First in-beam observation of excited states in $^{156}_{72}$Hf$_{84}$ using the Recoil-Decay Tagging Method

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Excited states in the proton rich nuclide $^{156}_{72}$Hf$_{84}$ were observed for the first time using the ^{102}Pd(^{58}Ni,2p2n)^{156}Hf reaction at 270 MeV. Gamma rays were detected with the AYEBALL array of Compton suppressed Ge detectors, placed in front of the Fragment Mass Analyzer, and were assigned to individual reaction channels using the Recoil-Decay Tagging Method. Prompt γ-ray cascades were associated with the alpha decay of both the ground state and the 8^+ isomeric state in ^{156}Hf. The level scheme constructed for ^{156}Hf is compared with level schemes of lighter even-even N=84 isotones and is discussed within the framework of the Shell Model.

I. INTRODUCTION

The structure of nuclei situated along the N=82 neutron shell closure, above the Z=64 line have for a long time been an aim of numerous studies. Interest in this region of the chart of nuclides increased after the discovery that $^{146}_{64}$Gd$_{82}$ can be regarded as a doubly magic core [1]. This has been attributed to the presence of a large energy gap between the $g_{7/2}$, $d_{5/2}$ proton orbitals, which are filled in ^{146}Gd, and the remaining proton orbitals of the Z=50-82 major shell, i.e. $h_{11/2}$, $s_{1/2}$ and $d_{3/2}$. The immediate neighbors of ^{146}Gd can be produced with relatively large cross sections using heavy-ion induced fusion-evaporation reactions and there exists a vast amount of experimental data on their structure. For a summary of a large body of experimental work see ref. [2]. Deduced single-particle energies and two-body matrix elements, with respect to the ^{146}Gd core, have been used in several shell-model calculations which successfully reproduce excited states observed in nuclei which have more than two valence nucleons outside the ^{146}Gd core [2,3].

The N=82 isotones heavier than $^{146}_{64}$Gd$_{82}$ are an ideal testing ground for studying the proton-proton residual interaction, and it is worth noting that their yrast high spin states, can be accurately described using the $(\pi h_{11/2})^n$ configuration space. The N=84 isotones heavier than $^{148}_{64}$Gd$_{84}$ on the other hand are crucial for determining both the interaction between neutrons in the $f_{7/2}$ and $h_{9/2}$ orbitals (which are the two lowest neutron orbitals) and the interaction of these neutrons with protons gradually filling the $h_{11/2}$ orbital. In addition, the $i_{13/2}$ neutron orbital also plays a significant role at higher excitation energies, due to its large angular momentum which effectively contributes to the total spin.

Another interesting aspect of studies of light nuclei with N≥82 and Z≥64 is the close proximity of the proton drip-line. This presents an opportunity to address questions related to the interplay between γ decay and proton decay, the formation of proton halos in heavy nuclei, and the impact of the continuum on loosely bound states. In fact, a number of new proton emitters have been recently identified in this region in a series of experiments performed at the ATLAS accelerator using the Fragment Mass Analyzer (FMA) [4]. Every odd-Z element between Ta and Bi has been found to have at least one isotope which decays by proton emission. In addition, there exists a vast amount of data on alpha decay in this region (see [5] and references therein).

However, studies of the level structure of proton rich nuclei in the N≥82, Z≥64 region are impeded by very small reaction cross sections due to the lack of suitable stable target and beam combinations, strong competition from fission and fragmentation of the fusion-evaporation cross section. The nucleus $^{154}_{72}$Hf$_{82}$ is the heaviest N=82 isotone with known excited states. The decay of its 10^+ isomer has been observed using the Daresbury Recoil Separator [7]. Excited states of even-even N=84 isotones through $^{154}_{70}$Yb$_{84}$ [8] and odd N=84 isotones through $^{153}_{69}$Tm$_{84}$ [9] have been investigated in a series of in-beam experiments summarized in ref. [3].

