INVESTIGATION OF NUCLEI NEAR N = 82 AND Z = 64 VIA RADIOACTIVE DECAY OF HIGH-SPIN ISOMERS*

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ABSTRACT

An island of very high-spin isomers has been found recently in neutron-deficient Gd-Lu nuclei near the N = 82 closed shell in (H.I.,xn) measurements. This exciting discovery has led to a large number of experiments trying to identify the structures of these isomers and the nuclei in which they occur. These attempts have been helped in many instances by available spectroscopic information at low excitation energies. We have been involved in a systematic investigation of the low-lying structure of nuclei near N = 82 and $Z \gtrsim 64$. Heavy-ion beams are used to produce proton-rich isotopes which are then transported, with the use of gas-jet systems, to shielded areas where singles and coincidence γ-ray measurements can be made. Earlier investigations dealt with the decay of terbium ($^{146-149}$Tb) and dysprosium ($^{147-152}$Dy) nuclei. During the past two years the research program was extended to holmium nuclides ($A \leq 152$) produced in ^{10}B bombardments of samarium. Two new isotopes, ^{149}Ho and ^{148}Ho, were identified. The decay data of 21-s ^{149}Ho supplement in-beam results[1] and locate the $h_{9/2}$ neutron state in ^{149}Dy to be at 1091 keV. The most intense γ-ray associated with 9-s ^{148}Ho has an energy of 1688 keV. It is possibly the first-excited to ground-state transition in ^{148}Dy. Recent in-beam measurements[2] have shown that the first-excited state in ^{146}Gd is, unexpectedly, 3^- in contrast to doubly even N = 82 nuclei below gadolinium where it is 2^+. It would be interesting to determine whether the 1688-keV level in ^{148}Dy, the next nucleus in this isotonic series, is 2^+ or 3^- in character.

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[1]A.M. Stefanini, P.J. Daly, P. Kleinheinz, M.R. Maier and R. Wagner, Nucl. Phys. A258, 34 (1976); A.M. Stefanini, P. Kleinheinz and M.R. Maier, Phys. Lett. 62B, 405 (1976).

[2]P. Kleinheinz, S. Lunardi, M. Ogawa and M.R. Maier, Z. Phys. A284, 351 (1978).

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1. INTRODUCTION

The investigation of nuclei near the N = 82 closed shell is of interest since it should be possible to describe their low-lying structure in terms of a single-particle framework. Nuclei in this region with $Z \leq 63$ have been studied in several ways, including direct nuclear reactions. This particular method, however, cannot be applied to nuclei whose atomic numbers are greater than 63 because stable isotopes with $N \sim 82$ are unavailable beyond ^{144}Sm. They must therefore be investigated either by the in-beam γ-ray technique and/or through radioactive decay.

An island of very high-spin isomers has been found recently (see e.g., Ref. 1) in neutron-deficient isotopes near N = 82 in (H.I., xn) in-beam measurements. The discovery has led to a number of experiments which are designed to identify the structures and mass assignments of these isomers. In many instances the experiments have been aided by low-energy spectroscopic information already available for nuclei in this mass region. Some of the information had been obtained at the Oak Ridge isochronous cyclotron as part of our investigation of short-lived, proton-rich, radioactive nuclides in the rare earths. In the present contribution we will consider recent data obtained primarily from the decay of terbium, dysprosium, and holmium nuclei and discuss systematics of low-lying levels in N = 81, 82, and 83 isotones.

2. RESULTS AND DISCUSSION

The experiments were done with the use of a gas-jet capillary system. Products knocked out of thin targets by incoming heavy-ion beams were first thermalized in a chamber containing helium and then transported through a Teflon capillary tube to a shielded area by pumping on the gas. Singles and coincidence γ-ray measurements were made simultaneously. The coincidence data were accumulated in a three parameter, γ-γ-τ, mode; singles data were taken and stored in a spectrum multiscale mode so that half-life information can be obtained for the observed photon peaks.

