BETA-DELAYED PROTON ACTIVITIES: ^{147}Dy AND ^{149}Er

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SUMMARY

The present paper discusses mainly the β-delayed proton spectra of ^{147}Dy and of the hitherto unknown isotope, ^{149}Er. However, following the submittal of the abstract for this conference we have now observed delayed protons following the decay of ^{145}Dy. Additionally, we have identified a 0.5-s delayed-proton emitter and tentatively assign it to the new isotope, ^{151}Yb.

We recently completed an investigation[1] 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. (The $h_{11/2}$ state was not observed; however, in a recent note[2] 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 (see e.g. Refs. 3 and 4). To understand more fully the influence of the Z = 64 gap on the quasiparticle energies, we suggested[1] 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}C + ^{144}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[5] and ^{149}Ho γ rays were observed, no transitions could be ascribed to ^{149}Er decay. Proton spectral measurements[6] for A = 147 nuclei have recently attributed a delayed-proton branch to ^{147}Dy. Because of the energetics involved one would also expect ^{149}Er to have the same mode of decay. 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.

Based on a brief survey run with ^{142}Nd, an incident energy of ~ 135 MeV was found to produce the maximum yield for the ^{147}Dy^{m} 678.7-keV M4 transition.[1] 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_α 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, $I_{protons}/I_{679\gamma}$, was then determined to be ~ 1.3 x 10^{-3}. Because the 678.7-keV γ ray is estimated[7] to be ≲ 40% of the total ^{147}Dy decay strength, the nuclide's delayed-proton branch is ~ 5 x 10^{-4}.

The A = 147 mass-separated delayed-proton spectrum observed by Klepper <u>et al.</u>[6] 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 to 8 MeV, assigned to ^{147}Er (2.5 ± 0.2 sec), and a spectrum dominated