A procedure, termed the Recoil-Decay Tagging (RDT) method, has recently been employed for identifying in-beam prompt γ rays in nuclei which undergo α or proton decay. The method was successfully used for the first time for α and proton emitters in the ^{100}Sn region and yielded very promising results [6].

In the present work, prompt γ-ray cascades correlated with the two α lines, previously assigned to ^{156}Hf, were identified using the RDT method. The level scheme obtained for ^{156}Hf will be discussed in the framework of the Shell Model and compared with the excited states observed in neighboring nuclei.

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II. EXPERIMENT

A 270 MeV ^{58}Ni beam from the ATLAS accelerator was used to bombard a 1 mg/cm^2 ^{102}Pd target in order to populate excited states in $^{156}_{72}$Hf$_{84}$ via the 2p2n fusion-evaporation channel. Gamma rays were detected with AYEBALL [10], an array of 16 HPGe detectors and 2 LEP spectrometers surrounding the target, placed in front of in the FMA. Detected γ rays were assigned to individual reaction channels using the RDT method [6]. Residual recoiling nuclei were dispersed in the FMA according to their mass to charge state ratio and implanted into a Double-Sided Silicon Strip Detector (DSSD) placed behind the focal plane of the FMA. The subsequent characteristic α decays observed in the same pixel of the DSSD as the implantation allowed complete identification of the implanted residues and thus of γ rays detected at the target position.

The ground state of ^{156}Hf has a half life of 23 ms and is known to decay predominantly by emitting an α particle with an energy of 5.87 MeV. Another α line with an energy of 7.78 MeV and a half-life of 0.52 ms has been assigned to the decay of an isomeric state in ^{156}Hf [5]. The isomeric state has been found to be populated following the β decay of the $[\pi h_{11/2}\nu f_{7/2}]_{9+}$ state in ^{156}Ta, and, as a result, has been assigned as a $[\nu h_{9/2}\nu f_{7/2}]_{8+}$ configuration in analogy to heavier N=84 isotones [11]. In the present experiment, prompt γ-ray cascades could be associated with both ^{156}Hf alpha lines.

The energy spectrum of α particles collected in the DSSD during the experiment is shown in Fig. 1.
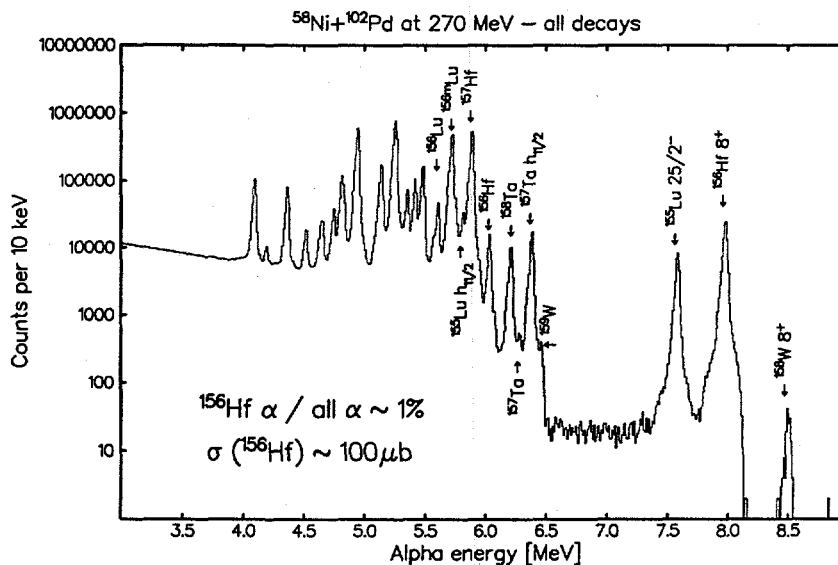

FIG. 1. Energy spectrum of alpha particles measured in the DSSD.