A. N = 81 Nuclei

On the neutron-deficient side of the N = 82 shell, as a result of M4 transitions between $h_{11/2}$ and $d_{3/2}$ neutron states, many isomers have been identified in nuclides with odd A but even Z. [Their partial half-lives (and resultant radial matrix elements) are useful for testing single-particle models (Ref. 2 of example).] The most extensively investigated series is the one for N = 81 nuclei, where isomers have been found from ^{133}Te to ^{145}Gd. However, while the 721-keV M4 transition in ^{145}Gd has been known[3] since 1969 the excitation energies of the $h_{11/2}$ and $d_{3/2}$ levels remained undetermined. This is due to the fact that the ^{145}Gd ground state has a spin of $1/2^+$ in contrast to the isotones with lower atomic numbers. Their ground states are $3/2^+$ so that the energies of the M4 transitions locate the $h_{11/2}$ levels. Therefore, as part of the search for the next nucleus in the series, i.e., ^{147}Dy, we looked for the $d_{3/2}$ to $s_{1/2}$ transitions in both ^{147}Dy and ^{145}Gd.

Dysprosium isotopes were produced by bombarding ^{141}Pr with ^{14}N ions. A new 59-sec activity was observed and identified as the $h_{11/2}$ state in ^{147}Dy. In the course of the investigation it was concluded that two γ-rays found to follow its decay represented the $h_{11/2} \rightarrow d_{3/2}$ (687 keV) and $d_{3/2} \rightarrow s_{1/2}$ (72 keV) transitions in ^{147}Dy. In these irradiations ^{145}Gd^m was also produced by means of the ^{141}Pr (^{14}N, α6n) reaction. A 27 keV γ-ray was observed to decay with the isomer's characteristic 85 sec half-life and was established to be the missing $d_{3/2} \rightarrow s_{1/2}$ M1 transition in ^{145}Gd.

Fig. 1 shows the energies of the three single-neutron states in N = 81 nuclei. The $3s_{1/2}$ orbital drops in excitation energy as Z increases and becomes the ground state in ^{145}Gd and ^{147}Dy. Contrastingly, the $d_{3/2}$ orbital which represents the ground state up through ^{143}Sm becomes the first-excited state in ^{145}Gd (27 keV) and ^{147}Dy (72 keV). The $h_{11/2}$ state increases in excitation and then levels off at ∿ 755 keV. Our data for ^{145}Gd and ^{147}Dy clearly establish the trend predicted by Silverberg.[4] His shell-model calculations for the N = 81 isotones showed that the splitting between the $h_{11/2}$ and $d_{3/2}$ states (M4 transition energies) would first increase with atomic number, reach a maximum at about ^{139}Ce, and then begin to decrease.

B. N = 83 Nuclei

Low-lying states in N = 83 isotones can be described in terms of neutron orbitals beyond N = 82. In Fig. 2 their energies are traced from ^{137}Xe to

^{149}Dy. The information is from a variety of sources, including our data from the decay of ^{145}Eu, ^{147}Tb, and of the new isotope, ^{149}Ho. In a study[5] of ^{145}Sm, a similar plot showed that as Z increased excitation energies increased for all but one of the single-neutron levels. This level (thought to be $9/2^-$ but shown[6] recently to be $13/2^+$) dropped markedly in energy (see Fig. 2). On the basis of these smooth behaviors, it was possible to predict[5] the locations in ^{147}Gd of the two $h_{9/2}$ states as well as the $f_{5/2}$ and $p_{1/2}$ levels; the $i_{13/2}$, 997-keV, and the $p_{3/2}$, 1153-keV levels had been identified by earlier investigators. In our subsequent study[7] of ^{147}Tb decay the $9/2^-$ and $5/2^-$ levels in ^{147}Gd were found close to the predicted energies.

