

## SPECTROSCOPY OF PROTON-RICH NUCLEI IN THE RARE EARTH REGION

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## Abstract

The isotope separator facility OASIS, on-line at the Lawrence Berkeley Laboratory SuperHILAC, was used to investigate proton-rich rare earth nuclei. Single-particle states near the 82-neutron shell were delineated, numerous new isotopes, isomers, and  $\beta$ -delayed proton emitters were discovered and the  $\alpha$ -decay properties of some nuclides with  $N > 84$  were reexamined. In this contribution the experimental program is summarized briefly, the excitation energies of the  $s_{1/2}$  and  $h_{11/2}$  proton states in this mass region are discussed, and results on the  $\beta$ -delayed-proton spectra of  $^{145}\text{Dy}$  and  $^{147}\text{Er}$  are presented.

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## 1. Introduction

We have investigated the decay properties of many short-lived neutron-deficient rare earth nuclei with  $65 < Z < 71$  by using the OASIS separator facility [1], on-line at the Lawrence Berkeley Laboratory SuperHILAC. These isotopes were produced in fusion reactions in which targets of  $^{96}\text{Ru}$ ,  $^{92}\text{Mo}$ ,  $^{94}\text{Mo}$ ,  $^{95}\text{Mo}$ ,  $^{96}\text{Mo}$ , and  $^{93}\text{Nb}$  were bombarded with  $^{64}\text{Zn}$  and  $^{58}\text{Ni}$  projectiles. Following mass separation the radioactive products were assayed with a Si particle  $\Delta E$ -E telescope, a thin plastic scintillator, and a hyperpure and two n-type Ge detectors.

Figure 1 shows a portion of the nuclidic chart which encompasses the mass region where these radioactivities are located. Some of the nuclei are at or close to the proton drip line. For many of them  $\beta$ -delayed-proton (and in a few instances direct-proton) emission becomes a probable mode of decay. Note that while all nuclei in fig. 1 with  $N > 84$  are  $\alpha$ -particle emitters, no  $\alpha$  decay has been observed in rare earth isotopes with  $N < 84$ . This is due to the influence of the  $N = 82$  closed shell which enhances the  $\alpha$ -decay energies of nuclides with neutron numbers of 84 and slightly higher but drastically reduces these energies for nuclides with  $N < 83$ .

Among our studies, we have unraveled (EC +  $\beta^+$ ) decay schemes in an effort to delineate single-particle levels and have investigated numerous  $\beta$ -delayed-proton emitters to help elucidate the nature of the sharp structure observed in proton spectra for some emitters with  $N = 81$ . In this paper we: (a) discuss one phase of our decay-scheme studies, i.e., the determination of excitation energies for the  $s_{1/2}$  and  $h_{11/2}$  single-proton states in odd-Z, even-N nuclei, and, (b) present data concerning the  $\beta$ -delayed protons emitted by the  $N = 79$  nuclides,  $^{145}\text{Dy}$  and  $^{147}\text{Er}$ , and contrast them with those of the  $N = 81$  precursors.

2. The  $s_{1/2}$  and  $h_{11/2}$  single-proton states near  $N = 82$

Separation energies between the  $s_{1/2}$  and  $h_{11/2}$  proton levels in the rare earth region are important for deducing masses from  $Q_{EC}$  and  $Q_{\alpha}$  measurements and for providing level energies to compare with shell-model calculations. However, they have been difficult to obtain because the two states are not connected by isomeric  $\gamma$  rays and it is only recently that many of these separation energies have been determined.