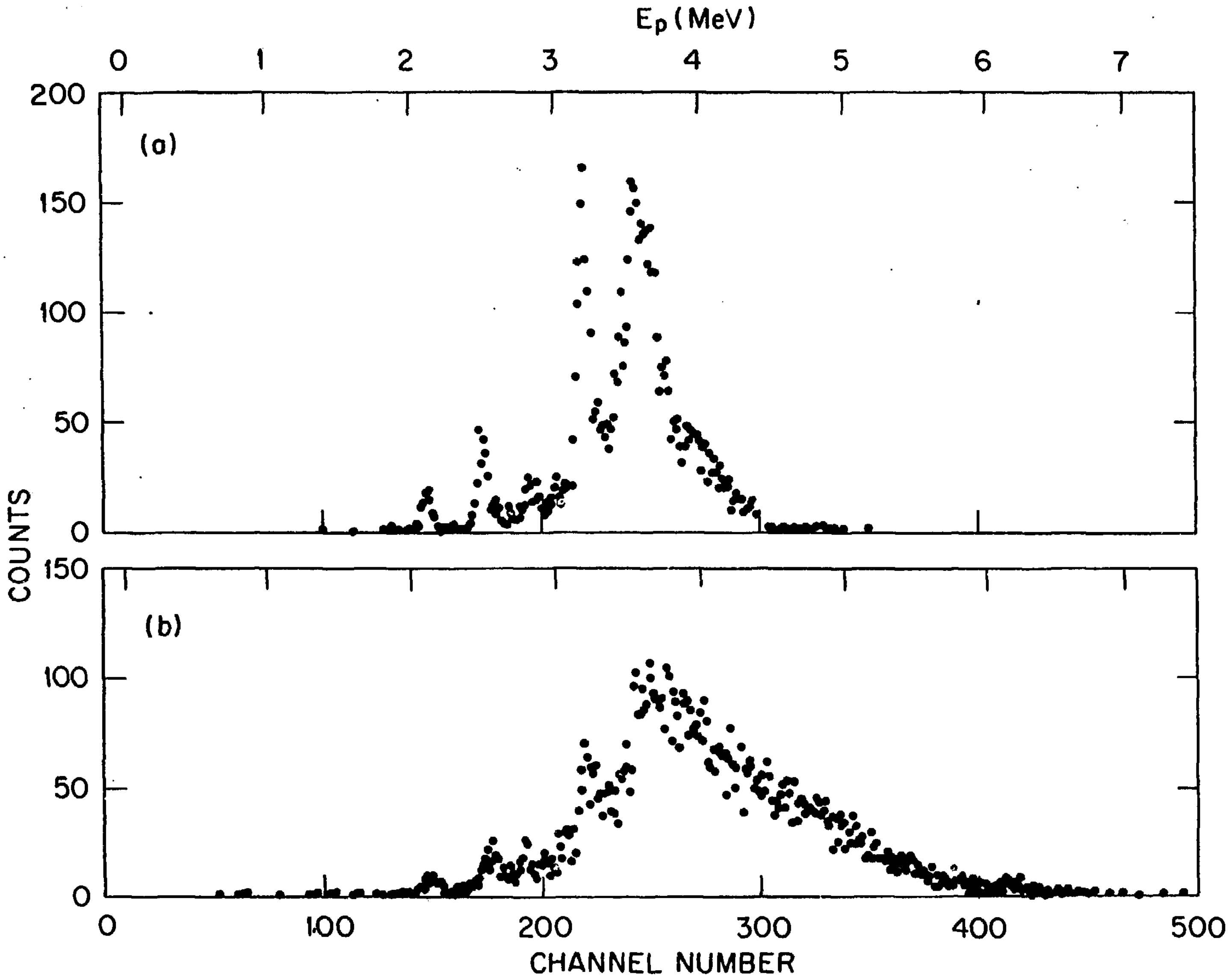

Fig. 1. Delayed-proton spectra observed in $^{12}C + ^{142}Nd$ [part (a)] and $^{12}C + ^{144}Sm$ [part (b)] irradiations made at an incident energy of ~ 135 MeV.

by sharp peaks, with a cutoff at ~ 5 MeV and a half-life of 57 ± 4 sec, assigned to $^{147}Dy^m$. These conclusions about the second component agree with our assignment of ^{147}Dy as the precursor of the delayed-protons in Fig. 1(a).

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 Fig. 1(a) and Fig. 1(b). Most of the peaks seen below 4 MeV in Fig. 1(a) are also seen in Fig. 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 $^{144}Sm(^{12}C,\alpha\ 5n)$ 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 Fig. 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 ± 2 sec (Ref. 5); ^{150}Ho, $T_{1/2}$ = 26 ± 2 sec and 90 ± 20 sec (Ref. 5); ^{149}Ho, $T_{1/2}$ = 21 ± 2 sec (Ref. 8); ^{148}Er, $T_{1/2}$ = 4.5 ± 0.4 sec (Ref. 9); and ^{148}Ho, $T_{1/2}$ = 9 ± 2 sec (Ref. 8). Although ^{148}Ho has a 9-sec half-life, its γ rays (Ref. 8) 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.

Next we expanded our study by searching for the delayed-proton branch of ^{145}Dy, an isotope whose half-life has been reported to be 18 ± 3 sec (Ref. 10) and 13.6 ± 1.0 sec (Ref. 9). In a series of ^{12}C + ^{142}Nd bombardments (from 135 to 195 MeV) yields were measured for γ rays belonging to ^{146}Dy (Refs. 9 and 11), ^{146}Tb (Ref. 12), ^{145}Dy (Refs. 9 and 10), ^{145}Tb (Refs. 9 and 13), and ^{144}Tb (Refs. 9 and 13). An energy of ~ 188 MeV was then selected to emphasize the $^{142}Nd(^{12}C,9n)$ reaction. Figure 3 shows the accumulated delayed-proton spectrum. We assign these β-delayed protons to ^{145}Dy on the basis of excitation function data and on the fact that they decayed with a (15 ± 4)-sec half-life.

Further, in an attempt to identify ^{151}Yb, proton and γ-ray spectra were investigated in ^{16}O + ^{144}Sm irradiations. Yields as a function of incident

