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EXCITED STATES OF CERIUM-138
AND PRASEODYMIUM-138 POPULATED
BY BETA DECAY

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16. Abstract

Gamma rays emitted in the beta decay of 2.02-hour ^{138m}Pr, 1.44-minute ^{138}Pr, and 5.7-hour ^{138}Nd were studied with a Ge(Li) spectrometer. Eighteen gamma rays (plus annihilation radiation) were attributed to the decay of ^{138m}Pr. These can be fitted into a level scheme of ^{138}Ce with excited levels as follows: 788.8, 2^+; 1826.4, 4^+; 2129.1, 7^-; 2217.3; 2765.0; and 3799.9 keV. Twelve gamma rays were attributed to the decay of ^{138}Pr. These were used to establish the following excited levels in ^{138}Ce: 788.8, 2^+; 1477.0, 0^+; 1510.9, (2^+); 2236.8; and 2340.3 keV. The most interesting result is the discovery of the (2^+) level of ^{138}Ce at 1510.9 keV. Discussion is given of the possible interpretation of this level, together with the 0^+ level at 1477.0 and the 4^+ level at 1826.4 keV, as a "vibrational triplet" of states. In addition, seven gamma rays attributed to the decay of ^{138}Nd have been fitted into a level scheme of ^{138}Pr with excited levels at 193.6, 199.0, 325.9, and 540.8 keV.

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EXCITED STATES OF CERIUM-138 AND PRASEODYMIUM-138

POPULATED BY BETA DECAY

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SUMMARY

Sources of 2.02-hour praseodymium-138 (^{138m}Pr) and 1.44-minute praseodymium-138 (^{138}Pr) were made by the (p,n) reaction on enriched cerium-138 (^{138}Ce), and sources of 5.7-hour neodymium-138 (^{138}Nd) were produced by the (α, 2n) reaction on enriched cerium-136 (^{136}Ce). A 40-cubic-centimeter Ge(Li) detector was used to detect gamma rays emitted by these sources. Eighteen gamma rays plus annihilation radiation were attributed to the decay of ^{138m}Pr. Some of these can be fitted into a level scheme of the daughter ^{138}Ce with excited levels having energy (keV), spin, and parity as follows: 788.8±0.1, 2$^+$; 1826.4±0.2, 4$^+$; 2129.1±0.3, 7$^-$; 2217.3±0.3; 2765.0±0.3; and 3799.9±0.4. Twelve gamma rays plus annihilation radiation were attributed to the decay of ^{138}Pr. These can be used to establish the following levels in ^{138}Ce: 788.8±0.1, 2$^+$; 1477.0±0.2, 0$^+$; 1510.9±0.2, (2$^+$); 2236.8±0.4; and 2340.3±0.3.

The most interesting result of this investigation is the discovery of the (2$^+$) level of ^{138}Ce at 1510.9 keV. Discussion is given of the possible interpretation of this level, together with the 0$^+$ level at 1477.0 keV, as a "vibrational triplet" of states.

In addition, seven gamma rays attributed to the decay of ^{138}Nd have been fitted into a level scheme of ^{138}Pr with levels at 193.6±0.2, 199.0±0.2, 325.9±0.2, and 540.8±0.3 kev.

INTRODUCTION

Results of many experiments have shown that a simple vibrational model (refs. 1 to 4) is not completely adequate for describing the nature of low-lying energy levels in nearly spherical, even-even nuclei. Difficulties for the model include the discovery of crossover transitions from the presumed two-phonon second excited states to the ground

state, which indicates that the vibrations cannot be purely harmonic, and the discovery of a considerable static quadrupole moment of the first 2^+ state of nuclei, which had been supposed to be nearly spherical (refs. 5 and 6). To help in the development of a more satisfactory theory, experimental data on the properties of nearly spherical even-even nuclei are needed.

This investigation was undertaken to obtain data on the excited states of cerium-138 (^{138}Ce). These states were populated in the beta-decay of 1.4-minute praseodymium-138 (^{138}Pr) and the 2-hour isomer of praseodymium-138 (^{138m}Pr). In the course of this study, new information was also obtained about excited states of the parent nucleus ^{138}Pr populated in the beta-decay of neodymium-138 (^{138}Nd).

The decay of the 2-hour ^{138m}Pr has been studied several times before, most recently with a 0.3-cubic-centimeter lithium drifted germanium detector (ref. 7). The 1.4-minute ground state, 1^+ ^{138}Pr, was recently discovered (refs. 8 and 9). From these studies the following levels (energy, spin, and parity) in ^{138}Ce were reported: ground state, 0^+; 786 keV, 2^+; 1478 keV, 0^+; 1817 keV, 4^+; 2118 keV, 7^-; 2206 keV, (5 or 6); and 2752 keV, (5 or 6). Of particular interest in the present work was the possible existence of a 2^+ second excited state near 1500 keV that is predicted by a simple vibrational model. If this 2^+ member of the triplet exists, then its population in the decay of 1^+ ^{138}Pr would be allowed by beta-decay selection rules.

EXPERIMENTAL PROCEDURE

Source Preparation

Sources of 2-hour ^{138}Pr were prepared for the present study by the (p, n) reaction on enriched ^{138}Ce obtained from the Oak Ridge National Laboratory. The target material contained 13.10 percent ^{138}Ce, 0.28 percent ^{136}Ce, 83.88 percent ^{140}Ce, and 2.74 percent ^{142}Ce. Dry powder targets, either as cerium oxide or cerium chloride, were bombarded for approximately 1 hour with 10-MeV protons in the Lewis Research Center cyclotron. No chemical separations of the irradiated material were performed.

Sources of 1.4-minute ^{138}Pr were prepared from the chloride target material as described previously but for a bombardment time of only 1 minute.

Sources of 5-hour ^{138}Nd were also prepared in this investigation as another way of making ^{138}Pr, in this case by beta-decay. The ^{138}Nd was made by the (α, 2n) reaction on enriched ^{136}Ce in the form of cerium chloride. The target material contained 22.24 percent ^{136}Ce, 0.56 percent ^{138}Ce, 71.41 percent ^{140}Ce, and 5.80 percent ^{142}Ce. Dry powder targets were bombarded for approximately 4 hours with alpha par-

ticles having energies of 19, 31, or 37 MeV. (Three bombarding energies were used to help identify contaminant activities.) These beam energies were obtained by passing the 42-MeV cyclotron beam through metallic beryllium foils of the proper thickness. No chemical separations were performed on the targets after bombardment.

Equipment

Gamma rays from the irradiated targets were recorded with a 40-cubic-centimeter lithium drifted germanium detector, a low noise pulse amplifier, and a 4096-channel pulse-height analyser. The resolution of this spectrometer was about 5 keV full width at half maximum for 1-MeV gamma rays.

Data Analysis

The gamma ray spectra were analyzed by using the least-squares method to fit curves representing peaks, Compton edges, and a background continuum to the data. The values of peak location and intensity and also the statistical uncertainties in these quantities were obtained from these fits.

