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Limits of the energy-spin phase space beyond the proton drip line: entry distributions of Pt and Au isobars

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Abstract

Entry distributions in angular momentum and excitation energy have been measured for several very proton-rich isotopes of Pt and Au. This is the first systematic study of the energy-spin phase space for nuclei near and beyond the proton drip line. Comparisons are made between the distributions associated with proton-unbound Au nuclei and more stable Pt isobars. In ^{173}Au the first evidence is seen for the limits of excitation energy and angular momentum which a nucleus beyond the proton drip line can sustain.

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The proton drip line defines one of nature's fundamental limits to the stability of the atomic nucleus. Nuclei lying beyond this limit are energetically unbound to the emission of a proton from either their ground state or from excited states [1]. Such nuclei provide an ideal laboratory for the study of the amount of energy and angular momentum which a weakly-bound system can sustain. Since nuclei are quantum many-body systems, their limits of stability, and the means by which weakly-bound nuclei decay, present a statistical problem of considerable current interest in the field of physics.

The limits of nuclear existence can be determined by measuring the entry distribution [2,3] for proton drip-line nuclei populated in heavy-ion fusion-evaporation reactions. The entry distribution is the initial population distribution as a function of excitation energy E and angular momentum I, after particle evaporation from the compound system, from which γ emission to the ground state originates. For nuclei close to the line of β stability, the energy-spin phase space reflects the number of particles evaporated from the compound system. However, in a proton-unbound nucleus it has been suggested that only a small region of the energy-spin phase space, just above the yrast line, does not decay by proton emission [4]. While states in this region preferentially decay by the emission of γ rays, at rather low excitation energy the decay widths (Γ) for γ and proton emission are predicted to be comparable [4], i.e., $\Gamma_{\rm p} \sim \Gamma_\gamma$, and at higher excitation energy, proton emission dominates ($\Gamma_{\rm p} > \Gamma_\gamma$). As a consequence, the region dominated by γ emission, and thus the entry distribution, of a proton-unbound nucleus is expected to be limited compared to that of its more stable isobars [4].

In this Letter, the shapes of the entry distributions that characterize ($Z = 79$) ^{173,175,177}Au nuclei, all of which lie beyond the proton drip line [1], are reported and compared to those of the proton-bound $^{173,175,177}_{\ \ 78}$Pt isobars produced under the same experimental conditions. For the first time, a limit is observed in the population of an isotope beyond the drip line, namely, ^{173}Au, in comparison to its isobar ^{173}Pt.

High-spin states in the isotopes of interest were populated following the bombardment of ^{92,94,96}Mo targets by beams of ^{84}Sr, provided by the ATLAS accelerator facility at Argonne National Laboratory. The bombarding energies employed varied, depending on the target used in the reaction, as follows: 390 and 395 MeV for the ^{92}Mo target, 380 and 385 MeV for ^{94}Mo and 380 MeV for ^{96}Mo. The isotopically-enriched ($> 90\%$) self-supporting Mo targets had thicknesses of approximately 700 μg/cm^2. Recoiling fusion-evaporation products were identified using the Argonne fragment mass analyzer (FMA) [5] and the recoil-decay tagging (RDT) technique [6,7] was used to select the α-decaying isomers of interest. Isotopic identification was performed through measurements of the mass-to-charge ratio M/q, in a parallel-grid avalanche counter (PGAC), and through correlation, within a time interval of approximately three half-lives, of an α decay of interest with an implant in the same pixel of a double-sided Si strip detector (DSSD). The known α-decay characteristics [8–12] of the states of interest were exploited. Prompt γ rays were detected using the 101-element GAMMASPHERE Ge detector array [13] as a calorimeter, with no heavimet collimators in front of the BGO suppression shields. An additional five BGO shields occupied the most forward positions, in order to cover a solid angle as close to 4π as possible. Total modular energy H and modular multiplicity K were measured, a module consisting of a Ge detector plus its BGO shield (or the shield alone). In this configuration, GAMMASPHERE has a granularity of 106 modules and a sum-energy efficiency of 72% (for 898 keV γ-rays). Preliminary results from the current (H, K) data have been discussed in Ref. [14]. The discrete γ-ray spectroscopy of ^{173,175,177}Au was presented in Ref. [15].