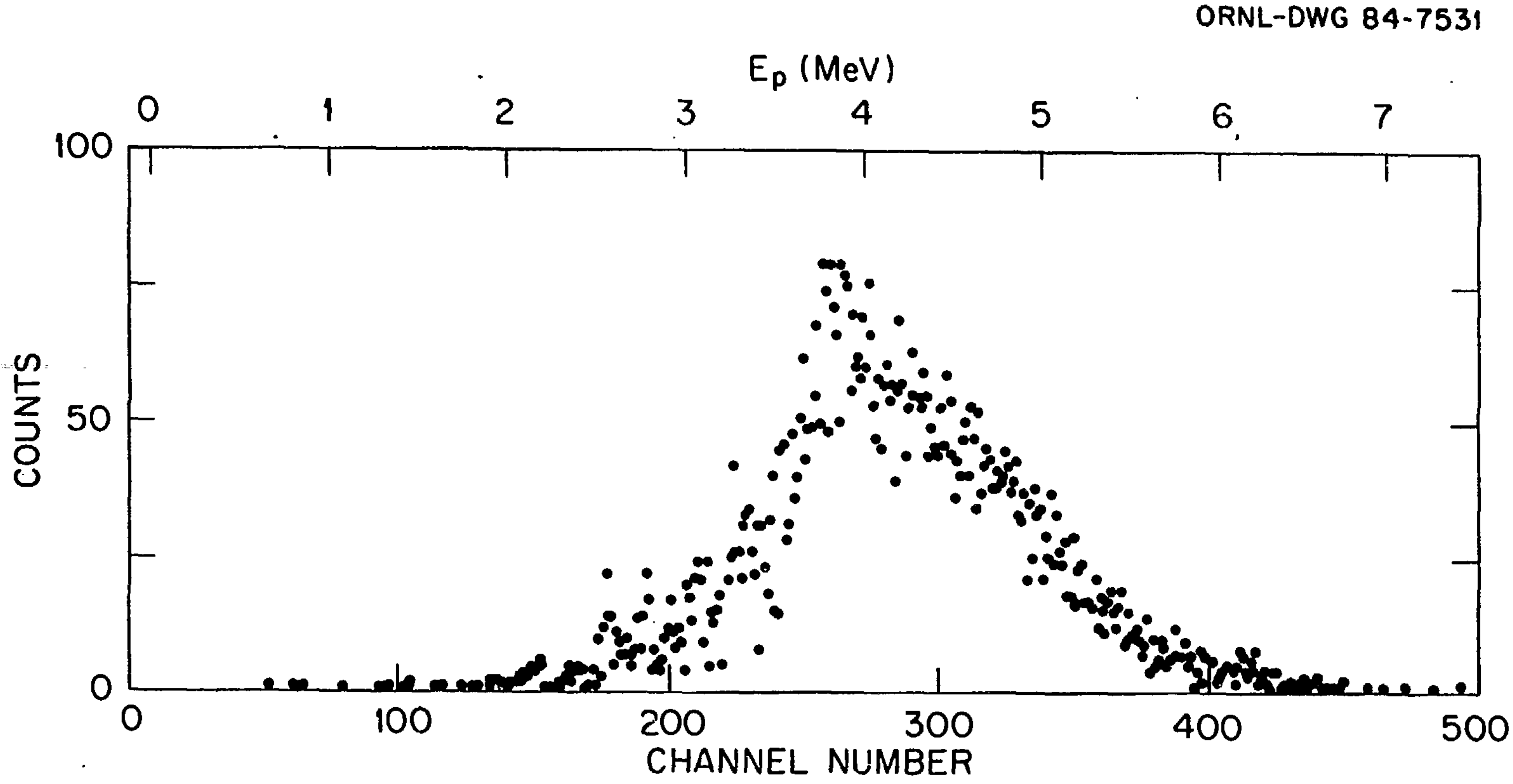

Fig. 2. Delayed-proton spectrum resulting after the subtraction from Fig. 1(b) the spectrum in Fig. 1(a).