Figure 2 summarizes the information that we utilized to deduce the excitation energies of the  $s_{1/2}$  isomers in  $^{149}\text{Ho}$  and  $^{153}\text{Tm}$ . In a detailed study [2] of the  $^{149}\text{Er}^g$  ( $\nu s_{1/2}$ ) and  $^{149}\text{Er}^m$  ( $\nu h_{11/2}$ ) ( $EC + \beta^+$ ) decay schemes the  $s_{1/2}$  isomer in  $^{149}\text{Ho}$  was determined to be 49.0(1) keV above the  $h_{11/2}$  ground state. This was established by observing the deexcitation of several levels not only by transitions that proceed directly to the ground state but also by transitions to the  $g_{7/2}$  proton level. These decay patterns determine the excitation energy of the  $g_{7/2}$  level to be 1001.2 keV. Since the energies of the three cascading  $\gamma$  rays that deexcite and connect the  $g_{7/2}$ ,  $d_{5/2}$ ,  $d_{3/2}$ , and  $s_{1/2}$  proton states are known, the energies of all four of these levels are then determined. In a similar fashion the  $s_{1/2}$  isomer in  $^{153}\text{Tm}$  was deduced to be 43.2(2) keV above the  $h_{11/2}$  ground state in an investigation [3] of the ( $EC + \beta^+$ ) decay scheme of  $^{153}\text{Yb}$  ( $\nu f_{7/2}$ ). This decay, in particular, feeds a level at 1101.7 keV which deexcites to several states and serves as a linchpin that locks together the population by  $^{153}\text{Yb}$  of both high- and low-spin levels in  $^{153}\text{Tm}$  and thus establishes the energy of the  $s_{1/2}$  level. Also, by combining the excitation energy of the  $^{149}\text{Ho}$   $s_{1/2}$  isomer and the  $Q_{\alpha}$  values reported [4] for the two  $^{153}\text{Tm}$   $\alpha$  groups (see fig. 2) that connect the respective  $h_{11/2}$  and  $s_{1/2}$  states in  $^{153}\text{Tm}$  and  $^{149}\text{Ho}$ , one can determine the  $s_{1/2}$  isomer in  $^{153}\text{Tm}$  to be 43(7) keV above ground.

In ref. [5] where we discussed fine structure in the  $\alpha$  decay of  $^{153}\text{Tm}$  (these transitions to the  $d_{3/2}$  and  $d_{5/2}$  levels in  $^{149}\text{Ho}$  are shown in fig. 2) a proposal was made that the  $^{155}\text{Tm}$  4.45-MeV  $\alpha$  group [6] is in fact a doublet. As in the case of  $^{153}\text{Tm}$ , these two  $\alpha$  transitions originate from the  $s_{1/2}$  and  $h_{11/2}$  proton states in  $^{155}\text{Tm}$  and feed the corresponding levels in  $^{151}\text{Ho}$ . Based on the reported [7] 41.4(9)-keV excitation energy of the  $s_{1/2}$  isomer in  $^{151}\text{Ho}$  we then suggested that the  $s_{1/2}$  level in  $^{155}\text{Tm}$  was  $\sim 41$  keV above the ground state. We now have data [8] which confirm the existence in  $^{155}\text{Tm}$  of an  $s_{1/2}$  isomer [ $T_{1/2} = 44(4)$  s] in addition to the  $h_{11/2}$  ground state [ $T_{1/2} = 21.6(2)$  s]. However, the  $\alpha$  decay of  $^{155}\text{Tm}$  could not be investigated due to the presence of intense 4.517- and 4.606-MeV peaks from the  $\alpha$  decay of  $^{151}\text{Ho}$  produced in our  $A = 155$  sources from the  $^{155}\text{Yb} \xrightarrow{\alpha} ^{151}\text{Er} \xrightarrow{\beta} ^{151}\text{Ho}$  decay sequence. With these same sources we investigated the  $(\text{EC} + \beta^+)$  decay of  $^{151}\text{Er}$  and were able to establish the excitation energy of the  $s_{1/2}$  isomer in  $^{151}\text{Ho}$  to be 41.1(2) keV, a value that agrees with but is more precise than the above-mentioned energy from ref. [7].