Levels in ^{149}Dy, the next nucleus in the series, were recently investigated[8] in-beam by means of the ^{152}Gd (α, 7n) reaction. The first-excited level, the $i_{13/2}$ intrinsic state, was located at 1073-keV and found to deexcite to the $f_{7/2}$ ground state via an E3 transition. In a series of ^{144}Sm + ^{10}B bombardments we were able to identify a 21-sec activity as being ^{149}Ho. In addition to the E3 1073-keV transition, an intense 1091-keV γ-ray was found to be associated with the new activity. We propose that this intense transition deexcites a 1091-keV level in ^{149}Dy which is the principal $h_{9/2}$ neutron state populated by the allowed (log ft $\sim$ 4.3) β transition, $\pi h_{11/2} \rightarrow \nu h_{9/2}$.

The two sets of new data show (see Fig. 2) that the smooth trends, at least for the $i_{13/2}$ and $h_{9/2}$ states, have been disrupted at ^{149}Dy. The disruption may be due to the closure at Z = 64 (see e.g., Ref. 9) where the $g_{7/2}$ and $d_{5/2}$ proton orbitals are filled so that ^{149}Dy (its last two protons are in $h_{11/2}$ orbitals) is the first N = 83 nucleus to occupy the new subshell. Shell-model calculations[10] for nuclei in this region have been made with the assumption of an (N=82 + Z=50) core. Because of the complexities involved, the $h_{11/2}$ proton orbital was not considered; it should be included for nuclei at Z $\gtrsim$ 64, since occupation of that orbital becomes important at this atomic number. Further theoretical studies are needed. With the available experimental evidence perhaps such calculations could utilize an (N=82 + Z=64) core to explore the structure of nuclei with Z $\geq$ 66.

C. N = 82 Nuclei

Low-lying levels in doubly-even N = 82 nuclei can be explained in terms of two-quasiparticle excitations. They have also been considered as core states for the interpretation of levels in N = 83 nuclei. Systematics for the lowest 2^+, 4^+, 6^+, and 3^- states in N = 82 isotones (^{134}Te to ^{148}Dy) are summarized graphically in Fig. 3. Information indicated for ^{146}Gd is from ^{146}Tb decay[7] and recent in-beam studies;[11,12] levels shown for ^{148}Dy are observed in the decay of the new isotope ^{148}Ho.

The general trend in Fig. 3 is that the 2^+, 4^+, and 6^+ states increase gradually in energy as Z increases while the 3^-, octupole, level drops precipitiously. The ^{146}Gd first-excited state at 1580 keV had been assumed to be 2^+ as expected for an even-even nucleus. A recent investigation,[11] however, has shown that it is 3^- instead. A subsequent study located[12] the lowest 2^+ level at 1971 keV. Thus, the accumulated evidence is that ^{146}Gd is one of the few doubly-even nuclei whose first-excited states are not 2^+. These exceptions are found in nuclei with special closed shell structures, such as ^{16}O, ^{40}Ca, and ^{208}Pb. It seems, therefore, that ^{146}Gd, with a 3^- first-excited state, may be doubly magic. The 5^- and 7^- levels shown in Fig. 3 for ^{146}Gd had originally been thought to be 4^+ and 6^+, respectively. This does not appear to be likely because they are connected[11] by E2 transitions to the 3^- state. Possible candidates are the two levels seen in decay[7] above the 7^- state.

The new isotope, ^{148}Ho, was identified at the highest bombarding energy used, ∿ 96 MeV, in the ^{10}B + ^{144}Sm experiments. It has a half-life of 9 sec and has, in its decay, three γ-rays in coincidence with one another. Their intensities establish the following cascade (and sequence of levels) in keV: 504 (2854) → 662 (2350) → 1688 (1688) → ^{148}Dy ground state. This situation resembles the one found[7] in ^{146}Tb decay, i.e., 441 (3099) → 1078 (2658) → 1580 (1580) → ^{146}Gd ground state. Conversion coefficient measurements are not available as yet. One cannot say, therefore, if the lowest excited state in ^{148}Dy shown in Fig. 3 is 2^+ or 3^-. As a result the three excited levels are tentatively characterized as (2^+, 3^-), (4^+, 5^-) and (6^+, 7^-).

