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NUCLEAR STRUCTURE NEAR AND BEYOND THE PROTON DRIP LINE*

Jolie A. Cizewski, Kwan Ying Ding and Martin B. Smith

Department of Physics and Astronomy, Rutgers University
New Brunswick, New Jersey, 08903 USA

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Two nuclear systems near and beyond the proton drip line are examined following spectroscopy with Gammasphere coupled to the Fragment Mass Analyzer. The proton-rich $N = 84, 85$ isotones are found to have an yrast structure dominated by $\nu h_{9/2}$ configurations. In ^{173}Au the first evidence is seen for the limit of energy which a nucleus beyond the proton drip line can sustain.

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1. Introduction

Traditionally nuclear structure studies have been limited to nuclei near the line of stability, or neutron-deficient nuclei populated in fusion reactions following the evaporation of a few neutrons. Recent developments in experimental techniques allow studies near and beyond the proton drip line to probe possible changes in single-particle structure for systems in which the last proton is at best weakly bound.

There is also considerable interest in the limits of excitation energy and angular momentum that weakly bound nuclear systems can sustain. Recently, the energy-spin (E, I) phase space of ^{254}No [1] has been determined. These distributions show that this very heavy nucleus, which would be unstable against spontaneous fission but for shell corrections, is surprisingly robust. Nuclei which are unstable to decay by proton emission, either from their ground state or from an isomeric state, provide another laboratory for the study of the amount of energy and angular momentum which a weakly bound system can withstand.

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This paper will focus on two systems near and beyond the proton drip line: nuclear structure of proton-rich N=84,85 isotones near the proton drip line and the limits of energy and angular momentum in weakly bound Au nuclei beyond the proton drip line.

2. Experimental techniques

The measurements reported here were performed at the ATLAS accelerator facility at Argonne National Laboratory and exploited the power of the Gammasphere array of γ-ray detectors coupled to the Fragment Mass Analyzer (FMA) recoil separator. For both measurements Gammasphere consisted of 101 Ge detectors, each surrounded by an array of BGO scintillators for Compton suppression; the hevimet shields in front of the BGO detectors were not in place. For the Au measurements, an additional 5 BGO shields were placed at forward angles, for a total of 106 modules, to cover a solid angle as close to 4π as possible.

The FMA selects M/Q of the evaporation residues. At the focal plane, a position-sensitive Parallel-Grid Avalanche Counter (PGAC) was used to identify the M/Q of residues, which were subsequently implanted in a 48×48 Doubled-sided Silicon Strip Detector (DSSD) placed 40cm behind the PGAC.

The information recorded included γ-ray energies (E_γ) and time with respect to the radio frequency (RF) of the accelerator, the position ($X_{\rm PGAC}$, $Y_{\rm PGAC}$) and energy loss ($\Delta E_{\rm r}$) of the evaporation residues in the PGAC, and the position (X,Y) and energy ($E_{\rm r}$) of recoils in the DSSD. The Time Of Flight (TOF) of the recoils between (i) the PGAC and DSSD and (ii) the recoils and the prompt γ-ray flash at the target position were also recorded, as well as the energy (E_α) and position (X,Y) of the decay particles of the implanted residues. In addition, the time from an absolute clock was recorded for every event throughout the experiment to obtain the time elapsed between implantation and decay of a recoil.

The data analysis exploited the Recoil–Decay Tagging technique (RDT), in which prompt γ-ray events in Gammasphere at the target position were correlated with the isomer-specific decay of implanted evaporation residues, milliseconds to seconds after the prompt reaction.