Figure 3 shows energy systematics for the  $s_{1/2}$  and  $h_{11/2}$  proton orbitals in terbium, holmium, and thulium nuclei. Data shown are taken from the following investigations:  $^{147,149,151}\text{Tb}$  (refs. [7, 9, 10]),  $^{149,151,153}\text{Ho}$  (refs. [2, 8, 11]),  $^{153}\text{Tm}$  (ref. [3]), and  $^{155}\text{Tm}$  (refs. [6, 7]). We also include values for  $^{147}\text{Tm}$  (ref. [12]) deduced from direct-proton decay results. One notes that in terbium ( $Z = 65$ ), after the  $g_{7/2}$  and  $d_{5/2}$  orbitals have been filled at  $Z = 64$ , the  $s_{1/2}$  orbital is the ground state; at  $Z = 67$  this level becomes a hole state, and the  $h_{11/2}$  orbital is the ground state in holmium ( $Z = 67$ ) and thulium ( $Z = 69$ ) nuclei. The next proton orbital above the  $s_{1/2}$  level is the  $d_{3/2}$  state but the  $(d_{3/2} - s_{1/2})$  separation energy in the  $N = 82$  isotones decreases as the atomic

number increases, i.e., it is 253 keV in  $^{147}\text{Tb}$  (ref. [13]), 171 keV in  $^{149}\text{Ho}$  (ref. [2]), and 109 keV in  $^{151}\text{Tm}$  (ref. [14]). Thus, for some element above thulium the  $d_{3/2}$  state should drop below the  $s_{1/2}$  level. In fact, this reversal may be extant in  $^{147}\text{Tm}$  where the calculated [12] proton-decay half-life for the isomer at 67 keV is in better agreement with the experimental value if the level is assumed to be  $d_{3/2}$  rather than  $s_{1/2}$ .

### 3. Beta-delayed protons from $^{145}\text{Dy}$ and $^{147}\text{Er}$

One thrust of our program has been an attempt to understand the pronounced peaks seen in the  $\beta$ -delayed-proton spectra of the even- $Z$   $N = 81$  precursors  $^{147}_{66}\text{Dy}$ ,  $^{149}_{68}\text{Er}$ , and  $^{151}_{70}\text{Yb}$ . Such structure is unusual for nuclei with  $A \geq 70$  because of the large level densities in the  $\beta$ -decay daughters at excitation energies high enough for proton emission. We have shown [refs. 15, 16] that the proton peaks are associated with the  $\beta$  decays of the  $s_{1/2}$  ground states in these  $N = 81$  precursors and reflect regions of low densities of  $1/2$  and  $3/2$  levels in the range of 3.5 - 5.0 MeV in the  $N = 82$  daughters. Protons emitted by the  $h_{11/2}$  isomers in the same  $N = 81$  precursors, because of energetics and angular-momentum considerations, sample levels in the daughters that have a centroid at about 7 MeV. Here the level densities are higher and the proton spectra associated with the  $h_{11/2}$  states are structureless. For these three precursors one then finds peaks superposed on a statistical component which becomes progressively larger as the atomic number increases due to an increasing  $\beta$ -decay  $Q$  value. Gamma-ray decay studies,  $\beta$ -strength function measurements, and calculations of state densities and Gamow-Teller strength distributions, have led us to suggest [16] that the structure in delayed-proton spectra near  $N = 82$  may arise from the preequilibrium decay of doorway states populated in  $\beta$  decay.

We have also investigated the decay properties of the  $N = 79$  precursors  $^{145}\text{Dy}$  and  $^{147}\text{Er}$ . Their  $\beta$ -decay daughters have the same atomic numbers as those of  $^{147}\text{Dy}$  and  $^{149}\text{Er}$ , respectively, but have 80 rather than 82 neutrons. A comparison of delayed-proton spectra from these four emitters should therefore provide information concerning the relative importance of the  $N = 82$  and  $Z = 64$  closures with regard to the observed proton structures.