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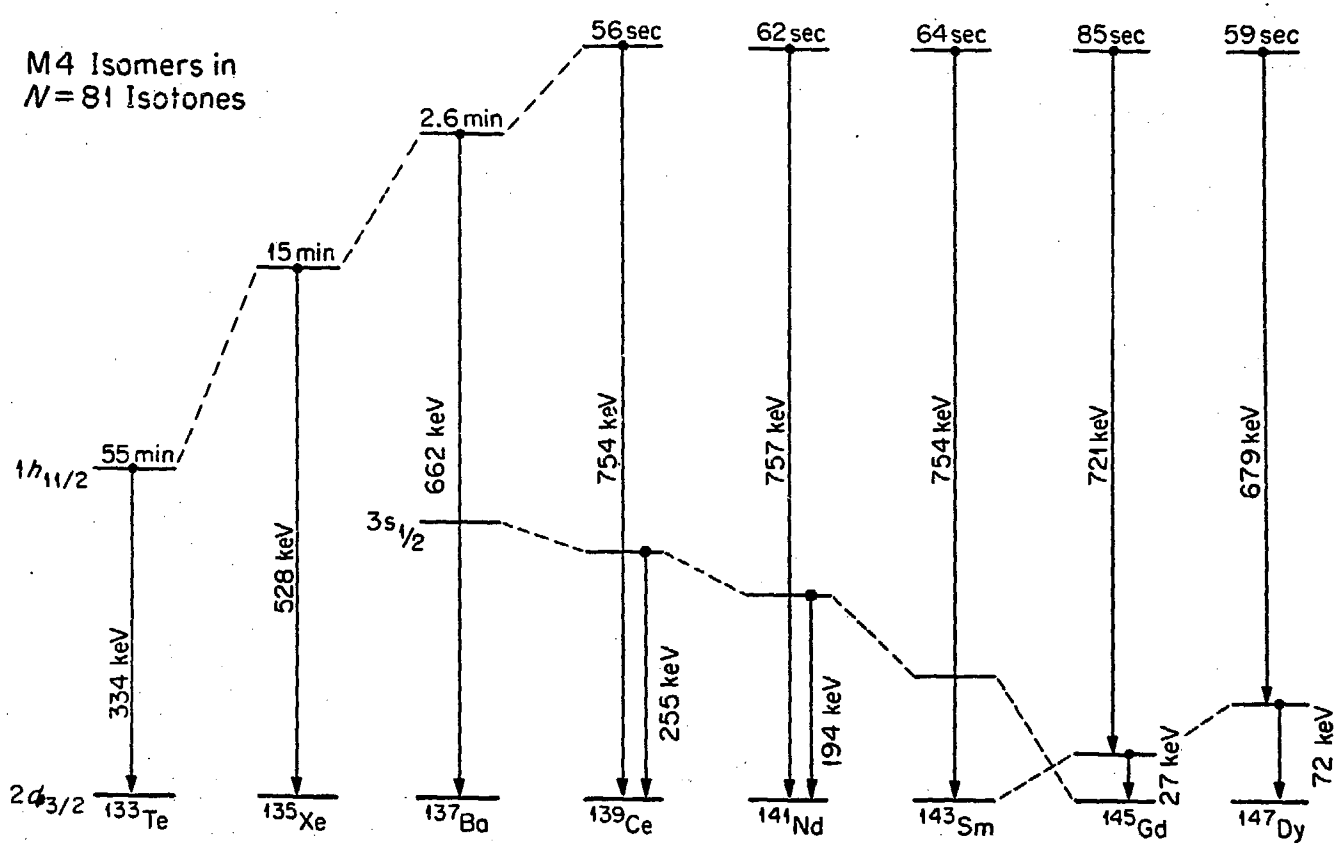
FIGURE CAPTIONS

Figure 1. Location of $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ neutron levels in N = 81 even-Z isotopes.

