electron intensities have been normalized through the K x-ray intensity to a 317-keV γ-ray intensity of 1.00.

[b] The accuracy of the absolute value of the conversion coefficients is estimated to be about ±30%.

[c] The experimental α_L value of 1.0 for the 87-keV transition indicates that it has $M1$ or $E2$ multipolarity ($\alpha_L = 0.2$ for an $M1$ and 1.5 for an $E2$ transition). Since $\alpha_K = 1.65$ for an $M1$ and 1.8 for an $E2$ transition, α_{87K} was taken to be 1.7, and its contribution was subtracted from the electron line intensity. Then α_{52L} was found to be 0.8, very close to the theoretical value of 0.9 for an $M1$ transition. ($\alpha_L = 0.2$ for an $E1$ and 16.5 for an $E2$ transition of 52 keV.)

[d] The $101K$ line could not be resolved from the presumably more intense $98K$ line.

[e] The 134-keV transition was taken to be $M1$ as indicated by the experimental value of 0.06 for α_{134L}. After subtraction of $\alpha_{134K} = 0.5$, the theoretical value for either an $M1$ or $E2$ transition, α_{98L} was calculated.

C. γ–X-Ray Coincidence Experiments

Coincidence experiments were performed in which either a xenon- or krypton-filled proportional counter was gated by pulses from the 317-keV photopeak (305–340 keV) detected in a 3-in.×3-in. NaI(Tl) detector covered with 1.85-g/cm² beryllium to absorb the β radiation. Low-energy electrons (≤ 130 keV) were not detected in the proportional counters because of the 23.5-mg/cm² beryllium windows. L x rays, which appeared to decay appropriately, were observed in the coincidence spectra from both types of experiments. Low-intensity 11- and 23-keV peaks were also observed in the coincidence spectrum from the krypton-filled counter. Although 23 keV is the same energy as the escape peak from the K_α x radiation, it is believed to represent a real γ ray since K x radiation itself was not observed in the coincidence spectrum. The peak at ≈ 11 keV would be the escape peak from a 23-keV photopeak. The small contribution ($\leq 10\%$) to the coincidence spectrum from the inclusion of some of the 293-keV photopeak from 33-h ^{143}Ce in the gate was determined at later times and subtracted. The 23-keV peak was not observed in the coincidence spectrum from the xenon-filled detector, presumably because of extremely low counting rates due to the relatively lower detection efficiency for that energy.

TABLE III. Conversion coefficients and probable multipolarity for some γ transitions.

Transition energy (keV)	α_K	α_L	K/L	Probable multipolarity
23	...	...	$L/M \approx 4.8$	($M1$)
52.0	...	0.8	...	$M1$
87.0	(1.7)	1.0	(1.7)	$E2$ (+$M1$)
98.3	1.0	0.11	9.0	$M1$
106.4	1.0	...	...	($M1$ or $E2$)
133.6	(0.5)	0.06	8.3	$M1$
141.2	0.3	0.07	4.3	$M1+E2$
210.3	0.039	...	...	$E1$
218.3	0.026	...	...	$E1$
250.9	≈ 0.08	...	...	($M1$,$E2$)
264.7	≤ 0.03	...	...	$E1$
316.8	0.008	...	...	$E1$

The 23-keV photopeak could not be seen in the singles spectra because of interference from the strong escape peak from K_α x radiation in the krypton detector, and from the escape peak of the 52-keV photopeak in the xenon detector.

IV. DECAY SCHEME AND DISCUSSION

The decay scheme shown in Fig. 4 is basically the same as that reported previously,[1] but incorporates the results of the present investigation in which more precise energies and additional conversion coefficients were determined. Furthermore, the low-intensity, higher-energy γ rays required a new level which was placed at 503.0 keV on the basis of energy difference considerations. The level is apparently fed by an ≈ 0.6-MeV β group with an intensity of $\approx 3\%$ and a logft value of ≈ 5.3, indicating an allowed β transition. The β-transition intensities were estimated on the

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[6] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Co., Amsterdam, 1958).

[7] Y. Y. Chu and M. L. Perlman, Phys. Rev. 135, B319 (1964).