Figure 4 displays our  $^{145}\text{Dy}$  delayed-proton data. The singles spectrum, shown in fig. 4(a), is basically structureless, though there are peaks at  $\sim 2.6$  and 2.9 MeV. By requiring positron coincidences one can enhance the fraction of protons emitted from low excitation energies, i.e., from levels found [15,16] to be associated with the pronounced peaks in the  $N = 81$  spectra. In the case of  $^{145}\text{Dy}$ , there are not very many positron-proton coincidences [see fig. 4(b)] because of the isotope's relatively low  $Q_{EC}$  and the high binding energy of the last proton in  $^{145}\text{Tb}$ . Nevertheless, the spectral centroid is at a lower energy in fig. 4(b) than in fig. 4(a) and despite the poor statistics the proton groups at  $\sim 2.6$  and 2.9 MeV [fig. 4(a)] seem to be present in fig. 4(b). Figure 4(c) shows x rays and  $\gamma$  rays (in  $^{144}\text{Gd}$ ) in coincidence with protons; these data tell us that 56% of the protons proceed to the  $^{144}\text{Gd}$  ground state with the remainder populating the  $2^+$  743-keV first-excited state. Statistical-model calculations predict that 91% of the protons associated with the  $s_{1/2}$   $^{145}\text{Dy}$  ground state proceed to the  $^{144}\text{Gd}$  ground state, while 71% of the protons from the  $h_{11/2}$  isomer (located at 118 keV in  $^{145}\text{Dy}$ ) populate the  $2^+$  743-keV  $^{144}\text{Gd}$  level. From experiment and calculation one then concludes that the  $s_{1/2}$  and  $h_{11/2}$   $^{145}\text{Dy}$  states each account for  $\sim 50\%$  of the observed protons.

A similar study of the  $^{147}\text{Er}$  delayed protons showed that  $\sim 85\%$  of them are associated with the  $h_{11/2}$  isomer and  $\sim 15\%$  with the  $s_{1/2}$  ground state, i.e., as in the case of the  $N = 81$  isotones the contribution from the  $h_{11/2}$  state

increases as the  $Q_{EC}$  value becomes greater. Figure 5 compares the singles protons [parts (a) and (b)] and protons in coincidence with positrons [parts (c) and (d)] for  $^{147}\text{Er}$  and  $^{149}\text{Er}$ , respectively. The structure observed in fig. 5(a) is indeed emphasized in fig. 5(c) though in neither spectrum are the peaks as pronounced as they are for  $^{149}\text{Er}$  [figs. 5(b) and 5(d)].

Thus the intense structures disappear from observed spectra almost as soon as the  $\beta$ -decay daughters no longer have a major closed-shell configuration. The role of the  $Z = 64$  subshell in lowering level densities must be a minor one. This and other points are addressed in a recent thesis [17] where the results obtained at the OASIS facility for delayed-proton precursors, ranging from  $^{119}\text{Ba}$  to  $^{154}\text{Lu}$ , are described and discussed.

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## Figure Captions

- Fig. 1. Portion of nuclidic chart where isotopes investigated in this experimental program are indicated by shaded squares.
- Fig. 2. Partial (EC +  $\beta^+$ ) decay schemes of  $^{149}\text{Er}$  and  $^{153}\text{Yb}$  and the  $\alpha$ -particle decay scheme of  $^{153}\text{Tm}$ .
- Fig. 3. Excitation energies of high- and low-spin isomers in Tb(Z = 65), Ho(Z = 67), and Tm(Z = 69) nuclei.
- Fig. 4. Delayed-proton data for  $^{145}\text{Dy}$ : (a) singles proton spectrum, (b) protons in coincidence with positrons, and, (c)  $^{144}\text{Gd}$   $\gamma$  rays in coincidence with protons.
- Fig. 5. Beta-delayed protons from  $^{147}\text{Er}$  [(a) and (c)] and  $^{149}\text{Er}$  [(b) and (d)]; (a) and (b) show singles spectra, while (c) and (d) display protons observed in coincidence with positrons.