The functions used in the least-squares fitting were derived by folding the expected electron energy spectrum into the response functions of the detector-amplifier system and the pulse-height analyzer. The electron energy spectrum of photopeaks was assumed to be a delta function at the full gamma-ray energy. The spectrum of Compton edges was obtained from the Klein-Nishina formula for the number-energy distribution by expanding that equation about the edge energy and dropping all but the first two terms in the expansion. The response function of the detector-amplifier system was assumed to be Gaussian, and the pulse-height analyzer was assumed to have perfectly sharp channel edges.

An empirical relative photopeak efficiency curve, figure 1, was used in determining relative intensities of gamma rays. The data points in figure 1 were obtained by comparing the measured relative peak intensities from a particular isotope to the relative gamma ray intensities reported in the literature for that isotope. Several isotopes were used (refs. 10 and 11); the data for each isotope were normalized to obtain an efficiency curve covering the entire energy range. The errors assigned to the relative intensity results of the present study allow for a 10-percent uncertainty in relative photoefficiency values from this curve.

The energies of gamma ray peaks were determined from a calibration equation for each spectrum in which the energy is given as a third order polynomial in pulse-height-analyzer channel number. Standards used for energy calibration were annihilation

(511.006 keV), bismuth-207 (569.62, 1063.44, 1769.71 keV), cobalt-56 (846.76, 1037.97, 1238.34, 1360.35, 1771.57, 2015.49, 2035.03, 2598.80 keV), cobalt-57 (121.94, 136.31 keV), iodine-131 (80.16, 284.31, 364.47 keV), potassium-40 (1460.75 keV), thallium-208 (2614.47 keV), and yttrium-88 (898.04, 1836.13 keV). The energies of intense gamma rays emitted by the isotopes under study were determined from spectra of these isotopes taken simultaneously with the standards. These intense gamma rays were then used as internal calibration peaks in determining energies of the weaker gamma rays not observed in the mixed source spectra. Uncertainties given for the gamma ray energy results include allowance for uncertainties in the energies of the calibration photopeaks and for uncertainties in the channel locations of both the calibration photopeaks and the unknown photopeaks.

Half lives of intense gamma rays were determined from peak intensities of successive spectra. With the source position fixed, spectra were recorded for several intervals of time. The half life was then determined by a least-squares analysis of the time dependence of the gamma ray peak intensities. In this analysis the time duration of each spectrum was taken to be that measured by the "live time" clock of the pulse-height analyser. The mean time of each interval, determined by an ordinary clock, was used to represent the time at which the corresponding spectrum was taken. The uncertainty reported for the half life is that caused by statistical uncertainties in the peak intensities and in the spectrometer live time. Occasionally a peak was found to be composed of two components with differing half lives. The analysis yielded the relative intensities of these components.

RESULTS AND LEVEL SCHEME FOR DECAY OF ^{138m}Pr

Gamma Ray Spectrum

Figure 2 shows a gamma ray spectrum of ^{138m}Pr recorded for a duration of 45 minutes, beginning about 2 hours after the end of the bombardment. Energies of the gamma rays attributed to the decay of ^{138m}Pr are indicated in figure 2 and are listed in table I with the gamma ray relative intensities (corrected for detector efficiency).

The first seven nuclear gamma rays listed in table I were sufficiently intense that their half lives could be obtained. These values are given in table II; the weighted average of these seven measurements is 2.023±0.003 hours and this is taken as the half life of ^{138m}Pr. (The small error given here takes into account only statistical fluctuations; the effect of possible systematic errors has not been included.) The other gamma rays listed in table I were attributed to the decay of ^{138m}Pr because, within statistical uncertainty, their relative intensities remained constant in time. Peaks at

1091, 1340, and 1824 keV, unlabeled in figure 2, are attributed to coincidence summing of the strong 303-, 789-, and 1038-keV gamma rays, since their relative intensities were found to depend on the distance (typically 5 to 10 cm) between source and detector.

^{138}Ce Level Scheme Excited in Decay of ^{138m}Pr

In the most recent investigation (ref. 7) of the decay of the 2-hour isomer ^{138m}Pr, the following excited levels in ^{138}Ce have been reported: 786 keV, 2^+; 1817 keV, 4^+; 2118 keV, 7^-; 2206 keV, (5 or 6); and 2752 keV, (5 or 6). The results of the present investigation are consistent with these results.

The proposed decay scheme for ^{138m}Pr is given in figure 3(a). Energy levels in ^{138}Ce have been assigned by using the results of previous workers (ref. 12) and by searching for combinations of gamma rays from table I whose energies add within experimental error (3σ) to the same sum. Evidence is inadequate for placing 10 of the 18 gamma rays attributed to ^{138m}Pr in the decay scheme of figure 3(a). The intensity of these ten gamma rays represents only 0.9 percent of the total nuclear gamma ray intensity observed.

The present results indicate excited levels of ^{138}Ce at 788.8±0.1, 1826.4±0.2, 2129.1±0.3, 2217.3±0.3, 2765.0±0.3 and 3799.9±0.4 keV. All but the last of these levels have been previously reported (ref. 7). The log ft values and relative intensities of the transitions from ^{138m}Pr were calculated from the intensities of the gamma rays (table I) and the maximum positron energy (ref. 12). For the two levels more weakly populated by positron emission, the intensity ratio of K-electron capture to positron emission was assumed to be the value obtained theoretically for allowed beta decay (ref. 13); the remaining positron intensity was ascribed to the group populating the 2129.1-keV level. Formulas and graphs in appendix IV of reference 13 were used to estimate that capture of electrons from higher shells was 16 percent of capture from the K shell for all capture transitions shown in figure 3(a). On the basis of the conversion electron studies in reference 12, it was assumed that only the 302.7-keV transition between the 2129.1- and 1826-keV levels is significantly converted. (It is calculated that 6 percent of the 302.7-keV transitions give rise to conversion electrons.)

RESULTS AND LEVEL SCHEME FOR DECAY OF ^{138}Pr

Gamma Ray Spectrum

Spectra of ^{138}Pr sources made by the 1-minute proton bombardments were recorded in four successive 1.5-minute intervals, the first interval beginning about 1.5 minutes after the end of the bombardment. The data for each interval were stored

in separate quarters of the 4096 channel memory of the pulse-height analyser. This process was repeated for 12 bombardments in order to obtain better counting statistics. The sum of the 12 spectra taken in the first of the 1.5-minute intervals is shown in figure 4.

The gamma rays having energies of 688, 789, and 1552 keV were sufficiently strong in these data for half-life analysis. The half life results are given in table III; the weighted average of these values is 1.44±0.09 minutes and this is taken as the half life of ^{138}Pr. The half-life analysis revealed that the spectrum of figure 4 contains gamma rays due to 2-hour ^{138}Pr, 13-minute ^{136}Pr (ref. 14 and data obtained from B. H. Ketelle of Oak Ridge National Laboratory) and 3.2-minute ^{140}Pr (ref. 15 and data obtained from W. H. Kelly of Michigan State University). The annihilation radiation from these contaminants, particularly ^{140}Pr, was so intense that a statistically significant value of the intensity of annihilation radiation from ^{138}Pr alone could not be measured.

