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Beta-delayed proton activities: ^{147}Dy and ^{149}Er

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The β-delayed proton spectra of ^{147}Dy and the hitherto unknown isotope ^{149}Er were investigated in ^{12}C bombardments of ^{142}Nd and ^{144}Sm, respectively. The $^{12}\mathrm{C}+^{142}\mathrm{Nd}$ data confirm preliminary results of Klepper *et al.* that the ^{147}Dy delayed-proton spectrum has a high-energy cutoff at ~ 5 MeV and is dominated by distinct peaks below 4 MeV in excitation. The proton spectrum following ^{149}Er decay has a half-life of 9 ± 1 sec and extends from about 2.0 to 6.5 MeV; it has less of the sharp structure observed for ^{147}Dy. The difference probably arises from the expected lower level density in ^{147}Tb, a nucleus with one proton outside the ^{146}Gd core.

As a result of the $Z=64$ subshell closure (Refs. 1 and 2) ^{147}Tb can be considered as consisting of a single proton outside a ^{146}Gd doubly closed core. Its low-lying levels should provide an insight into the proton shell structure in a mass region almost midway between the major closures at $Z=50$ and $Z=82$. We recently completed an investigation[3] of ^{147}Tb states populated in the decay of ^{147}Dy. The $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $g_{7/2}$ orbitals were identified. A concurrent study[4] arrived at the same low-lying structure in ^{147}Tb. (The $h_{11/2}$ state was not observed;[3,4] however, in a recent note[5] the $h_{11/2}$ and $s_{1/2}$ states in ^{147}Tb are reported to be at 0 and 50 keV, respectively.) With this information and earlier results, the location of these proton orbitals was traced as a function of atomic number in odd-Z $N=82$ nuclei from ^{135}I to ^{147}Tb. Their excitation energies varied smoothly with an indication that they may be more tightly bound in ^{147}Tb, perhaps due to the $Z=64$ subshell. To understand more fully the influence of the $Z=64$ gap on the quasiparticle energies, we suggested[3] that the investigation be extended to ^{149}Ho.

To locate the proton levels in ^{149}Ho, we searched for the β decay of ^{149}Er in a series of $^{12}\mathrm{C}+^{144}\mathrm{Sm}$ bombardments made at the Oak Ridge isochronous cyclotron. A helium gas-jet apparatus was used to transport radioactive products to a shielded area suitable for γ- and x-ray counting. Despite the fact that the new isotope ^{150}Er was identified[6] and ^{149}Ho γ rays were observed, no transitions could be ascribed to ^{149}Er decay. Possible explanations are (1) the maximum available on-target ^{12}C incident energy of 125 MeV was insufficient to reach the peak of the $^{144}\mathrm{Sm}(^{12}\mathrm{C},7\mathrm{n})$ excitation function, (2) the cross section for this (^{12}C,7n) reaction is small *vis à vis* cross sections for producing neighboring nuclides, (3) most of the ^{149}Er β decay is concentrated at or near the ^{149}Ho ground state, and (4) the ^{149}Er half-life is <0.5 sec, making it difficult for us to see the nuclide because of the 2-sec move time of the tape transport system used in the experiment.

Proton spectral measurements[7] for $A=147$ nuclei have recently attributed a delayed-proton branch to ^{147}Dy. One would also expect ^{149}Er to have the same mode of decay, since the proton binding energy in ^{149}Ho (1060 keV, Ref. 8) is about 0.8 MeV less than that in ^{147}Tb (1880 keV, Ref. 8) while the ^{149}Er Q_{EC} (7500 keV, estimate based on Q_{EC} values in Ref. 8 for nearby Dy and Er nuclei) is about 1.2 MeV more than the ^{147}Dy Q_{EC} (6300 keV, Ref. 8). In a further effort to identify ^{149}Er, we undertook a search for its β-delayed-proton decay.

Irradiations were made at the Lawrence Berkeley Laboratory 88-inch cyclotron to take advantage of its higher incident ^{12}C energies. A helium gas-jet apparatus thermalized product recoils and transported them to a collection box for assay with a Si particle telescope and a Ge detector. The telescope, consisting of a 20-μm ΔE detector combined with a 300-μm E detector, was necessary for the selective detection of low-energy protons in the presence of intense β radiation and a profusion of α particles emitted in the decay of nearby nuclides. The Ge detector was of the γ-x variety, suitable for detecting both low- and high-energy photons. Events registered in each detector were tagged with a time signal for half-life information. Coincidences between particles and γ rays were also recorded. To observe protons, however, the ^{12}C beam intensity was maintained at ~ 1.5 μA. The Ge detector had to be backed 12 cm away from the source spot and the greatly reduced geometry resulted in a very low particle-gamma coincidence rate.