The known sum-energy and multiplicity response functions of GAMMASPHERE enable the conversion of modular (H, K) into energy E and γ-ray multiplicity M_γ. The response functions were determined from measurements of an ^{88}Y source, using an event-mixing technique [16]. Based on these response functions, a two-dimensional Monte Carlo unfolding procedure [3,17] can be used to transform the (H, K) distribution into a spectrum of excitation energy vs. multiplicity. The dependence of efficiency on multiplicity is taken into account, in order to correct for the effect of trigger conditions. The multiplicity can be related to angular momentum I by realistic assumptions [2,3] of the angular momenta carried by the components of the γ-ray cascade. The initial spin of the evaporation residue is deduced using the expression

$$I = \Delta I(M_\gamma + M_e - N_{\text{stat}}) + \Delta I_{\text{stat}} \cdot N_{\text{stat}} + I_0, \quad (1)$$

where ΔI is the average spin removed per non-statistical photon, M_e is the multiplicity of conversion electrons, N_{stat} is the number of statistical γ rays emitted and I_0 is the angular momentum of the ground state (or isomer) of the nucleus of interest [12,15]. In this work, the following values were adopted: $\Delta I = 2\hbar$, $M_e = 0$, $\Delta I_{\text{stat}} = 0.25\hbar$ and $N_{\text{stat}} = 3$, appropriate for a collective nucleus, such as those discussed in this work, at moderate spin and excitation energy. Based on the level schemes of the Au isotopes [15], the conversion electron multiplicity for nuclei in this mass region is estimated to be small ($M_e < 1$). The effect of electron conversion, discussed in Ref. [2], is thus considered to be negligible in this work. It should be noted that the level scheme of ^{173}Au [15], established up to spin (21/2), reveals no signs of collectivity. The structure of this isotope above spin 21/2 is currently unclear (although it is likely that collective structures exist at higher spins) and it is possible that the assumption that $\Delta I = 2\hbar$ may not be appropriate in this case. However, if a slightly lower value of ΔI were applied to this nucleus, there would be only a small effect on the final angular momentum values.

Entry distributions have been measured for several isotopes of Pt and Au with mass $172 \leqslant A \leqslant 177$. For the Pt isotopes entry distributions have been determined for each of these six masses; for the proton-unbound Au nuclei entry distributions have been determined for $173 \leqslant A \leqslant 177$. For both ^{173}Au [11] and ^{177}Au [8,15], two α decays, from states of opposite parity, are observed, and the entry distribution associated with each has been determined. In this Letter only entry distributions leading to the high-spin yrast isomers of ^{173,175,177}Au, based on $h_{11/2}$ proton configurations, and the ground states of $^{172\text{–}177}$Pt are discussed. Further distributions determined from the present data will be presented in a forthcoming publication.

Fig. 1 shows representative two-dimensional (E, I) distributions for the isobars $^{173\text{m}}$Au and ^{173}Pt, and for ^{175}Au and ^{175}Pt. The yrast lines for these nuclei, obtained from the analysis of discrete γ-ray transitions [12,15], are also shown. For each of the three ^{84}Sr + Mo reactions used, the results presented include the data for all bombarding energies in order to increase statistics. The differences in the shapes of these distributions at different beam energies have been investigated, were found to be statistically insignificant and have, thus, been neglected. A further test was applied to the ^{173}Pt data to measure the effect of random correlations. Background-subtracted coincidences were required with known γ rays [12] in ^{173}Pt, in addition to the RDT α-decay correlation. The entry distribution of ^{173}Pt determined using this method was found to be consistent, despite the low statistics, with the distribution shown in Fig. 1.

The gradients of the entry distributions follow closely those of the yrast lines, as expected for statistical evaporation of particles from the compound system. In Ref. [2] the entry distribution of ^{254}No was observed to exhibit a slope significantly steeper than that of the yrast line, suggesting that very heavy nuclei are populated via a mechanism other than pure statistical evaporation from the compound nucleus. Fig. 1 suggests that statistical evaporation is the dominant process populating nuclei close to and beyond the proton drip line. It can be seen from Fig. 1 that the entry distributions for proton-unbound ^{175}Au and its isobar ^{175}Pt are effectively the same, extending to the same approximate energy and spin. However, the distributions for $^{173\text{m}}$Au and ^{173}Pt are very different, with significantly less population of ^{173}Au at the highest energies and spins.