Both ^{156}Hf α lines represent about 1% of the entire spectrum. Singles γ-ray spectra tagged on the ^{156}Hf alpha lines are presented in Fig. 2. Three strong γ-ray lines are correlated with the ground state α decay of ^{156}Hf. The spectrum correlated with the α particles emitted from the isomeric state is somewhat more complicated, indicating fragmentation of the decay path at higher excitation energies. A preliminary level scheme for ^{156}Hf is proposed in fig. 3.
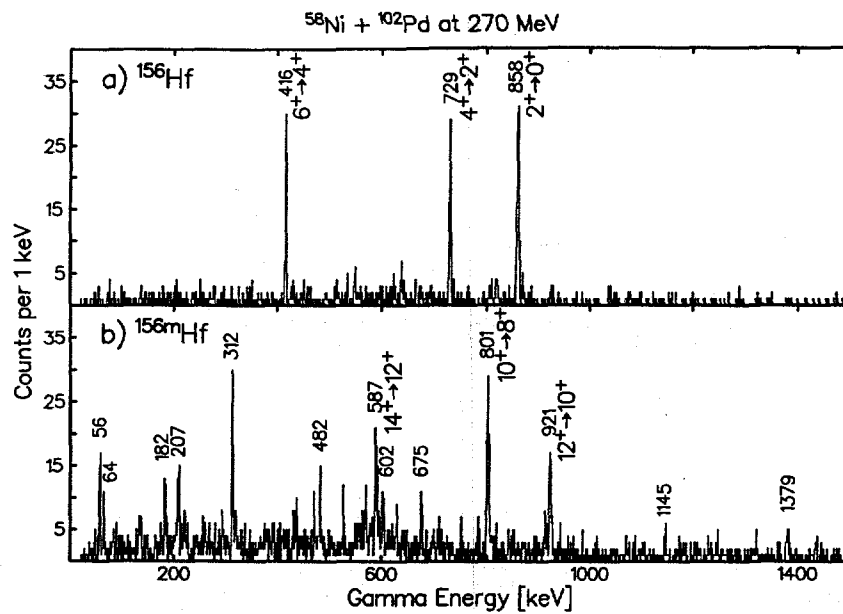
FIG. 2. Gamma-ray singles spectra tagged on a) the ground state α decay of ^{156}Hf and b) the α decay of the 8^+ isomeric state in ^{156}Hf.
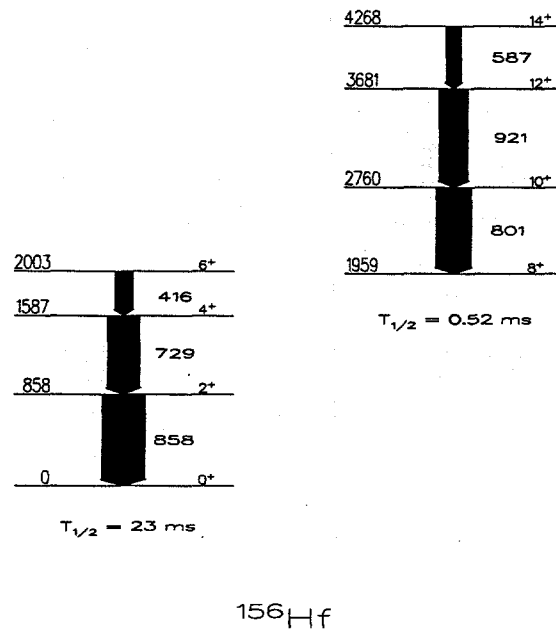

FIG. 3. A preliminary level scheme for ^{156}Hf.

Gamma-ray transitions were ordered solely on the basis of the measured γ-ray intensities in the singles recoil-decay tagged spectra. Because of the low statistics, only the strongest transitions have been placed in the level scheme. The spins and parity assignments of the proposed levels were obtained using fragmentary angular distribution information. These assignments are, however, supported by comparison with the systematic behavior of states in the lighter known even-even N=84 isotones. They should nevertheless be regarded as preliminary.