3. Structure of $N=84,85$ isotones near the proton drip line

The ^{58}Ni reaction on an enriched ^{102}Pd target at 270 MeV was used to populate $N=84,85$ isotones near the proton drip line. Since the proton-rich ^{160}W compound system has a large number of exit channels and the fusion-evaporation process has strong competition from the dominant fission channel, recoil tagging was essential to select γ-ray transitions associated with particular nuclei. For the more weakly populated isomers, which decay by alpha-particle emission, the RDT technique was critical. Figure 1, in which the α-decays correlated with M/Q are summarized, illustrates the richness of this reaction measurement, as well as the importance to have both α-decay and mass information to select a specific isomer. Excitations in the $N = 84$ Lu, Hf, Ta, and W isotopes, as well as $N = 85$ Yb and Lu isotopes were deduced [2–5].

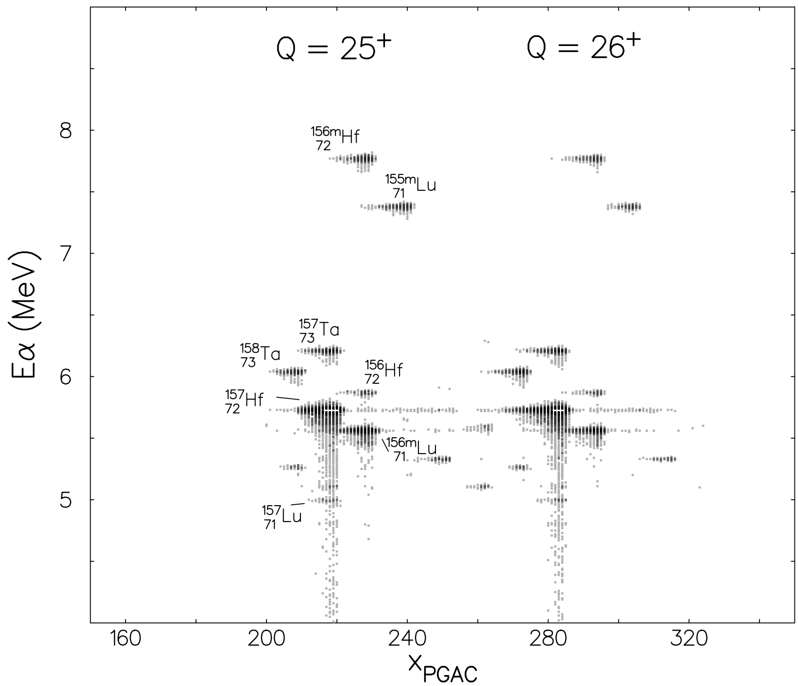

Fig. 1. Two-dimensional display of the E_α *vs* $X_{\rm PGAC}$ matrix for decays which occurred within 200 ms after implantation.

The doubly-magic nature of $^{146}_{64}$Gd was originally identified by Kleinheinz and coworkers [6]. Above the $Z = 64$ gap, the high-spin proton level is $h_{11/2}$ — this orbital will be the dominant proton orbital populated in high-spin studies. On the neutron side, the first orbital is $f_{7/2}$ with a sizeable gap before the $i_{13/2}$ orbital and the $h_{9/2}$ orbital lies at even higher energy. Therefore, near ^{146}Gd the low-lying structure is expected to be dominated by the $f_{7/2}$ neutrons.

However, the single-neutron structure changes when protons are added above $Z = 64$. While the $h_{9/2}$ neutron excitation is at almost 1.4 MeV in ^{147}Gd, it drops to as low as 400 keV in ^{155}Hf, with 8 more protons. This dropping of the energy of the $h_{9/2}$ neutron orbital also affects the even–even

$N = 84$ isotones, displayed in Fig. 2. In ^{148}Gd the yrast $2^+, 4^+, 6^+$ states, formed by coupling two neutrons in the $f_{7/2}$ orbital, are well separated from the 8^+ state formed by coupling $(\nu f_{7/2} h_{9/2})_{8^+}$. This 8^+ state becomes lower in energy as the neutron number increases, below the 6^+ states in ^{156}Hf and ^{158}W. The α decay of these 8^+ isomers has enabled spectroscopy above these excitations, in particular, for ^{156}Hf, using the RDT method [4].