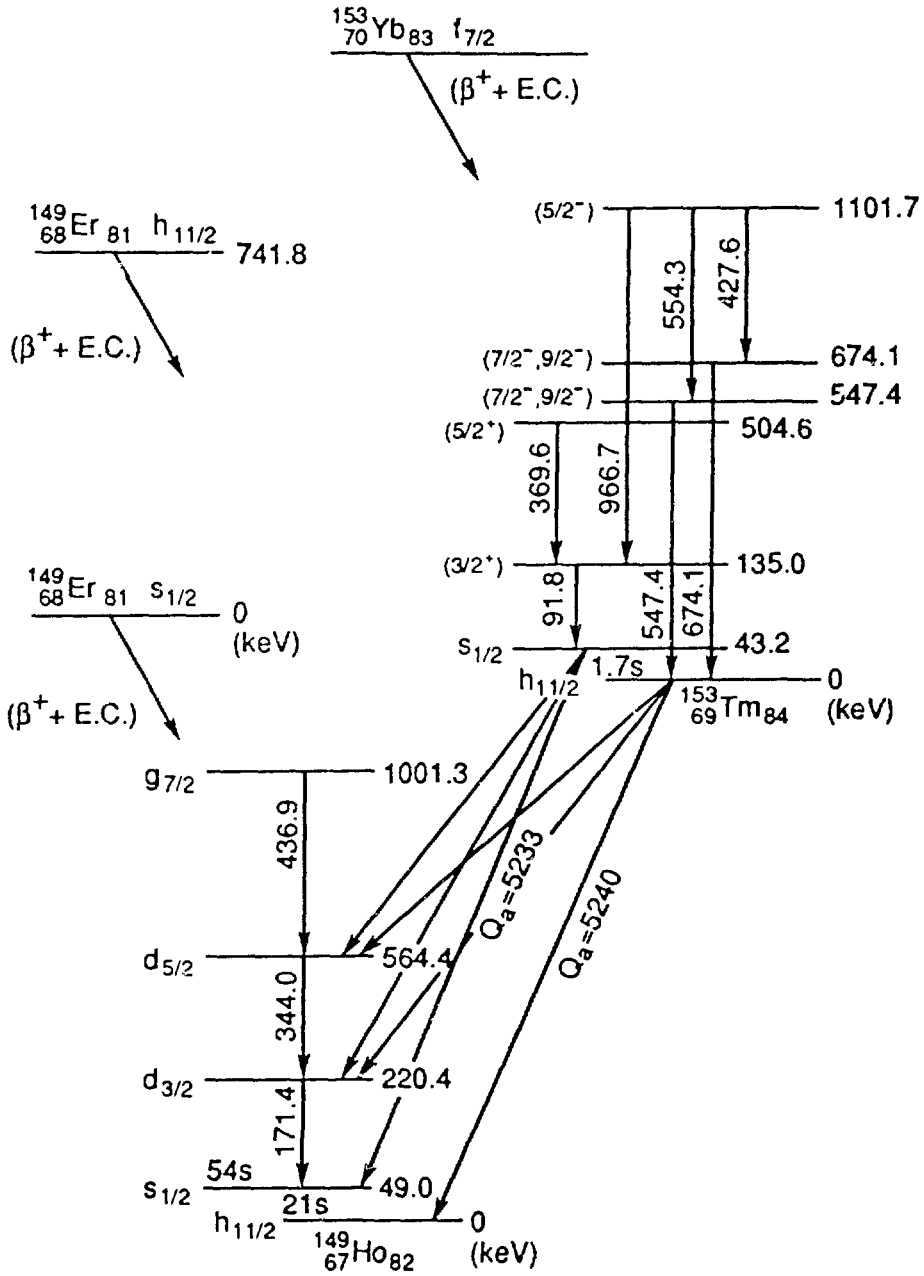


Fig. 2

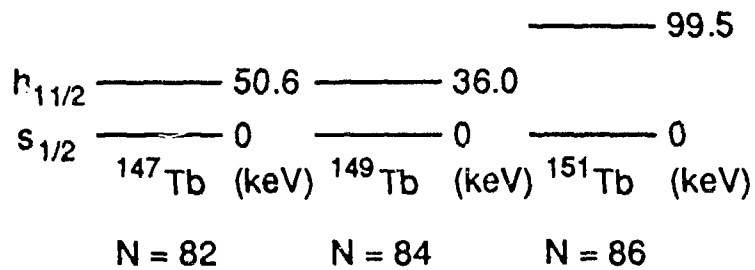
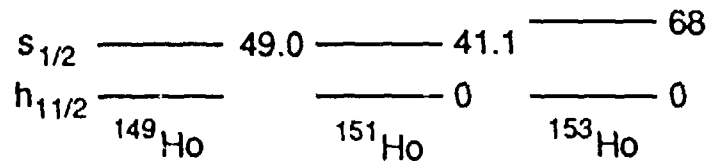
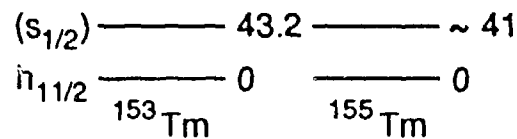
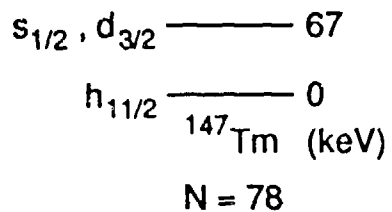