Gamma rays from the decay chain ^{138}Nd → ^{138}Pr → ^{138}Ce were also studied in the present investigation. Figure 5 shows a spectrum of gamma rays emitted by a target of enriched ^{136}Ce bombarded with 31-MeV alpha particles. This spectrum was obtained by counting for $1\frac{1}{2}$ hours, beginning 17 hours after the bombardment ended. Background has been subtracted. Although the contamination is considerable, several gamma rays plus annihilation are attributed to the ^{138}Nd → ^{138}Pr → ^{138}Ce chain.

Gromov obtained a value (ref. 9) of 5.2±0.1 hours for the half life of ^{138}Nd. This is too close to the 5.5-hour half life (ref. 16 and data obtained from W. H. Kelly of Michigan State University) of ^{139m}Nd for the two isotopes to be conveniently sorted out by their half lives. Hence, ^{139m}Nd was produced separately so that its gamma rays could be identified. For this purpose 19-MeV alpha particles were used to bombard the ^{136}Ce target. This energy was sufficient to produce ^{139m}Nd but not ^{138}Nd. As a further aid to identification of contaminants in the spectrum of figure 5, a target bombarded at 37 MeV was also studied. In figure 6, the spectrum of these three sources (19-, 31-, and 37-MeV alpha energy) is compared. Only the middle spectrum, which is a duplicate of the data in figure 5, has had background subtracted.

The spectrum of ^{139m}Nd, figure 6(c), is in good agreement with that reported in reference 16. Gamma rays from ^{139m}Nd and its daughters are marked with a ∇ symbol in the 31-MeV spectrum of figure 5. The present study, like those of Gromov (refs. 8 and 9), has revealed no evidence of the 22-minute ^{138}Nd activity reported by Stover (ref. 17). Other contaminants observed are ^{141}Nd (ref. 18) marked with a □ symbol, ^{142}Pr (ref. 13) marked with a ○ symbols, ^{138}Pr (energies given in parentheses), and ^{135}Ce (ref. 19) marked with a 1 symbol.

Gamma rays were assigned to the ^{138}Nd → ^{138}Pr → ^{138}Ce decay chain if their intensities relative to the 688-keV peak remained constant in time within statistical uncertainty, and also remained the same whether 37- or 31-MeV alpha particles were

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used to produce the source. The intense low energy gamma rays which passed these tests but were not seen in the decay of ^{138}Pr (fig. 4) were attributed to the decay of ^{138}Nd to ^{138}Pr. The energies of these gamma rays are underscored in figures 5 and 6. Energies of gamma rays attributed to the decay of ^{138}Pr to ^{138}Ce are indicated in figures 4 to 6 and are listed in table IV with the gamma ray relative intensities. The weakest of these gamma rays cannot be seen in figure 4, but counting statistics in the spectrum of figure 4 are poor enough that such weak gamma rays should not be visible there.

The apparent half lives of the 688- and 1552-keV peaks in the ^{138}Nd → ^{138}Pr → ^{138}Ce spectra were determined; the mean value obtained was 5.7±0.3 hours, in fair agreement with the value 5.2±0.1 hours obtained by Gromov (ref. 9) for the half life of ^{138}Nd. (The 788-keV peak was not included because it had both the 1.4-min and the 2-hr components.)

^{138}Ce Level Scheme Excited in Decay of ^{138}Pr

In the more detailed study of ^{138}Nd and ^{138}Pr (ref. 9), beta rays and conversion electrons were studied with a plastic scintillator and a magnetic spectrometer; gamma rays were detected with a 30 by 30 millimeter sodium iodide crystal. It was reported (ref. 9) that ^{138}Pr decays with a half life of 1.5±0.15 minutes and populates a 0^+ level of ^{138}Ce at 1478 keV as well as the ground and first-excited states. The decay properties of ^{138}Pr indicate it is 1^+. The results of the present investigation are consistent with these earlier results.

The proposed decay scheme for ^{138}Pr is given in figure 3(b). Levels in ^{138}Ce have been assigned by using the results of reference 9, the energy and intensity values given in table IV, and from combinations of gamma ray energies in the manner described in the section on ^{138m}Pr decay. These results indicate excited levels of ^{138}Ce at 788.8±0.1, 1477.0±0.02, 1510.9±0.2, and 2236.8±0.4 keV.

One more level may be tentatively assigned. By analogy with the level schemes of nuclei expected to be similar to ^{138}Ce, the 1551.5-keV transition most likely terminates on the 788.8-keV level of ^{138}Ce. This would put a level in ^{138}Ce at 2340.3±0.3 (shown dotted in fig. 3(b)); this level might be analogous to the 2141-keV level in barium-136 (^{136}Ba), which is comparatively strongly fed in the beta decay of 1^+ lanthanum-136 (^{136}La) (refs. 20 and 21 and data obtained from R. A. Meyer of the Lawrence Radiation Laboratory). It must also be admitted however that the 2237±1-keV transition (table IV) is just 2.7 keV away from the sum of 688.2±-.1 and 1551.5±0.2 keV. Hence, energy considerations suggest that the 1551.5-keV transition may be to the 1477.0-keV level

of ^{138}Ce. Also consistent with this possibility is the fact that the 1551.5-keV gamma ray is less intense than the 688.2-keV gamma ray.

Evidence is insufficient for placing in the decay scheme 5 of the 12 gamma rays attributed to ^{138}Pr. The intensity of these five gamma rays represents 6 percent of the total nuclear gamma ray intensity observed.

In constructing the decay scheme of ^{138}Pr, log ft values and relative intensities of transitions were calculated in a manner similar to that already described for ^{138m}Pr. For each of the levels populated directly by positron emission, the intensity of K-electron capture to positron emission was assumed to be the value obtained theoretically for allowed beta decay (ref. 13). The maximum positron energy was taken as 3.44 MeV (ref. 9). For table IV and for the log ft calculations it was assumed that essentially all of the positrons emitted in the chain ^{138}Nd → ^{138}Pr → ^{138}Ce are emitted by ^{138}Pr. This seems a reasonable assumption for the following reasons. While there are no measured values for the nuclear mass difference between ^{138}Nd and ^{138}Pr, a theoretically calculated value (ref. 22) is 1.31 MeV. This would indicate that for decays of ^{138}Nd to the ground state of ^{138}Pr, positron emission is only about 1/35 as frequent as electron capture; for decays to excited states of ^{138}Pr, the ratio would be even smaller.

Decay of ^{138}Nd to ^{138}Pr

Intense low-energy gamma rays, attributed to the decay chain ^{138}Nd → ^{138}Pr → ^{138}Ce but not observed in the decay of ^{138}Pr alone (fig. 4), are assumed to be emitted in the decay of ^{138}Nd to ^{138}Pr. The energies of these gamma rays are shown underscored in figure 5 and are listed in table V together with their relative intensities. The intensity of annihilation radiation from ^{138}Nd has not been determined in this study; as mentioned in the preceding discussion, it is believed to represent only a small fraction of the annihilation radiation from the ^{138}Nd → ^{138}Pr → ^{138}Ce chain.