Figure 2. Excitation energies of single-neutron states in N = 83 even-Z isotones. The dashed level in ^{149}Dy at 1584 keV may correspond to the $9/2^-$ 1798-keV level in ^{147}Gd.

Figure 3. Low-lying levels in doubly-even N = 82 nuclei.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62 sec
64 sec
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59 sec
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2d3/2
334 keV
528 keV
662 keV
754 keV
757 keV
754 keV
721 keV
679 keV
255 keV
194 keV
27 keV
72 keV
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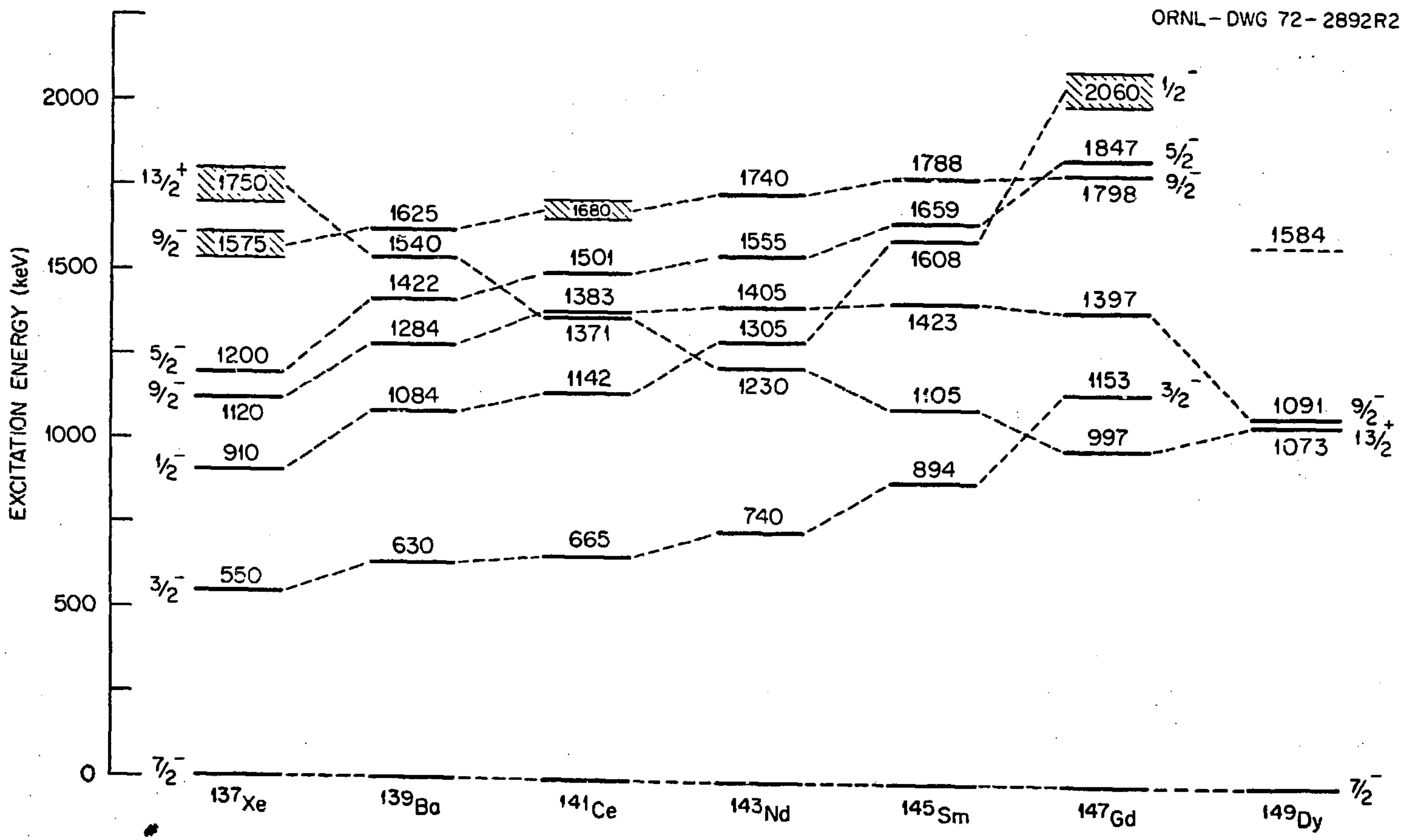
135Xe
137Ba
139Ce
141Nd
143Sm
145Gd
147Dy