Fig. 3

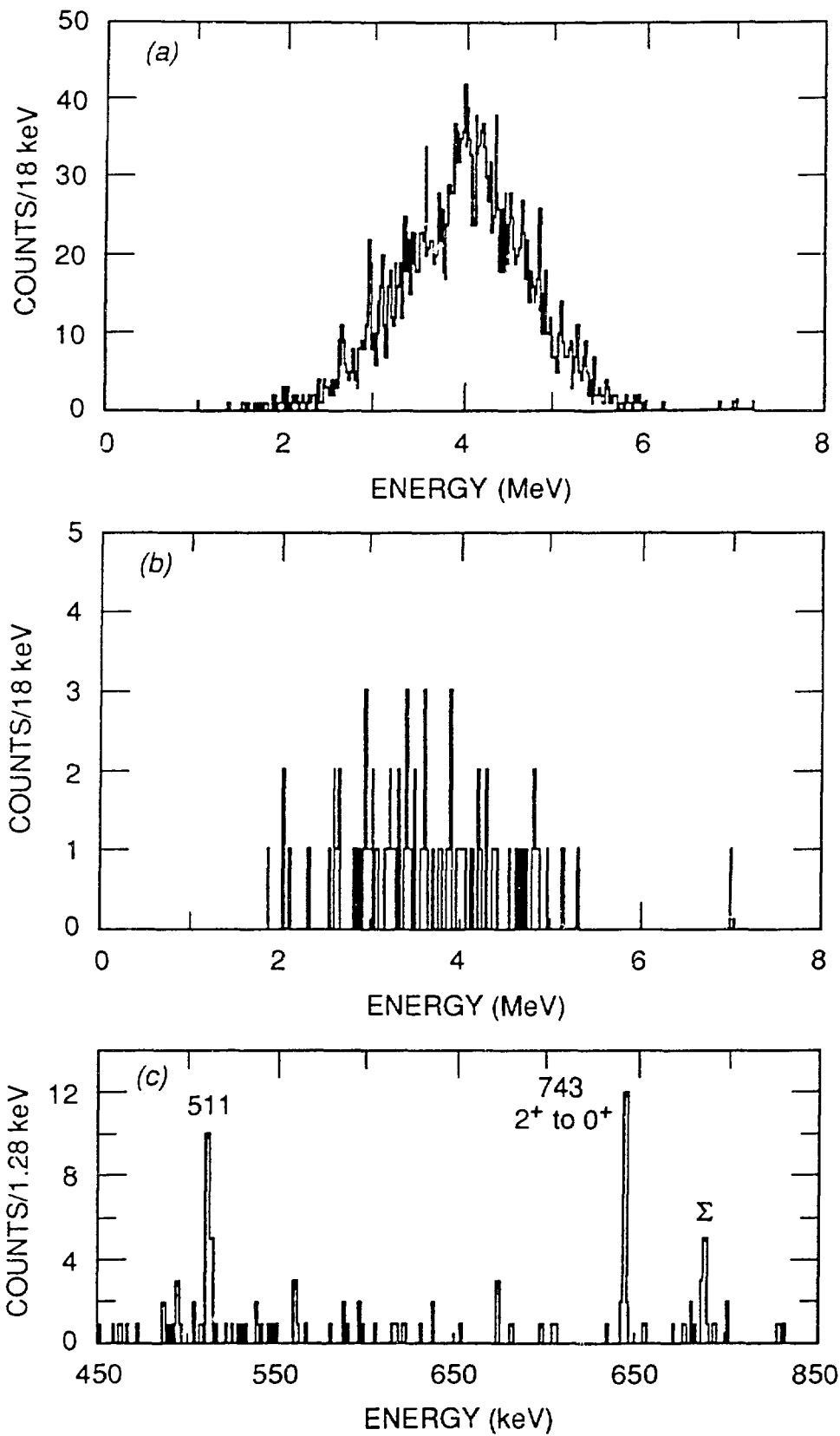