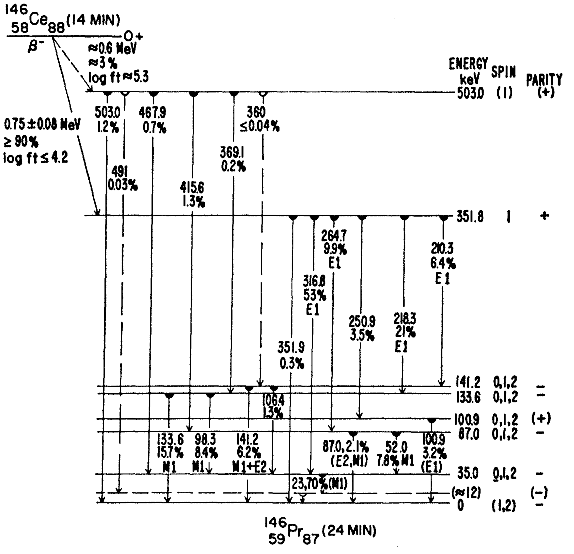

FIG. 4. Proposed decay scheme for 14-min ^{146}Ce. The open semicircles with dashed lines indicate doubtful transitions. The energy of the ≈0.6-MeV β transition was obtained by difference from the total decay energy (Ref. 1).

basis of the γ-transition intensities and the observation that there is little or no β population of the ^{146}Pr ground state and lowest energy levels.[1] If this β transition is indeed allowed, then the 503.0-keV level as well as the 351.8-keV level, is 1+. These even-parity states may be constructed from either spherical or deformed[8] orbitals, but in either case they originate from the same spherical basis states: $(h_{11/2})_p$ and $(h_{9/2})_n$ or $(f_{7/2})_n$. The 351.8-keV level has been postulated[1] to consist primarily of the configuration $(h_{11/2})_p \cdot (h_{9/2})_n$ to account for its population by rather allowed β decay ($\log ft = 4.2$) from the 0+ ground state of ^{146}Ce whose dominant configuration might be a pair of $h_{9/2}$ neutrons. Consistent with its population by less allowed β decay, the higher-energy 1+ level might be represented as the $h_{11/2}$ proton coupled to a $\frac{9}{2}-$ configuration resulting from three $f_{7/2}$ neutron holes.

It is interesting to point out that the population of the low-lying energy levels by these 1+ levels is quite different. The 503-keV level decays mostly to the ground and 87-keV states, while the 352-keV level principally excites the 35- and 134-keV levels. On the basis of the assigned spins and parities (Fig. 4), the 468-, 416-, and 369-keV transitions from the 503-keV level must be $E1$. Comparison of the ratio of the reduced transition probabilities for the 503- and 416-keV transitions with the theoretical single-particle estimates indicates that the 503-keV ground-state transition also has $E1$ multipolarity. The ^{146}Pr ground state is believed from studies of its β decay[9] to be 1−, 2−, or 3−, but the proposed $E1$ multipolarity of the 503-keV transition makes the 3− assignment unlikely. The presumably similar $E1$ ground-state transition from the 352-keV level seems to be highly hindered, again probably indicating a difference in the configurations of the two 1+ levels.

The levels at 141.2, 133.6, 87.0, and 35 keV are all populated by $E1$ transitions from the 352-keV level, establishing that they have negative parity and spins of 0, 1, or 2. There is no evidence for appreciable β population (<1%, $\log ft$ values >6.6) of the 87-, 101-, and 141-keV levels since a rather good intensity balance is obtained between γ population and de-excitation. On this basis there could be as much as 3% β population of the 134-keV level. However, this is within the estimated errors of our γ-intensity measurements, so the precision of the present data permits us to say only that the $\log ft$ value is ≥6.

The 101-keV level is fed by a 250.9-keV γ transition whose K-conversion coefficient of ≈0.08 indicates $M1$ or $E2$ multipolarity rather than $E1$ ($\alpha_K = 0.086$ for $M1$, 0.07 for $E2$, and 0.018 for $E1$). If the transition is either $M1$ or $E2$, the level has positive parity. The fact that the observed intensity of the 250.9-keV transition is comparable to those of the known $E1$ transitions also de-exciting the 351.8-keV level suggests an $M1$ rather than an $E2$ assignment. Spins of 0, 1, or 2 are then indicated for the 101-keV level. Although there is no evidence for any direct β feeding of the level, estimates of the extremes of our experimental errors enable us to set only a lower limit of 6.6 for this $\log ft$ value. The 101-keV level is de-excited by a 100.9-keV transition to the ground state. Its K-conversion line could not be resolved from the presumably stronger line from the 98-keV $M1$ or $E2$ transition. However, the experimentally measured α_K of 1.0 for the 98-keV transition is, if anything, lower than the theoretical values of 1.1 or 1.2 for $M1$ or $E2$ transitions and indicates that there is very little contribution from the 101-keV K line. A low α_K value for the 101-keV transition suggests that it is an $E1$ transition (theoretical $\alpha_K = 0.2$), again consistent with a positive parity assignment for the 101-keV level.