All the gamma rays attributed to the decay of ^{138}Nd have been fitted into the level scheme of the odd-odd nucleus ^{138}Pr (fig. 7). This includes levels of ^{138}Pr at 193.6±0.2, 199.0±0.2, 325.9±0.2, and 540.8±0.3 keV. These levels have been deduced on the basis of gamma ray energies and relative intensities. The use of gamma ray energies and intensities alone is risky since there are several low-energy transitions which will be significantly internally converted (ref. 23); no studies of conversion electrons have been made. (For example, the 132.6 keV - 193.6 keV gamma ray cascade may be inverted: when allowance is made for internal conversion the intensity balance may dictate placing a level at 132.6 keV rather than at 193.6 keV.) Both the

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193.6- and 199.0-keV levels are shown dotted because the total energies of the indicated gamma ray cascades are in only fair agreement with the energy of the indicated crossover transition.

DISCUSSION OF RESULTS

Excited States in ^{138}Ce

The excited states of ^{138}Ce identified in this study are given in figure 3. Those populated in the decay of ^{138m}Pr, aside from the newly reported level at 3799.9 keV, are in reasonable agreement with the levels identified by other workers (ref. 7). Three previously unreported levels populated in the decay of ^{138}Pr are proposed here.

The most interesting result of this study is the discovery of an excited state of ^{138}Ce at 1510.9±0.2 keV, or 1.92 times the energy of the 2^+ first excited state. If we assume allowed beta decay and if we assumed essentially all of the positrons emitted in the ^{138}Nd → ^{138}Pr → ^{138}Ce chain are emitted by ^{138}Pr, then the log ft calculated for beta decay to the 1510.9-keV level is 6.5, consistent with the assumption of allowed transitions. The 1510.9-keV level decays by a "crossover" transition to the ground state and by a "stopover" transition to the first excited state. The ratio of intensities of these two transitions is found to be $I(1510.5 \text{ keV})/I(722.3 \text{ keV}) = 1.7±0.5$

By analogy with neighboring nuclei, it seems likely that the 1510.9-keV level of ^{138}Ce is a second 2^+ level (here denoted $(2^+)'$). When this is assumed and when the $(2^+)' → 2^+$ transition is assumed to be a pure electric quadrupole, the previous intensity ratios correspond to a ratio of reduced transition probabilities of

$$\frac{B\left[E2; (2^+)' → 0^+\right]}{B\left[E2; (2^+)' → 2^+\right]} = \left[\frac{I(1510.5 \text{ keV})}{I(722.3 \text{ keV})}\right]\left(\frac{722.3}{1510.5}\right)^5 = 0.043±0.013$$

Apparently similar levels have been reported in recent studies of xenon-134 (^{134}Xe) and barium-136 (^{136}Ba), two isotones of ^{138}Ce. In their study of the decay of iodine-134 (^{134}I) to ^{134}Xe, Winn and Sarantites (refs. 24 and 25) reported finding a $2^{+'}$ level at 1.90 times the energy of the 2^+ first excited state. The crossover-to-stopover ratio $I(2^{+'} → 0^+)/I(2^{+'} → 2^+)$ was 1.08±0.10; if the $2^{+'} → 2^+$ transition is E2, then the corresponding ratio of reduced transition probabilities is 0.026. In studying the decay of lanthanum-136 (^{136}La) to ^{136}Ba, Griffioen, Meyer, and Gunnink (ref. 21) reported finding a $2^{+'}$ level of ^{136}Ba at 1.90 times the energy of the first excited state. Their result for the crossover-to-stopover ratio $I(2^{+'} → 0^+)/I(2^{+'} → 2^+)$ was 1.0±0.2; they

reported the ratio of reduced transition probabilities to be $B(E2; 2^{+'} \to 0^+)$ /$B(E2; 2^{+'} \to 2^+) = 0.023$. The nearby nuclei barium-134 (^{134}Ba, ref. 20) and xenon-132 (^{132}Xe, ref. 26) have $2^{+'}$ states at, respectively, 1.93 and 1.94 times the energy of the 2^+ first excited state, although for these nuclei the crossover transition is much less intense than the stopover transition.

Since the spin and parity of the 1510.9-keV level have not actually been measured, the probable assignment must remain enclosed in parentheses - (2^+). This level, together with the 0^+ level at 1477.0 keV, identified from conversion electron studies (ref. 8), and the 4^+ level at 1826.4 keV, identified from angular correlation and internal conversion coefficient measurements (ref. 12), constitute a close lying 0^+ - (2^+) - 4^+ triplet of states at about twice the energy of the 2^+ first excited state of ^{138}Ce. The crossover transition from the $(2^{+'})$ state is more intense than the stopover transition; this is not consistent with the assumption of harmonic or nearly harmonic vibrations. Nevertheless, it is possible to interpret these three states as the famous two-phonon 0^+ - 2^+ - 4^+ "vibrational triplet" of states, separated in energy due to anharmonicity in the nuclear potential (refs. 1 to 3). Kisslinger and Kumar (ref. 27) have pointed out that fairly intense crossover transitions from a "two-phonon" state can be explained if single- and multiple-phonon wave functions are mixed with the two-phonon wave function and the ground-state wave function. No definitive judgement can be made as to whether, or not these three states really constitute a two-phonon vibrational triplet until there is some experimental evidence - say from inelastic scattering off ^{138}Ce - that these states are collective excitations. An alternative interpretation which should be kept in mind is that the 4^+ state may be part of a "quasirotational band" (ref. 28) and that the 0^+ state may be related to the 0^+ state at 1903.0 keV in cerium-140 (refs. 13 and 15).

While neighboring nuclei are being compared, it must be pointed out that Griffioen, Meyer, and Gunnink (ref. 21) have identified close-lying 0^+, 2^+, and 4^+ states in ^{136}Ba and have interpreted them as a vibrational triplet. In the decay of ^{136}La to ^{136}Ba, as in the decay of ^{138}Pr to ^{138}Ce, the triplet member identified as 0^+ is much more strongly fed than the triplet member identified as 2^+. In addition, a 0^+ level has been tentatively reported (ref. 29) in ^{132}Xe, giving that nucleus a close-lying 0^+ - 2^+ - 4^+ group of states at about twice the energy of the 2^+ first excited state.

Excited States in ^{138}Pr

If ^{138}Pr is viewed in terms of the simple shell model, one concludes from spins and parities of levels in neighboring odd-mass nuclei (ref. 13) that an $s_{1/2}$, $d_{3/2}$, or $h_{11/2}$ neutron and a $d_{5/2}$ or $g_{7/2}$ proton combine to form the low lying levels of

^{138}Pr. Thus, the 1^+ ground state would consist of a $d_{5/2}$ proton coupled to a $d_{3/2}$ neutron. The $(7, 6, 8)^-$ isomeric state, which is not populated in the decay of ^{138}Nd but which can be placed 340 keV above the ground state of ^{138}Pr on the basis of positron measurements (ref. 9), would consist of a $d_{5/2}$ proton coupled to an $h_{11/2}$ neutron. Presumably the other states could be explained in terms of particles or quasiparticles in these shell model states.