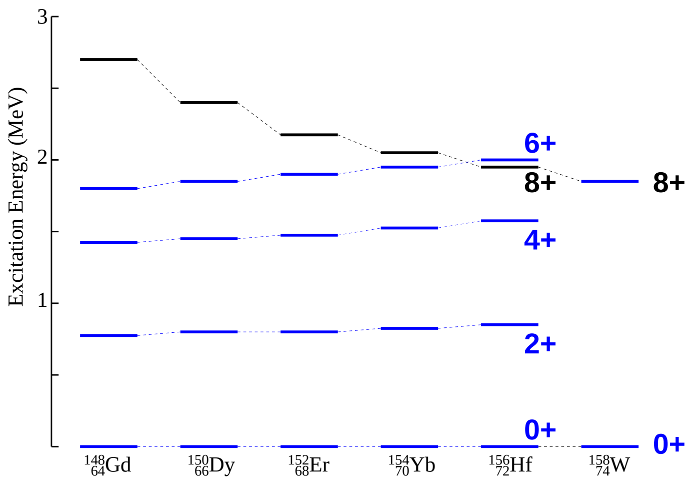

Fig. 2. Systematics of the yrast states in even-Z, $N = 84$ isotones. Taken from Ref. [4].

In the odd-mass $N = 84$ isotone, ^{155}Lu, three alpha-decaying isomers [7] were populated: the low spin $3/2^+$ ground state and the high-spin $11/2^-$ and $25/2^-$ isomers. The level scheme deduced for ^{155}Lu is displayed in Fig. 3. For the ground state there were insufficient statistics to establish a level scheme. The excitations above the $11/2^-$ isomer are predominantly the coupling of two $f_{7/2}$ neutrons to the valence $h_{11/2}$ proton. These excitations were previously identified in an RDT experiment with AYEBALL [4]. Excitations above the $25/2^-$ isomer have also been established. In Lu the $25/2^-$ state is isomeric because it lies below the fully-aligned $(\pi h_{11/2} \nu f_{7/2} h_{9/2})_{27/2^-}$ and $(\pi h_{11/2} \nu f^2_{7/2})_{23/2^-}$ states. Candidates for the yrast configurations which involve $i_{13/2}$ neutrons are also assigned, based on systematics.

The systematics of the odd-A, $N = 84$ isotones are displayed in Fig. 4, which includes our analysis of ^{155}Lu, as well as that of Uusitalo for ^{157}Ta [5] and earlier work by the Kleinheinz group [8]. For $Z = 65$ Tb, the yrast spectrum is dominated by two $f_{7/2}$ neutrons coupled to the $h_{11/2}$ proton, with the $(\nu f_{7/2} h_{9/2})_{27/2^-}$ state below the $25/2^-$ state. This state involves 3 protons in the $h_{11/2}$ orbital, one of which is coupled with a neutron in the