Normalized projections of the (E, I) distributions are shown in Fig. 2 for Pt and Au isotopes with $A = 173$, 175 and 177. The projections of excitation energy and angular momentum for the most proton-unbound isotope measured in this work, ^{173}Au, are shown in Fig. 2(a),(d). From Fig. 2(a) it is clear that the maximum excitation energy populated in ^{173}Au, produced via the p2n channel from the ^{176}Hg compound system, is significantly less than in the ^{173}Pt nucleus, populated following 2pn evaporation. This marked difference in maximum excitation energy is surprisingly large for these very proton-rich systems, and does not occur for the $A = 175$ and $A = 177$ cases (Fig. 2(b),(c)). The angular momentum distributions of the $A = 173$ and $A = 175$ Pt and Au isobars differ by $I = 1\hbar$ and $2\hbar$, respectively, at low spins, because of the spin of the isomer to which the entry distributions decay ($I = 13/2$ for ^{173}Pt, 7/2 for ^{175}Pt and 11/2 for both Au nuclei). However, the difference in spin between ^{173}Au and ^{173}Pt is greater than

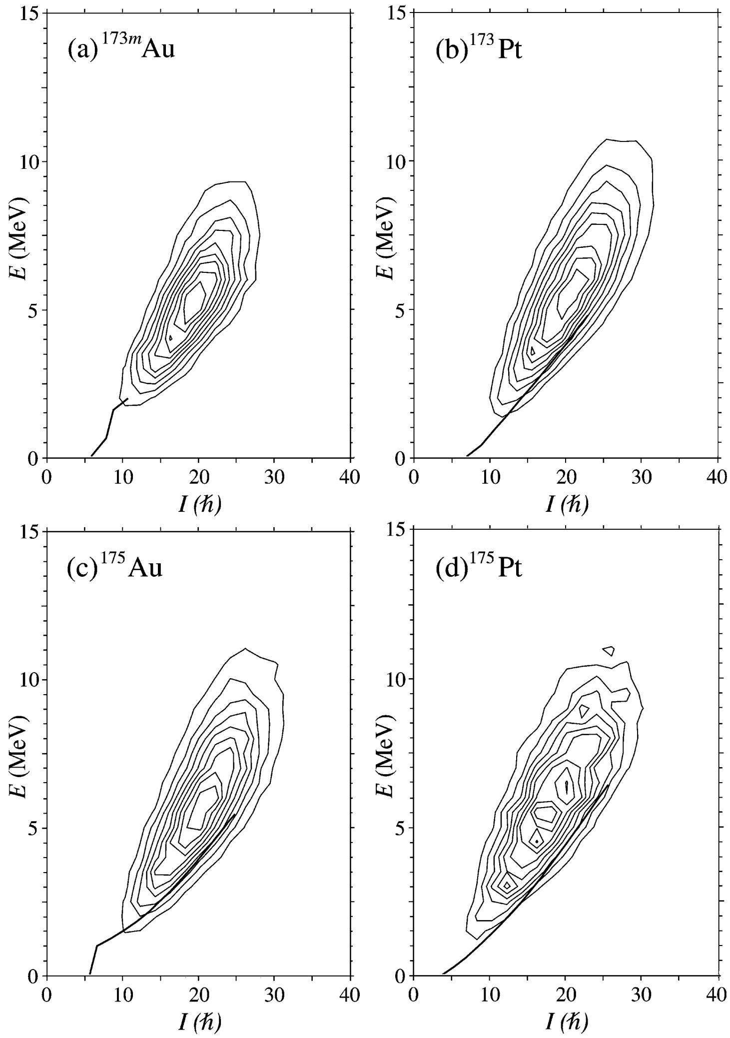

Fig. 1. Two-dimensional (E, I) entry distributions for (a) ^{173m}Au, (b) ^{173}Pt, (c) ^{175}Au and (d) ^{175}Pt. Each contour line represents a change of 10% of the maximum value. The yrast line [12,15] for each isotope is presented as a thick line.

$1\hbar$ at the highest spins, whereas it remains at $2\hbar$ in the $A = 175$ case; this again confirms the lower limits in the entry distribution of ^{173}Au relative to ^{173}Pt. For the $A = 177$ isobars the spin projections are again very similar, although they are shifted considerably relative to each other because of the angular momenta of the α-decaying state with which they are correlated ($I = 5/2$ for ^{177}Pt and $11/2$ for $^{177\mathrm{m}}$Au).