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TABLE I. - ENERGIES AND REL-

ATIVE INTENSITIES OF GAMMA

RAYS FROM ^{138m}Pr MEAS-

URED IN THIS STUDY

Energy, keV	Relative intensity
302.7±0.1	88±12
390.9±0.1	6.0±0.9
[a]511.006±0.002	63±11
547.8±0.1	5.2±0.7
635.9±0.1	1.8±0.3
788.8±0.1	100
1037.6±0.2	100±14
[b]1239.4±0.1	1.1±0.2
[b]1347.9±0.2	.39±0.07
[b]1453.0±0.3	.22±0.04
[b]1527.7±0.4	.10±0.02
1583.0±0.5	.14±0.03
1670.5±0.4	.12±0.02
[b]1709.4±0.4	.09±0.02
[b]1808.4±0.3	.20±0.03
[b]1864.6±0.3	.19±0.03
[b]1884.4±0.4	.10±0.02
[b]1956.8±0.5	.09±0.02
[b]2027.9±0.3	.22±0.04

[a]Annihilation radiation. Energy
  value adopted from ref. 10.
[b]Not placed in decay scheme of
  fig. 3.

TABLE II. - MEASURED HALF-LIVES OF

GAMMA RAYS FROM ^{138m}Pr

Gamma-ray energy, keV	Half-life, hr
302.7	2.017±0.0035
390.9	2.039±0.026
547.8	2.028±0.039
635.9	2.040±0.094
788.8	2.003±0.0056
1037.6	2.068±0.0064
1239.4	2.441±0.14
	Weighted average 2.023±0.003

TABLE III. - MEASURED HALF-LIVES OF

GAMMA RAYS FROM ^{138}Pr

Gamma-ray energy, keV	Half-life, min
688.2	1.41±0.11
788.8	1.43±0.17
1551.5	1.72±0.29
	Weighted average 1.44±0.09

TABLE IV. - ENERGIES AND REL-

ATIVE INTENSITIES OF GAMMA

RAYS EMITTED IN THE DECAY

OF ^{138}Pr TO ^{138}Ce

Energy, keV	Relative intensity
[a]511.006±0.002	[b]≲4300±700
688.2±0.1	33±5
722.3±0.2	2.1±0.5
788.8±0.1	[c]100
[d]1082.3±0.4	1.5±0.4
[d]1431.0±0.4	3.4±0.6
1447.9±0.4	4.8±0.8
1510.5±0.3	3.7±0.6
1551.5±0.2	17±2
[d]1893.5±0.3	2.6±0.5
[d]2116±1	1.2±0.3
2237±1	3.2±0.6
[d]2472±1	2.6±0.5

[a]Annihilation radiation. Energy value adopted from ref. 10.
[b]Number represents all the annihilation radiation from the ^{138}Nd → ^{138}Pr → ^{138}Ce chain.
[c]Correction was made for ^{138m}Pr contaminant made by ^{136}Ce(α,d) ^{138m}Pr.
[d]Not placed in decay scheme of fig. 3. fig. 3.
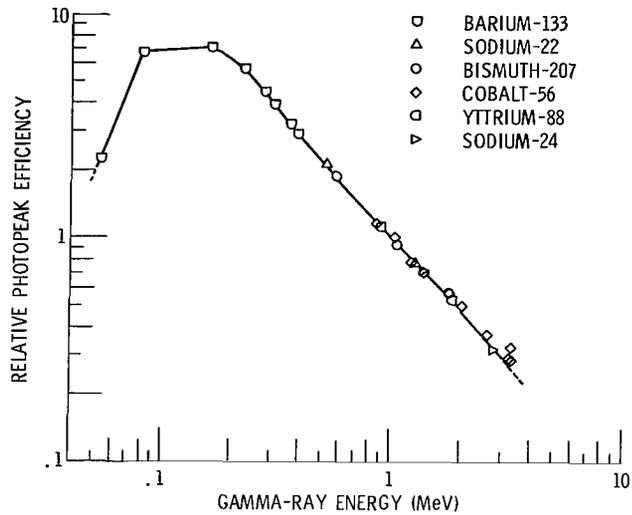
Figure 1. - Empirical relative-photopeak-detection-efficiency variation for 40-cubic-centimeter Ge(Li) detector. Actual relative gamma-ray intensities were obtained from references 10 and 11.

TABLE V. - ENERGIES AND REL-

ATIVE INTENSITIES OF GAMMA

RAYS EMITTED IN THE DECAY

OF ^{138}Nd TO ^{138}Pr

Energy, keV	Relative intensity
125.9±0.5	4.7±0.7
132.6±0.1	7.1±1
193.6±0.2	8.5±1
199.0±0.2	18±3
214.8±0.3	10±1
325.4±0.4	100
[a]511.006±0.002	-------
540.8±0.3	1.9±0.4

[a]Annihilation radiation. Energy value adopted from ref. 10. Intensity value not obtained in this study.

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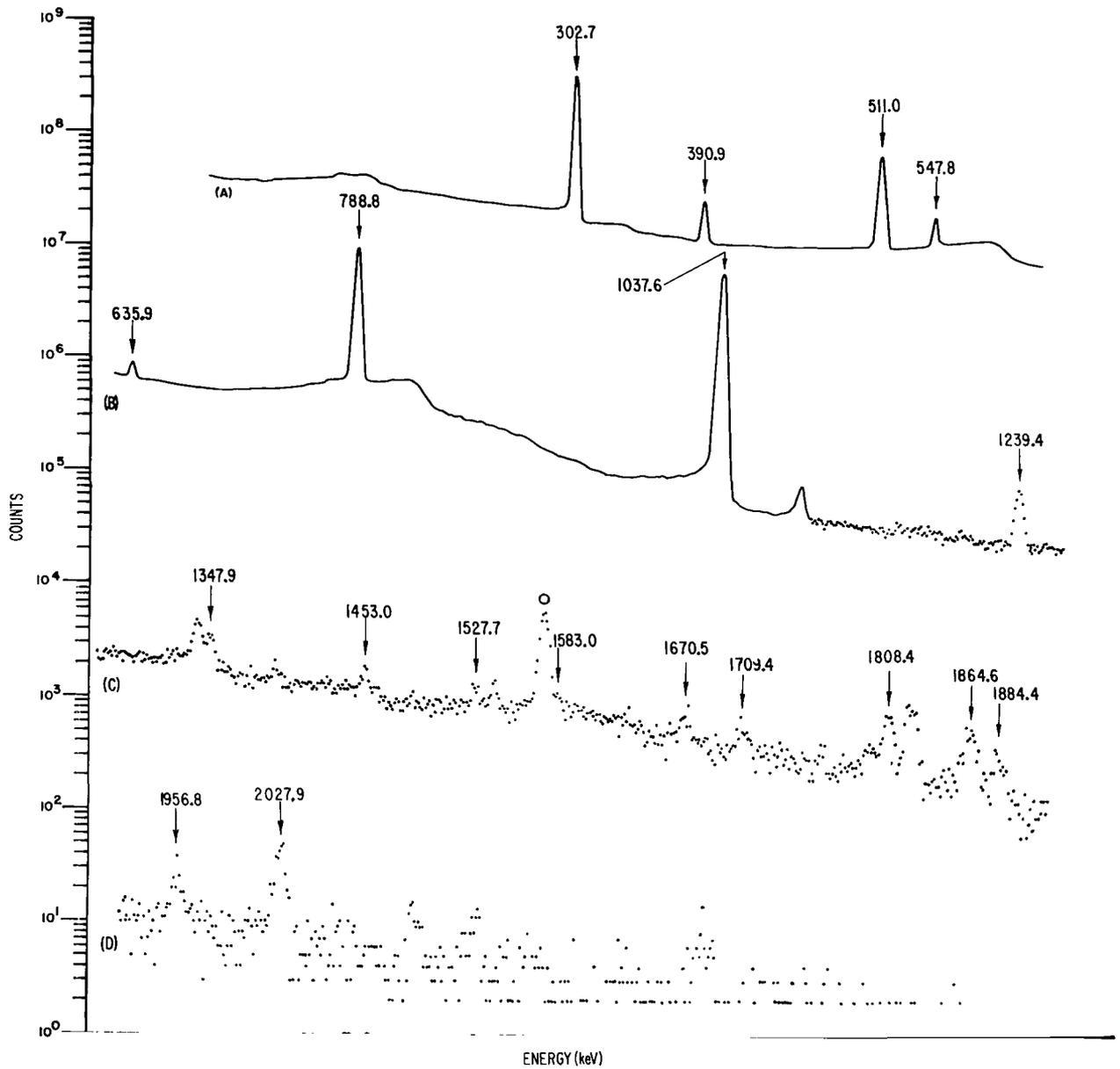
Figure 2. - Gamma-ray spectrum of 2-hour [138m]Pr. A peak due to [142]Pr is designated by the symbol ○. Energy scale graduation has been omitted and spectrum folded 4 times to reduce length. Individual data points are replaced by smooth line in part of spectrum. For convenience in reading, counts in part (A) have been multiplied by 1000, counts in part (B) have been multiplied by 100, and counts in part (C) have been multiplied by 10.