Fig. 1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2000
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139Ba
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147Gd
149Dy
13/2+
9/2-
5/2-
9/2-
1/2-
3/2-
7/2-
1750
1575
1200
1120
910
550
1625
1540
1422
1284
1084
630
1680
1501
1383
1371
1142
665
1740
1555
1405
1305
1230
740
1788
1659
1608
1423
1105
894
2060
1847
1798
1397
1153
997
1/2-
5/2-
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13/2+
7/2-

Fig. 2

ORNL-DWG 79-9360

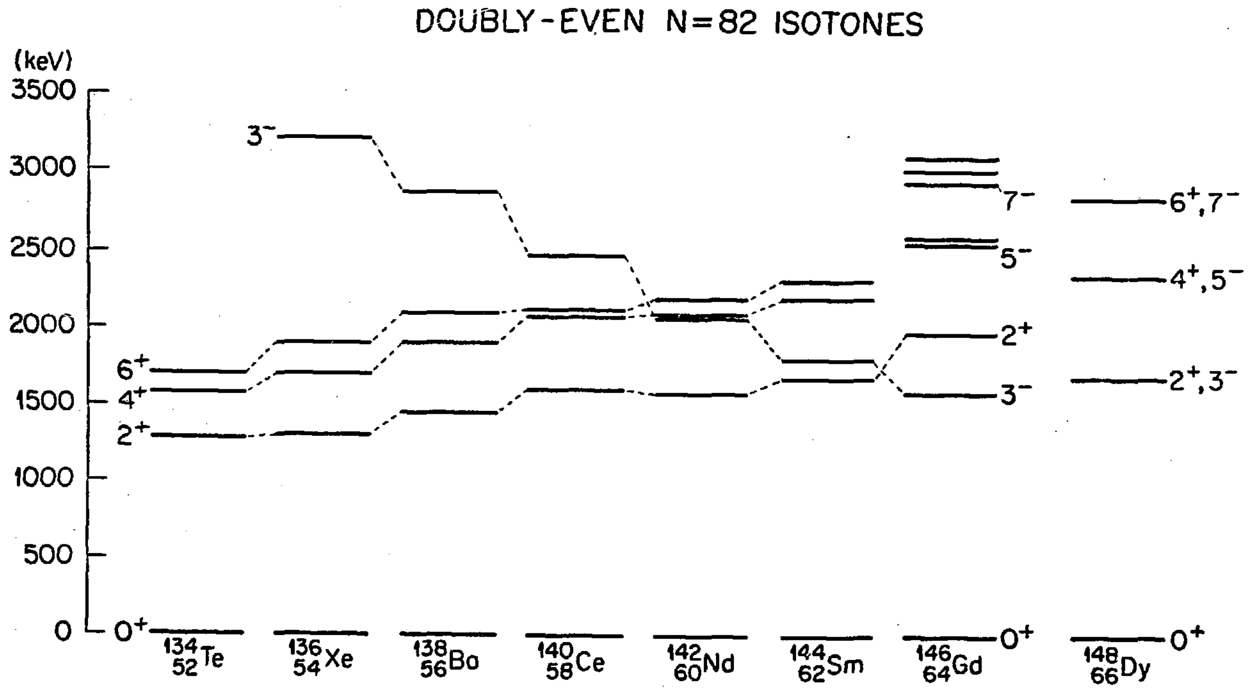

Fig. 3