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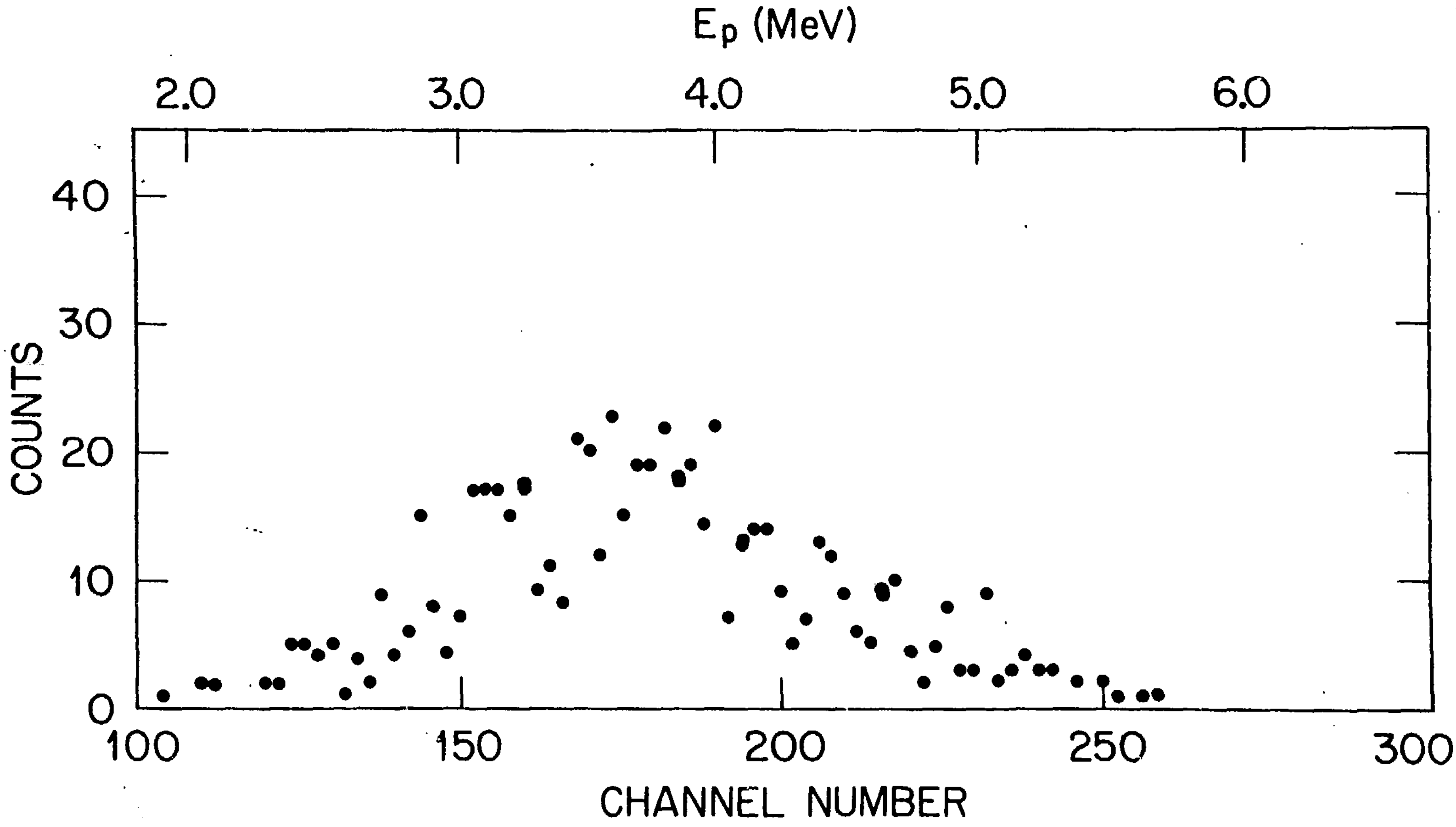

Fig. 3. Delayed-proton spectrum observed in 188-MeV ^{12}C bombardments of ^{142}Nd.

energy for γ rays known[14] to follow the β decays of ^{152}Yb, ^{152}Tm, and ^{151}Tm were used to select the peak of the (^{16}O,9n) excitation function. Preliminary analyses indicate the existence of a delayed-proton emitter with a half-life of ~ 0.5 sec which we tentatively assign to the new isotope ^{151}Yb.

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 full widths at half-maximum which are on the order of the ΔE-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 ($N = 82$ and $Z = 64$). In Fig. 2, while there are peaks in the lower half of the spectrum, the structure is much less distinct than in Fig. 1(a). This could be due to a larger level density in ^{149}Ho, a nucleus still with 82 neutrons but now having three protons beyond $Z = 64$. Finally, there is no indication of peaks in Fig. 3; here the β decay is sampling levels in a nucleus, ^{145}Tb, with no shell closures.

High-energy endpoints of delayed-proton spectra are fixed by differences between the electron-capture (EC) decay energies of the parents and the proton binding energies in the corresponding EC daughters. Predicted $Q_{EC} - B_p$ values from the 1977 Atomic Mass Evaluation[15] for ^{145}Dy, ^{147}Dy, and ^{149}Er are 5.70, 4.42, and 6.44 MeV, respectively. (Note, EC decay energies for ^{145}Dy and ^{149}Er are not listed in Ref. 15; based on decay energies for nearby isotopes we estimated the two Q_{EC} values to be 7.24 and 7.50 MeV, respectively.) These predictions are consistent with our data [see Figs. 1(a), 2, and 3].

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