17
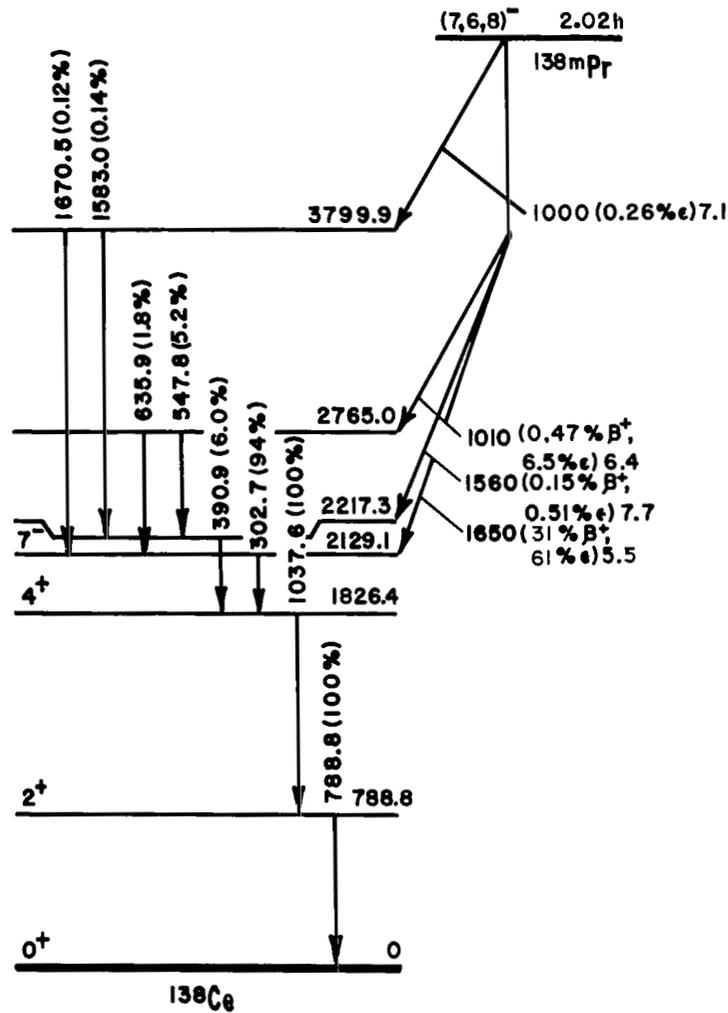
(a) Populated in beta decay of 2-hour ^{138}Pr. (Spin assignments are from ref. 12.)
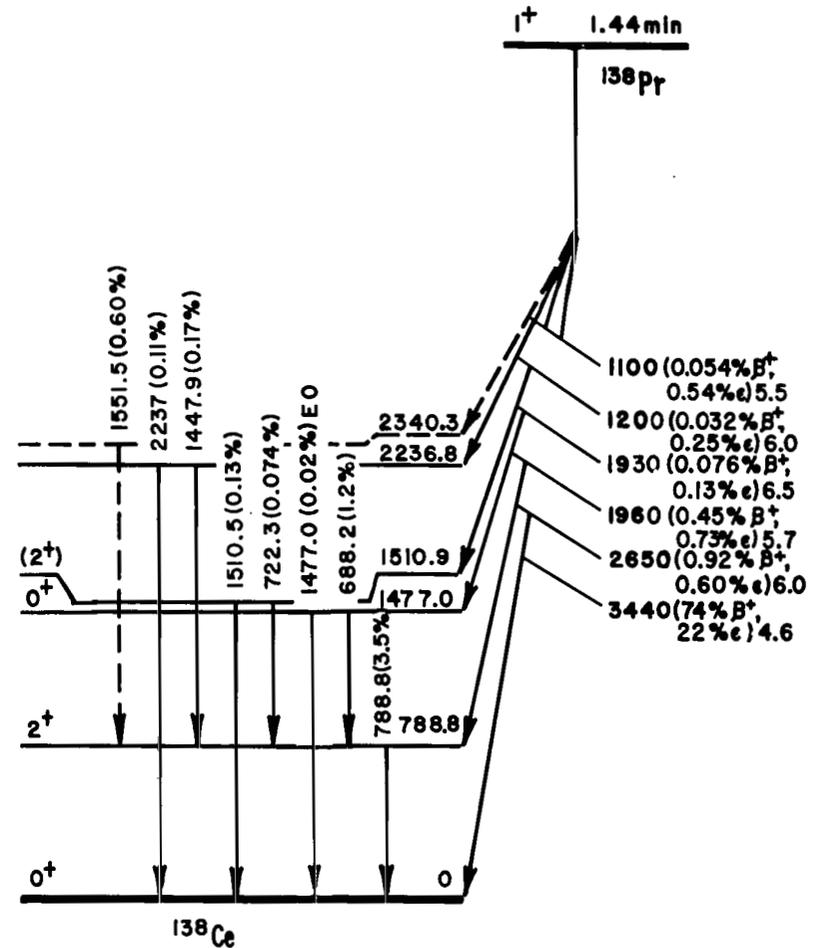
(b) Populated in beta decay of 1.5-minute ^{138}Pr. (Spin assignments, except for that of the 1510.9 keV level, are from ref. 9.)