Fig. 4

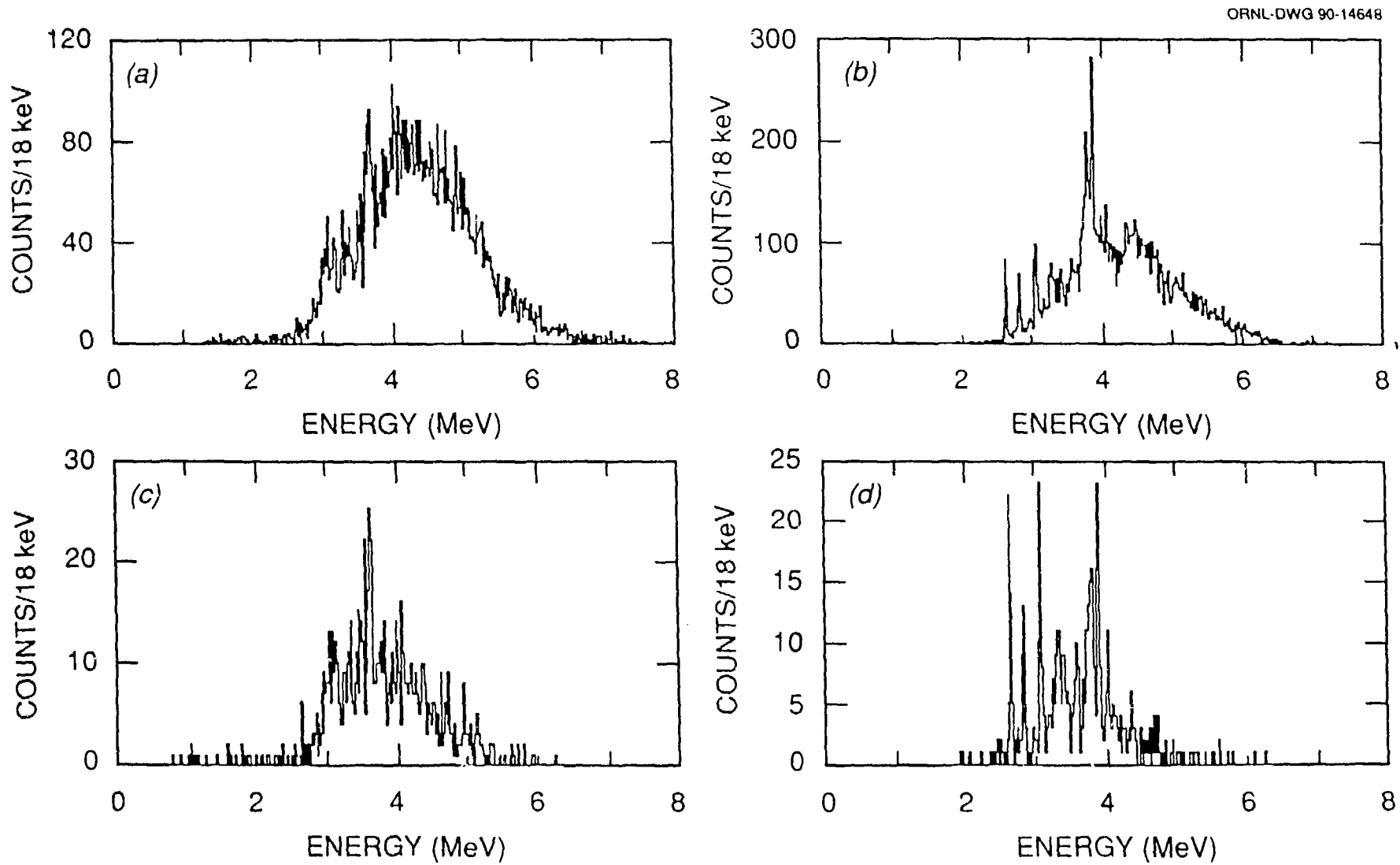


Fig. 5