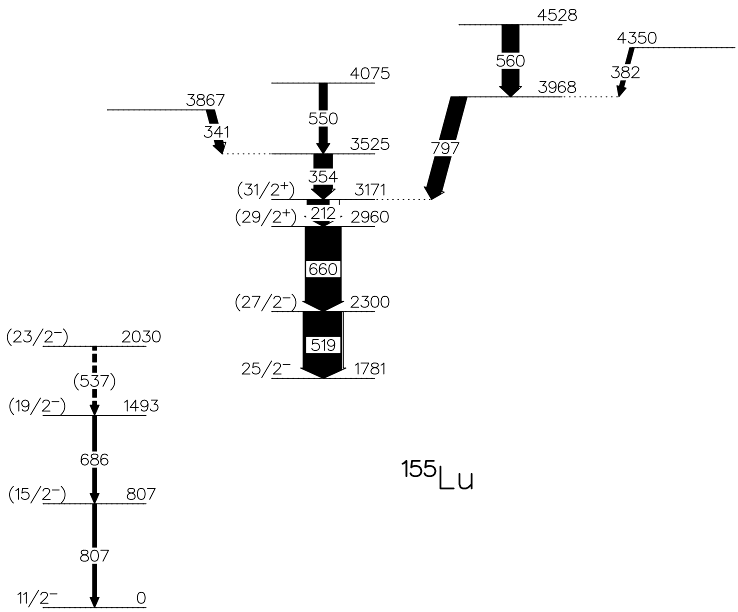

Fig. 3. Level structure above the $11/2^-$ and $25/2^-$ isomers in ^{155}Lu. The transitions above the $11/2^-$ state were taken from Ref. [4].

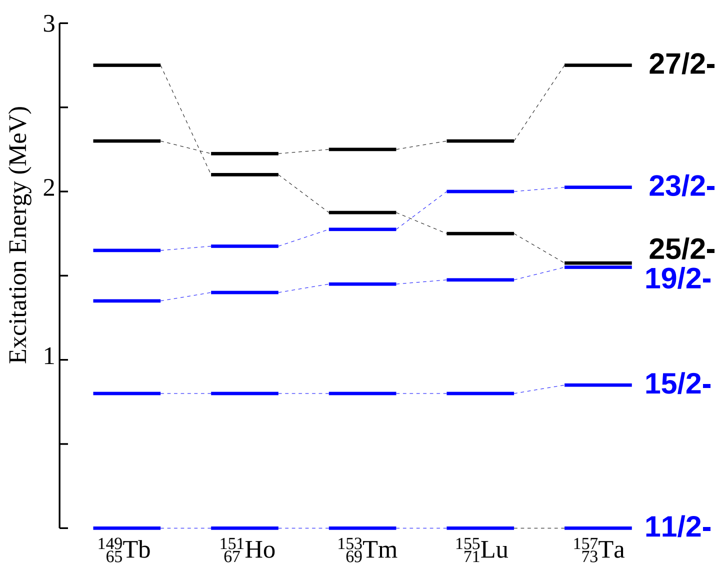

Fig. 4. Systematics of the low-lying yrast states above the $11/2^-$ isomers in odd-Z, $N = 84$ isotones, taken from Refs. [2–5, 8, 9].

$h_{9/2}$ orbital to the 1^+ configuration, an assignment originally proposed in the lighter $N = 84$ isotones by the Kleinheinz group [8]. This $25/2^-$ state rapidly decreases in energy as the proton number increases, coming below the $23/2^-$ $(\nu f_{7/2})^2$ state in ^{155}Lu and nearly degenerate with the $19/2^-$ member of the $(\nu f_{7/2})^2$ multiplet in ^{157}Ta.

The $N = 85$ isotones populated in the present work are ^{155}Yb and the odd–odd ^{156}Lu. In the lighter even-Z, $N = 85$ isotones, the yrast structure is built on the $\nu f_{7/2}$ configuration, with non-yrast $\nu h_{9/2}$ excitations. However, in ^{155}Yb and ^{157}Hf the yrast excitations are built on the $\nu h_{9/2}$ configuration, although the α-decaying isomer is the $\nu f_{7/2}$ state.

The interpretation of the yrast states of the odd–odd $N = 85$ ^{156}Lu isotone is rather complicated. The higher spin isomer was identified by Page and coworkers [7] as $(\pi h_{11/2} \nu f_{7/2})_{9^+}$. However, the yrast structure appears to be built on the 10^+ configuration obtained by coupling the $h_{11/2}$ proton to $\nu h_{9/2}$, and then to $(\nu f_{7/2})^2$. This interpretation is based on the systematics of both odd- and even-Z, $N = 85$ isotones, displayed in Fig. 5. In the lighter odd-Z, $N = 85$ isotones, excitations built upon both the 9^+, $(\pi h_{11/2} \nu f_{7/2})$ and 10^+, $(\pi h_{11/2} \nu h_{9/2})$ configurations are observed. Excitations built on