Figure 3. - Energy levels of ^{138}Ce. Energies are in keV. Gamma-ray intensities, expressed in terms of percent decays of the parent isotope, are shown in parentheses.
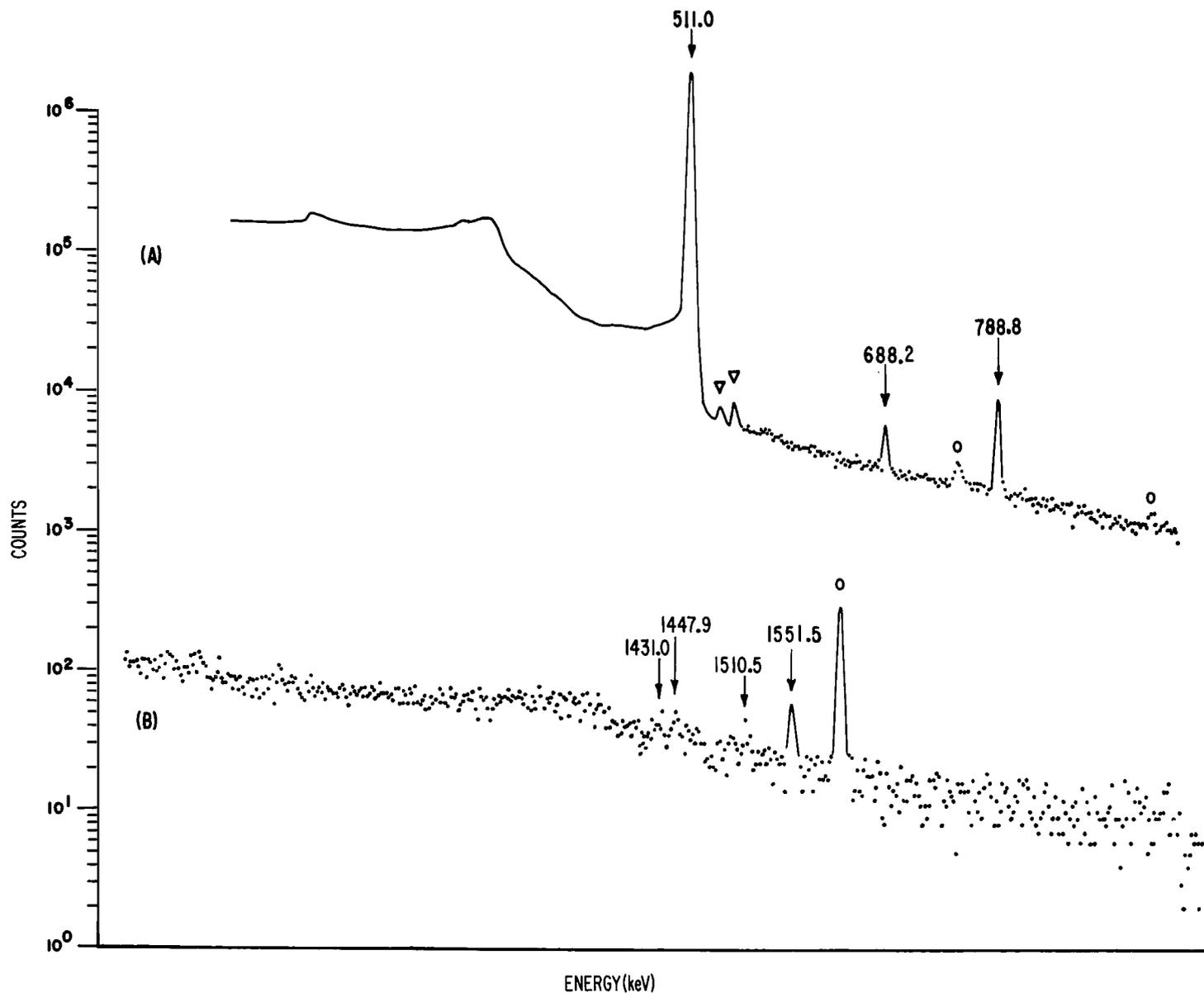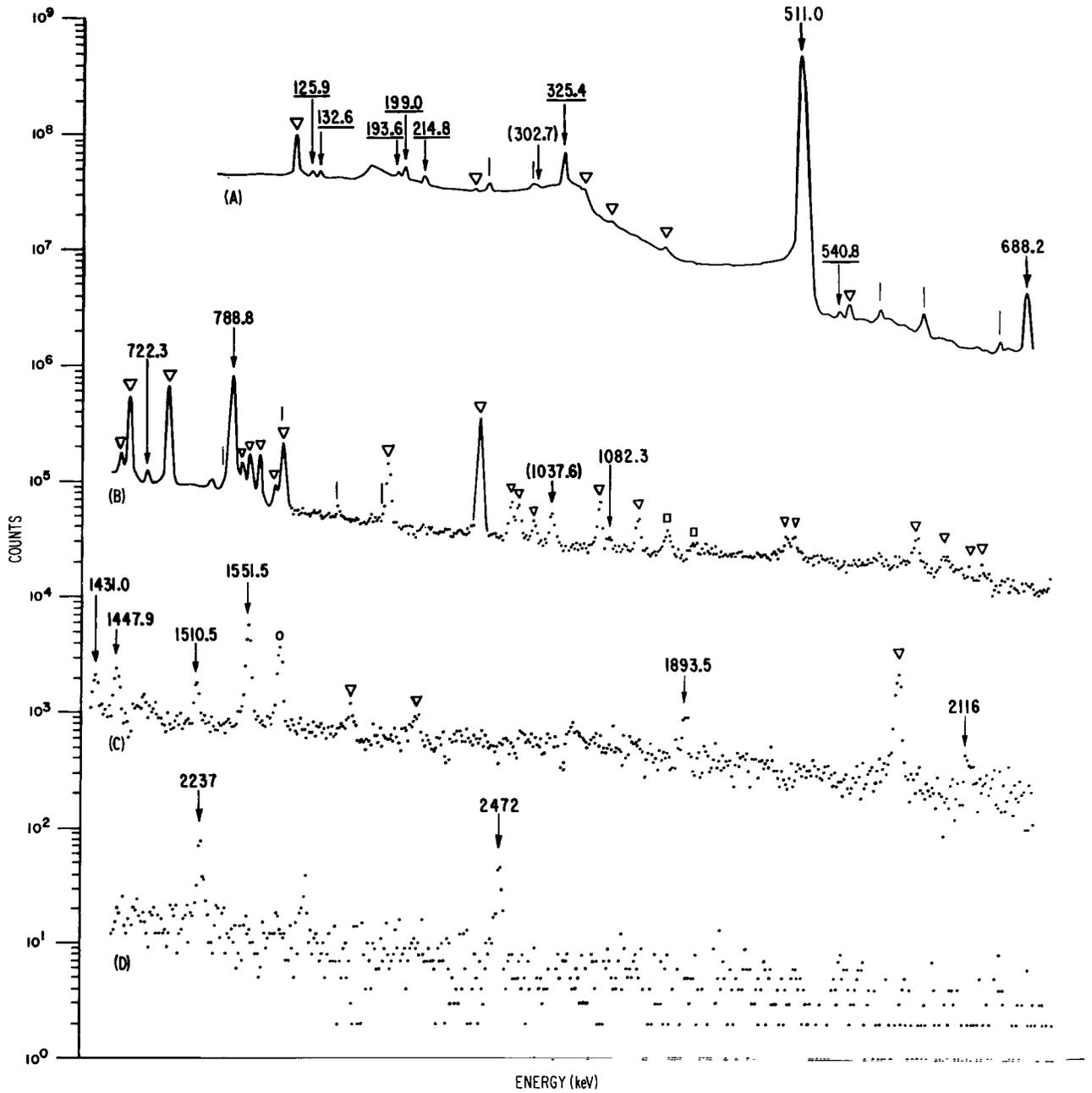
Figure 4. - Gamma-ray spectrum of 1.5-minute ^{138}Pr. Contaminants are indicated by the following symbols: ▽ for ^{136}Pr and o for ^{140}Pr. Energy scale graduation has been omitted and spectrum folded twice to reduce length. Individual points are replaced by smooth line in part of spectrum. For convenience in reading, counts in part (A) have been multiplied by 10.