III. DISCUSSION

The three strong γ-ray transitions feeding the ground state are placed in a cascade of stretched E2 transitions forming a $6^+ \to 4^+ \to 2^+ \to 0^+$ sequence of states. As shown in fig. 4, the resulting 2^+, 4^+ and 6^+ excitation energies follow the systematics of the lighter known even-even N=84 isotones and, together with the ground state, are proposed to form the $(\nu f_{7/2})^2$ multiplet.
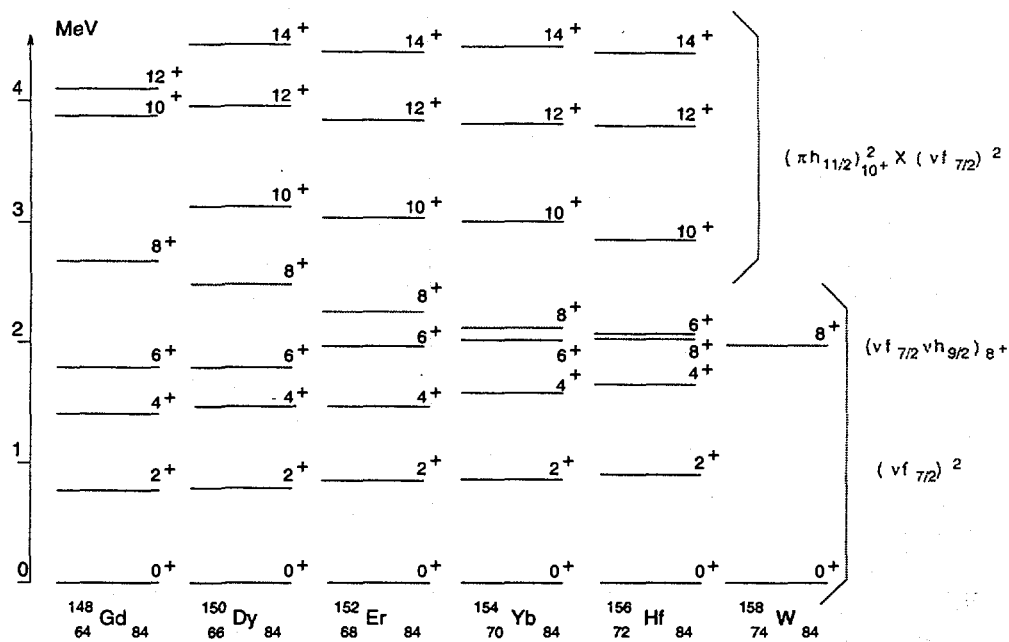

FIG. 4. Systematics of yrast states in even-even N=84 isotones. The configuration assignments proposed in this work are indicated on the right hand side of the figure. The 8^+ state shown for ^{158}W has only been oberved in α-decay studies.

The energy sum of these three γ-ray transitions places the 6^+ state above the 8^+ isomer. An E4 γ-ray transition is the only competition for the β and α decays from this state. The 8^+ state is thus a classical yrast trap. The lowering of the 8^+ state with respect to the 6^+ level as Z increases is mainly a consequence of the narrowing of the energy gap between the two lowest lying neutron orbitals, $\nu f_{7/2}$ and $\nu h_{9/2}$, as illustrated in fig. 5. In the heavier N=84 isotones this trend has been associated with the strong attractive interaction between the $h_{11/2}$ proton and the $h_{9/2}$ neutron when coupled to spin $I=1\hbar$ [3]. This attraction is taken advantage of by each successive proton pair added to the ^{146}Gd core.