Besides ^{144}Sm, ^{142}Nd was also irradiated to confirm the existence of ^{147}Dy delayed-proton activity, to help determine the peak energy for the (^{12}C,7n) excitation function, and to provide cross-bombardment information. The targets were rare earth oxides enriched in ^{142}Nd (97.7%) and ^{144}Sm (96.5%) deposited onto 12.5-μm-thick Be foils. The ^{12}C ions extracted out of the cyclotron had an energy of 162 MeV; however, after penetrating the entrance window of the gas-jet apparatus and the Be backing foil, the maximum ^{12}C energy on target was 155 MeV. Aluminum absorbers were then used as needed to degrade the beam energy further.

Based on a brief survey run with ^{142}Nd, an incident enery of ~ 135 MeV was found to produce the maximum yield for the ^{147}Dy^{m} 678.7-keV M4 transition.[3] Figure 1(a) shows the proton spectrum accumulated at that bombarding energy following repeated 120-sec irradiation and counting cycles. Subsequent excitation function data established that the proton yield paralleled closely that of the 678.7-keV γ ray. Further, a weak group of terbium $K\alpha$ x rays was observed in coincidence with the protons; thus, ^{147}Dy is established as the β-decay precursor. The intensities of α particles and γ rays in the well-known ^{212}Pb decay chain were used to normalize the geometries of the ΔE-E telescope and the γ-x detector with respect to one another. The ratio, $I_{\text{protons}}/I_{679\gamma}$, was then determined to be $\sim 1.3\times10^{-3}$. Because the 678.7-keV transition is estimated[9] to be $\lesssim 40\%$ of the total ^{147}Dy decay strength, the nuclide's delayed-proton branch is $\sim 5\times10^{-4}$.

The $A = 147$ mass-separated delayed-proton spectrum observed by Klepper *et al.*[7] in ^{58}Ni + ^{92}Mo bombardments is similar to the one shown in Fig. 1(a), particularly with regard to the distinct peaks seen below 4 MeV in excitation energy. Additional measurements mentioned in a "note added to proof" showed that their spectrum was made up of two components: a structureless spectrum extending from 1 to 8 MeV, assigned to ^{147}Er ($T_{1/2} = 2.5 \pm 0.2$ sec), and a spectrum dominated by sharp peaks, with a high-energy cutoff at ~ 5 MeV and a half-life of 57 ± 4 sec, assigned to ^{147}Dy^{m}. These conclusions concerning the second component agree with our assignment of ^{147}Dy as the precursor of the delayed-protons in Fig. 1(a). In our measurements, however, the protons decayed with a half-life of 95 ± 10 sec, rather than the (59 ± 3)-sec value determined[9] for ^{147}Dy^{m}. The longer time indicates a significant contribution from ^{147}Dy^{g}. (See the discussion in Ref. 3 concerning the apparent, or second-order, 80-sec half-life measured for γ rays which follow the decay of the $s_{1/2}$ ^{147}Dy ground state.) The difference between the half-lives measured in Ref. 7 and in the present study may arise from the production modes, i.e., in our experiment the compound nucleus is ^{154}Dy, while in Ref. 7 it was ^{150}Yb. The resultant ^{147}Dy^{m}/^{147}Dy^{g} ratios and the half-lives observed for the delayed-protons therefore need not be the same.

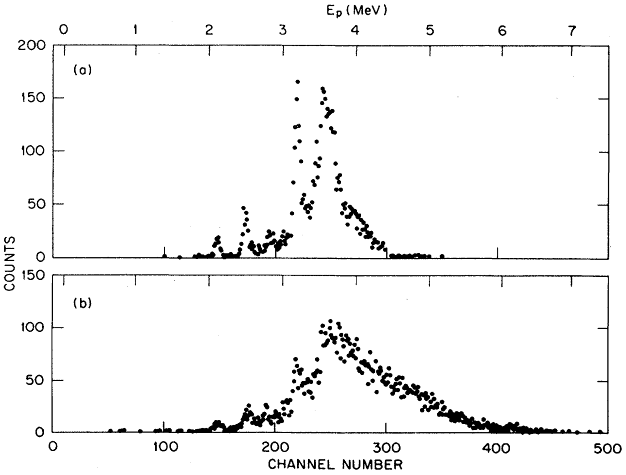

FIG. 1. Delayed-proton spectra observed in (a) ^{12}C + ^{142}Nd and (b) ^{12}C + ^{144}Sm irradiations made at an incident energy of ~ 135 MeV.

Figure 1(b) shows the proton spectrum accumulated in 135-MeV ^{12}C irradiations of ^{144}Sm. While the bombardment and counting cycles used to obtain the data were 20 sec, preliminary measurements were also done with 5- and 60-sec cycles. Differences and similarities can be immediately perceived between Figs. 1(a) and 1(b). Most of the peaks seen below 4 MeV in Fig. 1(a) are also seen in 1(b), though here they are superposed on a much more intense structureless spectrum which extends above 6.5 MeV. The indication is that ^{147}Dy produced in the ^{144}Sm(^{12}C, α5n) reaction is present (the ^{147}Dy^{m} 678.7-keV transition is clearly seen in the γ-ray spectra), together with another proton emitter. Figure 2 shows the spectrum that results after subtracting from Fig. 1(b) the contribution due to ^{147}Dy as illustrated by 1(a). The spectrum in Fig. 2 decays with a half-life of 9 ± 1 sec.