Figure 5. – Gamma-ray spectrum of ^{138}Pr in equilibrium ^{138}Nd. Contaminants are indicated by symbols as described in the text. Background has been subtracted.
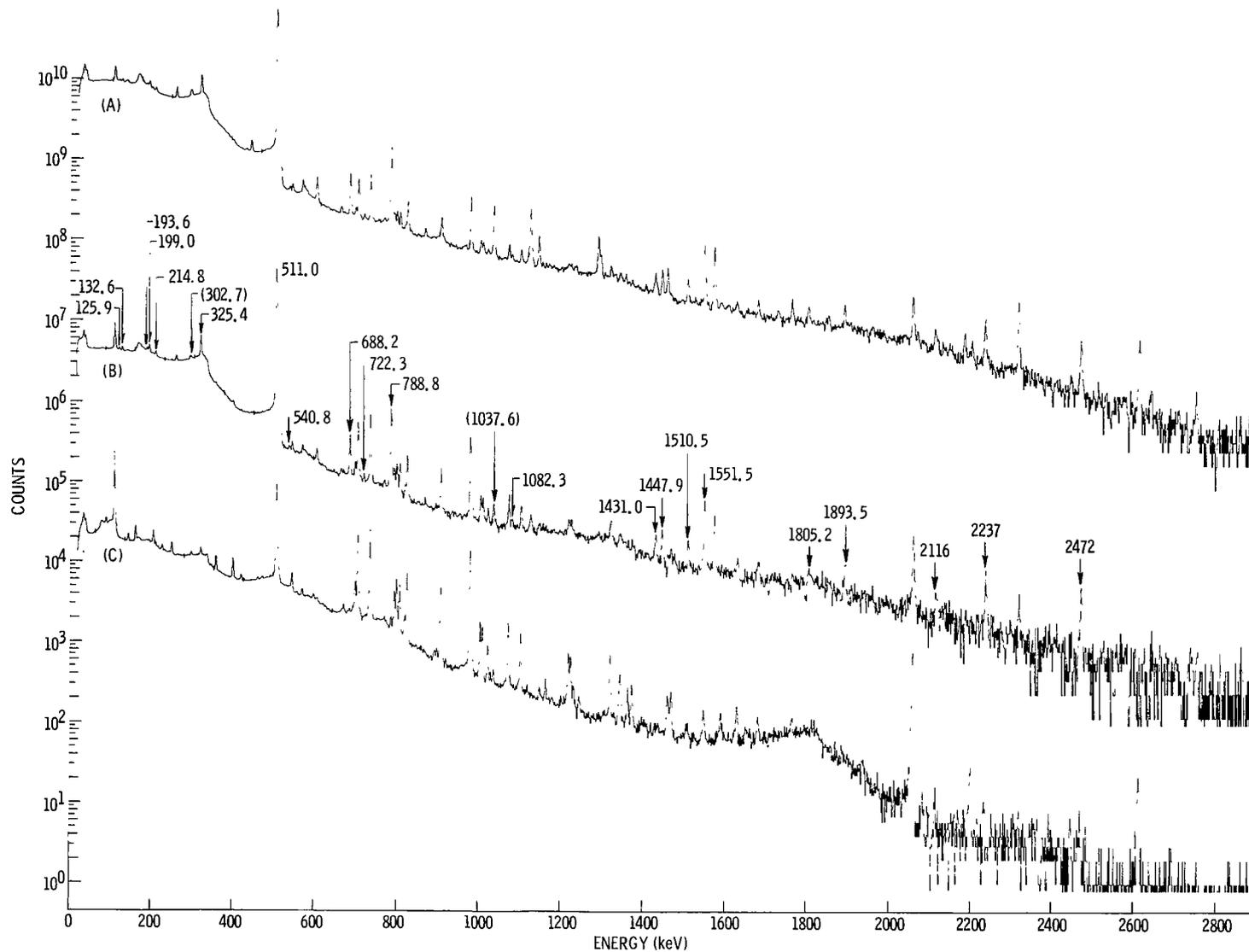
Figure 6. – Comparison of gamma-ray spectra from ^{136}Ce enriched targets bombarded with (A) 37-MeV; (B) 31-MeV; and (C) 19-MeV alpha particles. For convenience in reading, counts in part (A) have been multiplied by 10^4 and counts in part (B) have been multiplied by 100.
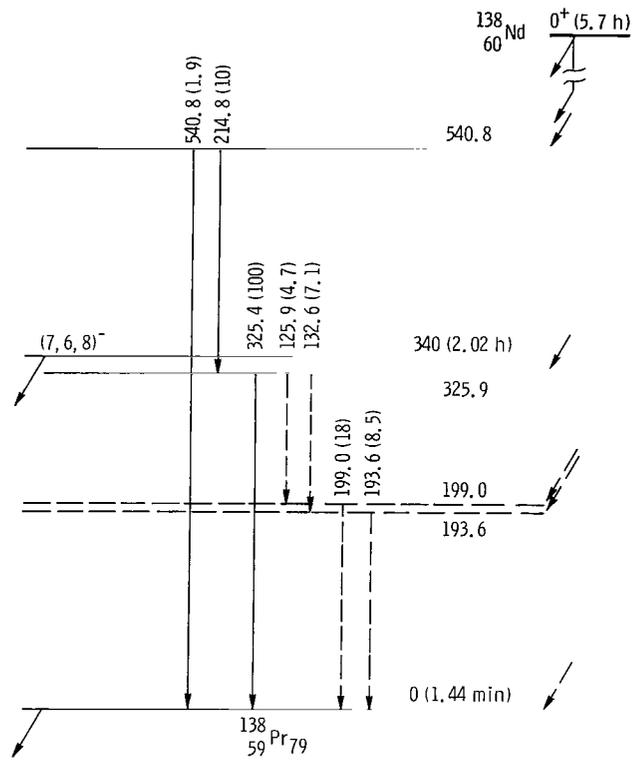
Figure 7. - Tentative level scheme of ^{138}Pr. Energies are in keV.
Gamma-ray intensities are relative to the 325.4 keV gamma-ray
which is arbitrarily taken as 100. Spin assignments are from
references 9 and 12. Included is the isomeric state ^{138m}Pr,
which is not populated in the decay of ^{138}Nd.

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