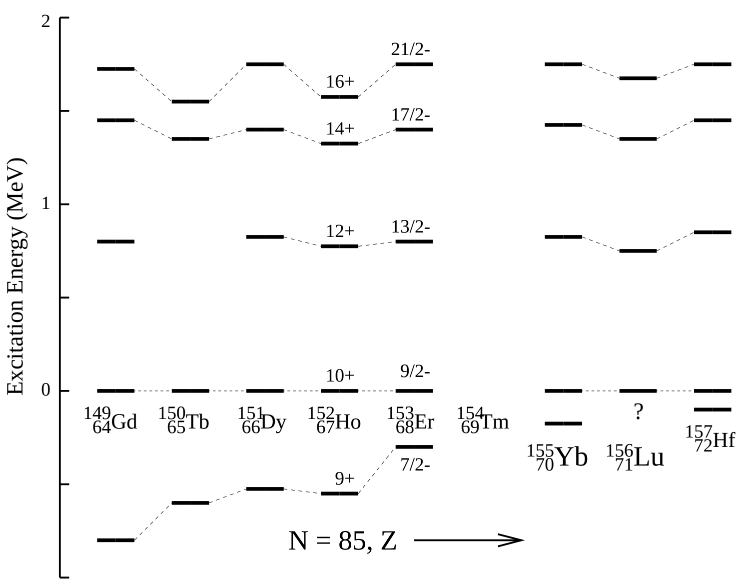

Fig. 5. Systematics of the cascades built on the $(\pi h_{11/2} \nu f^2_{7/2} h_{9/2})_{10^+}$ states in the $N = 85$ isotones. The excitation energies of the $(\nu f^3_{7/2})_{7/2^-}$ states relative to the $(\nu f^2_{7/2} h_{9/2})_{9/2^-}$ states in the even-Z, $N=85$ isotones are also displayed. Data taken from Refs. [2,3,10–14].

the $\nu h_{9/2}$ orbital follow the $(\nu f_{7/2})^2$ excitations in the even-even core, with similar spacings for even and odd-Z, $N = 85$ isotones. Since our yrast levels for ^{156}Lu are similar to those built on the $9/2^-$ levels in Yb and Hf isotones, the $(\pi h_{11/2} \nu h_{9/2})_{10^+}$ assignment is proposed for the yrast cascade in ^{156}Lu. The isomer is probably 9^+, as originally proposed [7]. We do not see any M1 transition at the bottom of this cascade. Therefore, the energy difference between the 10^+ and 9^+ states in ^{156}Lu is at most 100 keV, with an M1 transition which would be predominantly converted.

4. Limits of energy and angular momentum in Au isotopes beyond the proton drip line

For nuclei close to stability, the entry distribution in energy and spin following a heavy-ion fusion reaction reflects the number of particles evaporated from the compound system. However, as one moves towards the proton drip line, it is reasonable to expect that the weak binding of the last proton should affect the energy and angular momentum that the nucleus can sustain, when compared to an isobar in which the last proton is more strongly bound. In addition, the barrier for decay is dependent on the orbital angular momentum ℓ of the decaying state. The barrier is considerably higher for emission from a high-ℓ state, than for emission from a state of low ℓ. Therefore, it could be expected that the entry distribution for population of low-spin isomers could be restricted because of the lower barrier for proton emission. The high-spin population of these nuclei in heavy-ion reactions should also be limited by fission of the compound system. Since both low- and high-spin isomers have often been identified in the same nucleus, entry distributions leading to yrast and non-yrast excitations can be compared and contrasted.

The ^{84}Sr + ^{92,94,96}Mo reactions were used to populate neutron-deficient $A = 172$–177 Hg, Au, and Pt isotopes. The odd-A Au isotopes were produced via the $p2n$ channels. In the case of ^{173,177}Au two alpha-emitting isomers have been identified [15, 16], one with low spin, the other from the proton $h_{11/2}$ orbital. Gammasphere was again coupled to the FMA and the RDT method was used to select photons associated with specific isomers.