Since this proton emitter was not seen in ^{12}C + ^{142}Nd bombardments, it has to be either an erbium or a holmium nuclide. No coincident K x rays could be observed to establish the atomic number. Neighboring erbium and holmium isotopes have half-lives as follows: ^{150}Er, $T_{1/2} = 20 \pm 2$ sec (Ref. 6); ^{150}Ho, $T_{1/2} = 26 \pm 2$ sec and 90 ± 20 sec (Ref. 6); ^{149}Ho, $T_{1/2} = 21 \pm 2$ sec (Ref. 10); ^{148}Er, $T_{1/2} = 4.5 \pm 0.4$ sec (Ref. 11); and ^{148}Ho, $T_{1/2} = 9 \pm 2$ sec (Ref. 10). Although ^{148}Ho has a 9-sec half-life, its γ rays (Ref. 10) were not observed below 135 MeV and increased in intensity up to our maximum bombarding energy of 155 MeV. Such a variation with incident energy is inconsistent with that seen for the delayed protons; their yield as a function of energy was consistent with an $A = 149$ product. Therefore, we assign the 9-sec activity to the β decay of the hitherto unidentified isotope,^{149}Er. Further, we assume that the 9-sec half-life is due primarily (though not exclusively) to the $h_{11/2}$ isomer rather than the $s_{1/2}$ ground state, since the high-spin species should be the predominant product in a heavy-ion induced compound nuclear reaction (see, e.g., Ref. 12).

The intrinsic structure of delayed-proton spectra that accompany heavy mass precursors usually is not resolved due to the large density of states in the excitation energy range fed by the β decay. In Fig. 1(a), however, the peaks have

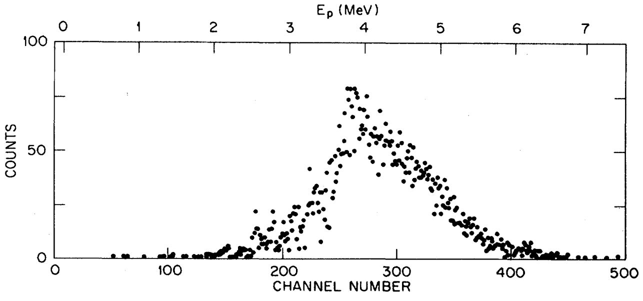

FIG. 2. Delayed-proton spectrum resulting after the subtraction from Fig. 1(b) the spectrum in Fig. 1(a).

full widths at half maximum which are on the order of the $\Delta E - E$ detector resolution, i.e., ~60 keV. The indication is that the ^{147}Dy β decay is sampling either selected ^{147}Tb states or else an energy region in ^{147}Tb where the level density is not high. The reader is reminded that ^{147}Tb consists of a single proton coupled to the doubly closed core of ^{146}Gd. In Fig. 2, peak structure, if any is present, is much less obvious. This could be due to a larger level density in ^{149}Ho, a nucleus which has three protons outside the ^{146}Gd core.

We were still unable to observe γ-ray transitions in ^{149}Ho. The explanation seems to be that most of ^{149}Er decay to levels below the proton separation energy proceeds either to the ground state or to low-lying levels in ^{149}Ho. Of these states, the $h_{11/2}$ proton orbital is expected to receive a large feeding. Because the orbital is either the ground state or a level close to it (see Refs. 3–5), observation of γ rays in ^{149}Ho would be difficult. Systematics[9] of single neutron levels in $N=81$ nuclei suggests that, besides decaying to ^{149}Ho, the $h_{11/2}$ isomer also deexcites *via* an $M4$ (~640 keV) plus $M1$ (~110 keV) γ-ray cascade to the $s_{1/2}$ ground state. Neither transition was seen in our spectra. The negative result is not inconsistent with the observation[9] that as the atomic number of the $N=81$ nuclei increases so does the amount of direct versus isomeric decay, from $\leq 0.01\%$ for ^{141}Nd^m to 4.7% for ^{145}Gd^m to an estimated 60% for ^{147}Dy^m. As the $(g_{7/2}-d_{5/2})$ proton subshell is filled, there is an increased occupancy of the $h_{11/2}$ orbital in the $N=82$ daughters which then leads to a progressively greater probability for direct β decay. Reduced $M4$ transition rates in $N=81$ nuclei up to ^{145}Gd^m have been considered in Refs. 13 and 14. We utilized and extended these rate systematics and calculated $M4$ branches of 41% and 2–5% (E_γ from 600 to 650 keV) for ^{147}Dy^m and ^{149}Er^m, respectively. The ^{147}Dy^m branch agrees with the experimental estimate[9] mentioned above, while the ^{149}Er^m value provides a good reason why the $M4$ and $M1$ transitions were not observed. The need for using mass-separated samples of ^{149}Er is clearly indicated if the low-lying structure in both ^{149}Er and ^{149}Ho is to be elucidated.

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