The three strongest transitions correlated with the α decay of the 8^+ isomer have also been assigned as stretched quadrupole transitions forming a cascade reaching a spin of $14\hbar$ and an excitation energy of about 4.3 MeV. This sequence resembles the cascades seen in the lighter N=84 isotones, and the proposed 10^+, 12^+ and 14^+ states can be interpreted as the $(\nu f_{7/2})^2_{0^+,2^+,4^+}$ states coupled to the aligned proton pair $(\pi h_{11/2})^2_{10^+}$. Gamma-ray lines remaining in fig. 2b have not yet been placed in the level scheme. They are most likely situated above 4 MeV excitation energy where the decay path is fragmented, as has been observed in ^{154}Yb [8].
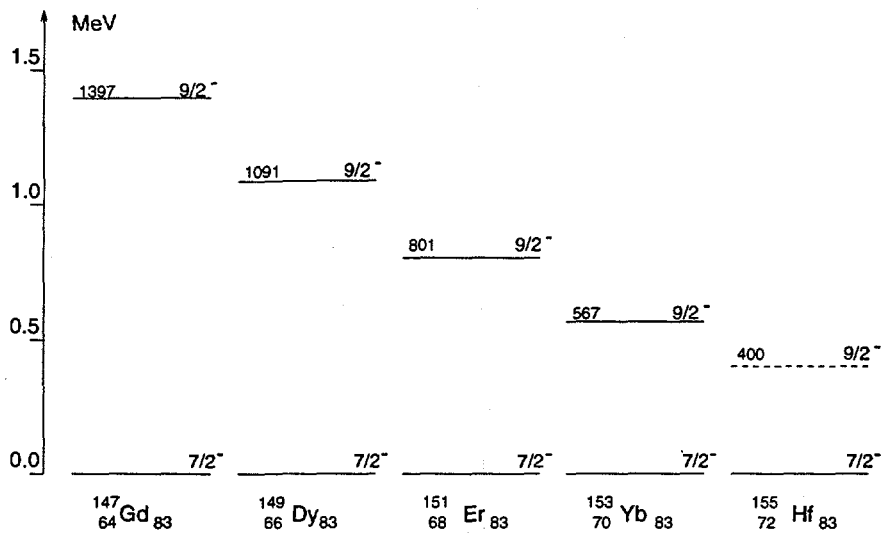
FIG. 5. Systematics of the neutron single-particle states in odd N=83 isotones. The 9/2⁻ state in ^{155}Hf was extrapolated.

Although the interpretation of the ^{156}Hf level structure proposed in this work appears to be quite strightforward, more in depth shell-model analysis may shed some light on the growing role of the $h_{9/2}$ neutron orbital. A simple extrapolation from known nuclei places this orbital only 200 keV above the $f_{7/2}$ neutron orbital in ^{156}Hf and both orbitals are almost degenerate in ^{158}W, a nucleus which has only 2 protons more than ^{156}Hf. One of the consequences of this degeneracy would be the mixing of the members of the $(\nu h_{9/2})^2_{0+,2+,4+,6+,8+}$ multiplet with the yrast $(\nu f_{7/2})^2$ band. Also any attempt to find footprints of the interaction between the continuum and the observed states requires data with much better statistics, which is necessary to extend the level scheme of ^{156}Hf to higher excitation energies, both along the yrast line and above it.