The response function of Gammasphere was determined from source measurements, using an event-mixing technique [17]. Based on these response functions, a two dimensional Monte Carlo unfolding procedure [18] was used to transform raw modular energy and modular multiplicity, (H, K), to excitation energy and multiplicity, (E, M). The dependence of efficiency on multiplicity was taken into account, in order to correct for the effect of the trigger condition. To convert multiplicity, M, to angular momentum, I, the standard assumption [1, 19] was made that non-statistical transitions carry 2 units of angular momentum and 3 statistical transitions each carry 0.25 units of spin. For the present study of Au isotopes, the multiplicity of conversion electrons was neglected.

An example of the entry distribution in energy-spin space is displayed in Fig. 6 for ^{175}Au and ^{175}Pt. Included in this figure are the yrast lines for these nuclei, determined by Kondev [20]. The slopes of the entry distributions are similar to those of the yrast lines, as expected for statistical evaporation of particles from the compound system.

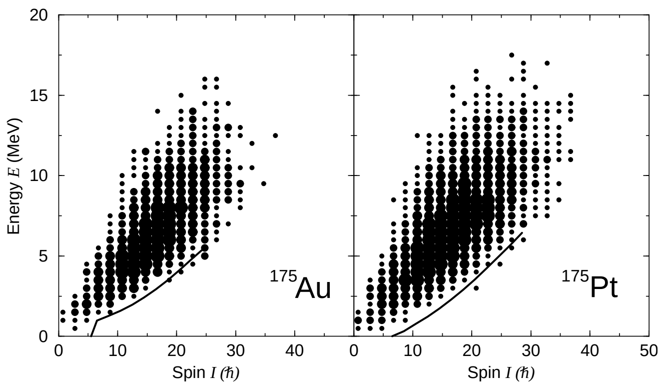

Fig. 6. Two-dimensional entry distributions for (a) ^{175}Au and (b) ^{175}Pt. The yrast lines are taken from Ref. [20].

In Fig. 7 the projections of energy, E, and spin, I, are summarized for ^{173,175,177}Au, the more stable Pt isobars, and ^{177}Hg. For mass 177, the energy distributions for Au, Pt, and Hg isobars are rather similar. However, there is a clear difference in the spin distribution in Fig. 7(f) for ^{177}Hg, populated in the $3n$ channel, compared to the ^{177}Au and ^{177}Pt channels. The average spin for ^{177}Hg is a full unit less than those of the Au and Pt isobars, and for ^{177}Hg the higher multiplicities are truncated. One explanation is the considerably higher fissility, comparable to that of ^{235}U, for Hg evaporation residues compared to less fissile Au and Pt isobars. From statistical cascade calculations it is known that neutron evaporation can compete with fission at every step of the cascade. An alternative explanation could be the differences in binding energies between neutrons and protons, which are very weakly bound. However, if the differences between Hg and Au were solely due to increased binding of neutrons, then a difference between Au (the $p2n$ channel) and Pt (the $2pn$ channel) should also be expected, in contrast to the data.

The other striking aspect of the projections of the entry distributions are shown in Figs. 7(a), 7(d) for the $A = 173$ Au and Pt isobars. Although the average spins and spin distributions have a similar shape, there is a