The existence of a level at 35 keV was postulated earlier on the basis of energy differences and coincidence data, although no means of depopulating the level was found. No evidence was found in the present study for a 35-keV γ transition, although the existence of a very weak transition cannot be ruled out. However, evidence for L x radiation, ≈16-keV conversion electrons and a possible weak 23-keV photopeak in coincidence with the 317-keV γ ray was found. The level is probably de-excited by a 23-keV transition of $M1$ multipolarity

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[8] The equilibrium deformation of ^{146}Pr has been calculated by G. P. Ford of this laboratory to be ≈0.10 to 0.15 by the method of Strutinsky [V. M. Strutinsky, Nucl. Phys. **A95**, 420 (1967)] using level energies calculated for a deformed Woods-Saxon potential.

[9] W. R. Daniels and D. C. Hoffman, Bull. Am. Phys. Soc. **9**, 562 (1964).

to a level at ≈12 keV. The only reason for placement of the level at ≈12 keV rather than 23 keV is the possible existence of a very weak 491-keV γ transition de-exciting the 503-keV level. The only evidence for depopulation of a 12-keV level would be L x radiation since even if it is $M1$, $E1$, or $E2$ it would be highly converted, and the ≈5-keV L- or ≈11-keV M-conversion electrons would be below our limits of detection. There was some evidence in the coincidence experiments for an excess of L x radiation over that expected for a pure $M1$ transition of 23 keV, but a quantitative number was not obtained.

There is still the possibility that the 12-keV level is de-excited by a higher multipole order transition and is delayed, or it could even be depopulated by two lower-energy transitions, one or both of which might not be energetic enough to be converted in the L shell.

ACKNOWLEDGMENTS

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Three-Quasiparticle Intruder State in Te^{125} and the Magnetic Moment of Sb^{125}†

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The levels of Te^{125} have been studied using Sb^{125} nuclei, polarized at $T=0.014$°K in an iron lattice, and Ge(Li) detectors. The magnetic moment of Sb^{125} was determined as $(2.59\pm0.03)\ \mu_N$. Levels (spins) were assigned at 35.9($\frac{3}{2}+$), 145.4($\frac{11}{2}-$), 322.2($\frac{9}{2}-$), 443.7(probably $\frac{3}{2}+$), 462.5($\frac{5}{2}+$), 525.4(probably $\frac{9}{2}-$), 636.1($\frac{7}{2}+$), 642.3($\frac{7}{2}+$), 671.6($\frac{5}{2}+$) (energies in keV). The even-parity levels could be identified with levels calculated by Kisslinger and Sorensen. Using their wave functions, we calculated $E2/M1$ mixing ratios and branching ratios, finding quite good agreement. The odd-parity states are of special interest. The $\frac{11}{2}-$ 145.4-keV state and $\frac{9}{2}-$ 525.4-keV state are assigned as $h_{11/2}$ quasiparticle and $h_{11/2}$ quasiparticle plus phonon. The $\frac{9}{2}-$ state at 322.2 keV is not predictable on a single-quasiparticle-plus-phonon theory, and is assigned as a three-quasiparticle $(h_{11/2})^3$ intruder state, bearing out Kisslinger's prediction that $(j^3)_{j-1}$ intruder states should be found in low-lying spectra for high j. Evidence for other intruder states in Rh^{100}, Ag^{109}, and Ag^{110} is given.

I. INTRODUCTION

ONE of the features of low-temperature equilibrium nuclear orientation which has been in the past alternately a boon and a serious limitation is the fact that it is a singles measurement (requiring no coincidence between the decay products observed) that yields rather directly the angular correlation coefficients F_k. Given the range of temperatures presently available, the maximum information about the angular distribution of the decay products from oriented nuclei may be obtained by using two detectors, usually along and normal to the axis of orientation, observing in each the decay product intensity as a function of energy and specimen temperature. In practice, in many cases this extreme simplicity has been lost through the failure of the detectors, in particular NaI(Tl) γ-ray detectors, to resolve the various components of the spectrum, and as a result the technique has been inapplicable to cases involving weak or closely spaced components in "complex" spectra.

The recent development of lithium-drifted germanium γ-ray detectors with resolutions of about 1–3 keV and efficiencies of the order of 10^{-3} at 500 keV has entirely changed the situation, with the result that many more transitions are accessible for study by the nuclear orientation method.

Another development of importance to nuclear orientation in recent years has been the polarization of nuclei of diamagnetic atoms when present as dilute impurities in a ferromagnet.[1] The ferromagnet is cooled to temperatures of the order 0.01°K by thermal contact with a paramagnetic cooling salt which is adiabatically demagnetized from magnetic fields of order 25 kOe at 1°K.

The present work combines these two extensions to

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

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[1] B. N. Samoilov, V. V. Skylarevski, and E. P. Stepanov, Zh. Eksperim. i Teor. Fiz. 36, 1366 (1959) [English transl.: Soviet Phys.—JETP 9, 972 (1959)].