In the same experiment, excited states in the odd-Z proton-rich N=84 isotones ^{155}Lu and ^{157}Ta were also observed for the first time. It is also worth mentioning that evidence was found that one of the states in ^{157}Ta, most likely the $\pi d_{3/2}$ state which have not been seen before, undergoes direct proton decay. Prompt γ-ray cascades were correlated with the α decays of the $h_{11/2}$ proton states in both nuclei and with the 25/2⁻ isomer in ^{155}Lu. Preliminary analysis of the γ-ray spectra correlated with α particles emitted from the $\pi h_{11/2}$ states revealed yrast bands similar to these observed in heavier odd-Z N=84 isotones (see fig. 6).
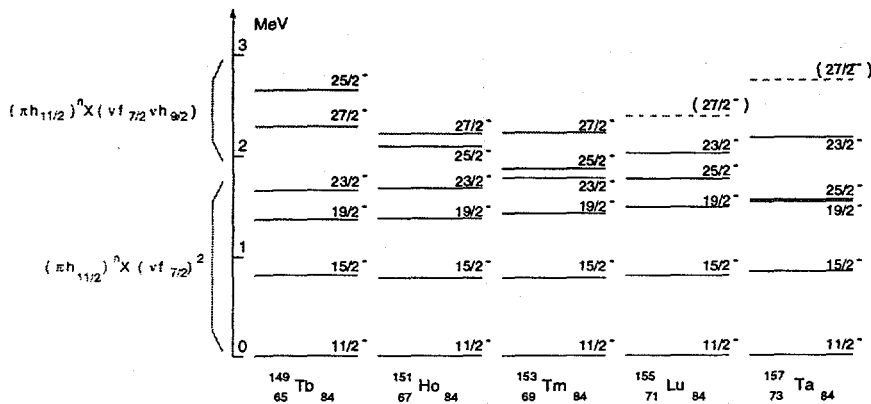

FIG. 6. Systematics of yrast bands built on the $h_{11/2}$ proton states in odd-Z N=84 isotones. The states shown for ^{155}Lu and ^{157}Ta are proposed for the first time from the present work. The suggested configurations are indicated on the left hand side of the figure.

The proposed E2 cascades feeding the $\pi h_{11/2}$ state reach spin $23/2^-$. The resulting $23/2^-$, $19/2^-$, $15/2^-$, $11/2^-$ sequence resembles the 6^+, 4^+, 2^+, 0^+ sequence in ^{156}Hf, and can be interpreted as the $(f_{7/2})^2$ multiplet aligned with the $h_{11/2}$ odd proton. In addition, possible $27/2^-$ states are suggested for both nuclei which would correspond to the maximum spin state of the $\pi h_{11/2} \otimes (\nu f_{7/2} \otimes \nu h_{9/2})_{8^+}$ configuration. In the $25/2^-$ state neutrons occupy the same orbitals as in the $27/2^-$ state but one proton $(h_{11/2})^2$ pair is broken. The results show that the yrast $25/2^-$ state drops below the yrast $23/2^-$ already in ^{155}Lu and comes down even more in ^{157}Ta forming an yrast trap. The lowering of the $25/2^-$ state with respect to the $23/2^-$ state simply mimics the drop of the $\nu h_{9/2}$ orbital with respect to the $\nu f_{7/2}$ orbital.

IV. SUMMARY

In this work results for excited states in three N=84 isotones, i.e. ^{156}Hf, ^{155}Lu and ^{157}Ta, are presented for the first time. Despite low statistics, the proposed γ-ray transitions were unambiguously assigned to the individual reaction channels using the RDT method and yrast cascades feeding the ground states, and the 8^+ isomer in ^{156}Hf, were proposed. The resulting level schemes, to a large extent, follow the systematics of the lower-Z N=84 isotones, allowing shell-model interpretation similar to that proposed in ref. [3]. More in-depth analysis requires data with better statistics.

The RDT method used in the present experiment, is seen to be a very powerful tool to identify in-beam γ-ray transitions associated with very weakly populated reaction channels at and even beyond the proton drip-line. Indeed, in another experiment, γ-ray transitions correlated with the ground state and isomeric state proton decay in ^{147}Tm were identified, truly representing in-beam γ-ray spectroscopy beyond the proton drip line. A large array of Ge detectors such as GAMMASPHERE, placed in front of the FMA, would increase the γ-γ coincidence efficiency by a factor of about 50 compared to AYEBALL, This would allow the extension of already known level schemes to higher excitation energies and studies even further beyond the proton drip-line. For example, the heavier even-even N=84 isotone ^{158}W, where the neutron orbitals $f_{7/2}$ and $h_{9/2}$ are almost degenerate, would be well within the range of such a detection system.

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