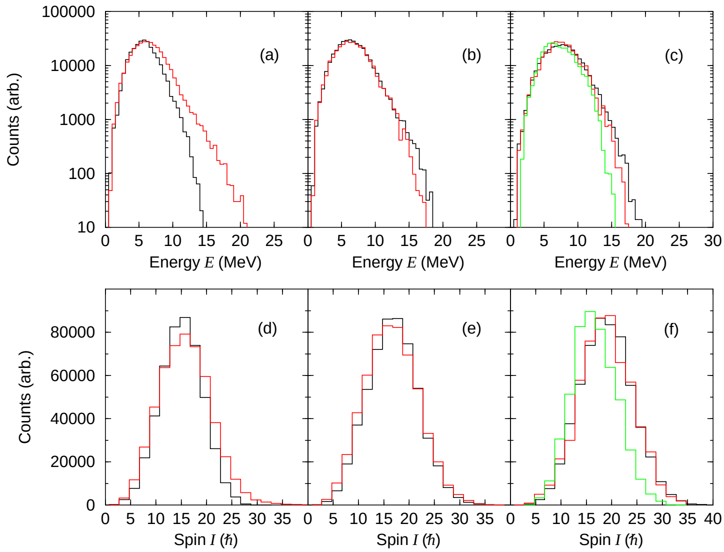

Fig. 7. Normalized entry distributions for Au (thick), Pt (thin), and Hg (dotted) isobars. The first three panels show energy distributions for (a) $A = 173$, (b) $A = 175$ and (c) $A = 177$. Panels (d), (e) and (f) show the analogous spin distributions. Taken from Ref. [21].

dramatic decrease in the energy that can be populated in ^{173m}Au compared to its more stable isobar, ^{173}Pt. Such a difference in the population of isobars is not observed for the $A = 175$ isobars in Fig. 7(b). The results in Fig. 7(a) are the first evidence for a limit in the excitation energy which can be populated in a nucleus beyond the proton drip line. The data do not suggest that there is proton emission from an excited state in ^{173}Au, since the shape of the entry distribution for the daughter of such a process, ^{172}Pt, is similar to heavier Pt isotopes populated as $2p2n$ channels. The data are consistent, however, with the $p2n$ channel being less favored compared to the $2pn$ channel far from stability, although there continues to be a sizeable cross section for the $p2n$ channel, as well as similar amounts of angular momentum, as in the $2pn$ channel.

Preliminary comparisons of the entry distributions associated with population of the ground state and high-spin isomer in ^{173}Au suggest that the excitation energy which can be populated above the low-spin ground state is further restricted compared to population of the high-spin isomer. Such a difference in entry distributions is not observed for the low- and high-spin isomers in ^{177}Au. The preliminary level scheme for ^{177}Au [20] does suggest that both isomers are fed by the same yrast sequence, and hence, the same entry distribution.

5. Summary and conclusions

The structures of two nuclear systems have been presented which are near and beyond the proton drip line. The knowledge of excitations near $N = 82$ and above $Z = 64$ has been extended. The attractive interaction between $h_{11/2}$ protons and $h_{9/2}$ neutrons in these spin-orbit partner orbitals lowers the $h_{9/2}$ neutron orbital so that it dominates the yrast structure in the $N = 84, 85$ isotones near the proton drip line. A similar change in single-particle levels has been observed in other parts of the periodic table [22] — it is not unique to nuclei near the proton drip line. In fact, because we have been able to use the behavior of nuclei near stability to understand the structure of nuclei near the proton drip line, nuclear structure is robust, perhaps surprisingly robust, even far from stability.

In the case of the ^{173,175,177}Au isotopes, all lie beyond the proton drip line, although none of these are sufficiently unbound that proton decay can be observed to compete with alpha-particle emission. The first evidence for the limit to the energy that such a weakly bound system can sustain was observed by comparing entry distributions of ^{173}Au to its more stable isobar ^{173}Pt, as well as to analogous distributions in heavier Au isotopes.

These studies have only begun to probe weakly bound systems near and beyond the proton drip line. Plans are to continue such entry distribution studies using an array of BGO detectors coupled to the FMA. This will allow further studies of entry distributions, not only in proton unbound nuclei, but also for the heaviest elements. In the far future, with the advent of the next generation of radioactive ion beam accelerators, such studies would be extended to neutron-rich nuclei, where the increased diffuseness of the nuclear surface could affect the maxima in energy and angular momentum in unexpected ways.

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