The result for ^{173}Au is the first evidence for a limit in the excitation energy and angular momentum which can be populated in a system beyond the proton drip line. This limit provides evidence for a decrease in the γ-ray dominated region of the energy-spin phase space for the ^{173}Au system. The current data suggest that ^{173}Au does not undergo proton emission from excited states up to around 8.5 MeV at the highest spins, considerably above the yrast states (assuming a rotational yrast line, likely to have an energy of around 7 MeV at $I = 25\hbar$). In contrast, the predictions of Khoo [4], for the proton emitter ^{167}Ir, suggested that Γ_{p} becomes larger than Γ_γ for states less than 2 MeV above yrast at zero spin, with the γ-ray dominated region meeting the yrast line at $I \approx 20\hbar$. However, this simple statistical calculation does not

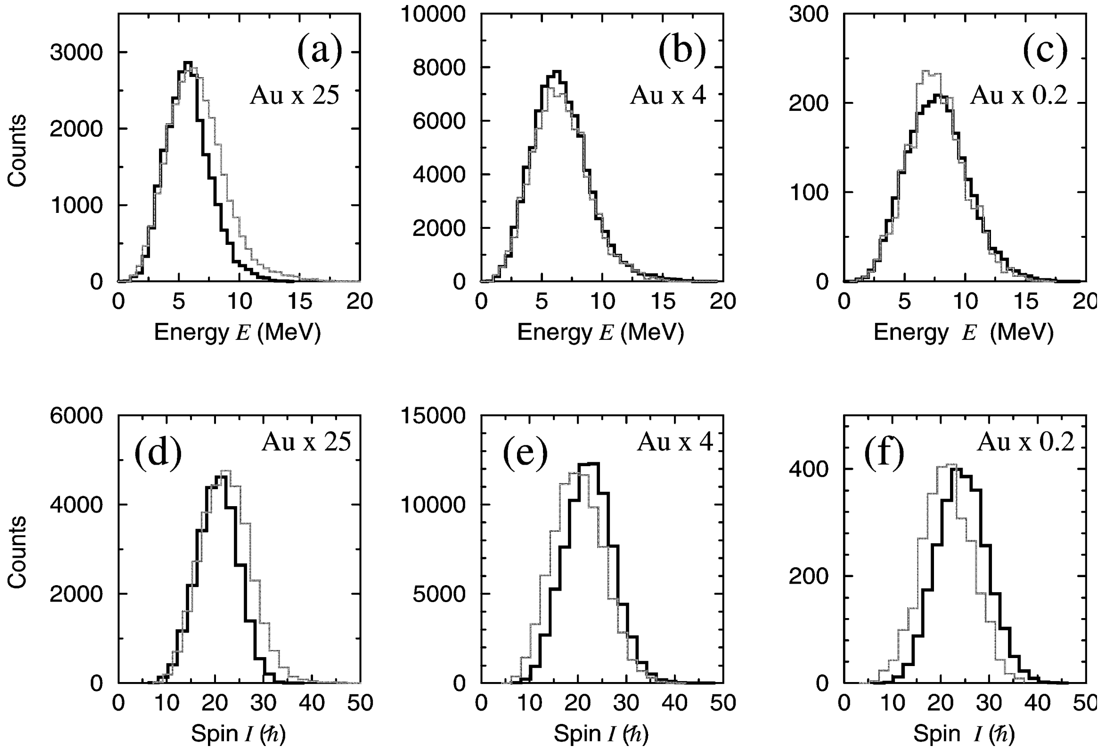

Fig. 2. Normalized entry distribution projections for odd-A Au (thick line) and Pt (thin line) isobars. The first three panels show excitation energy distributions for (a) $A = 173$, (b) $A = 175$ and (c) $A = 177$. Panels (d), (e) and (f) show the analogous angular momentum projections. The spectra are normalized by multiplying the Au data by the factors displayed.

consider selection rules for the decay of excited states, which would have the effect of reducing the rate of proton decays, thus increasing the region where $\Gamma_p < \Gamma_\gamma$ to higher excitation energies. Selection rules are important at low excitation energies. However, at higher energies, chaotic (statistical) decay of hot states dominates.

Simple calculations based on Q-values suggest that the Au nuclei, populated via p2n evaporation, should be populated with approximately the same excitation energy as the corresponding Pt isobars produced by the 2pn channels. Evaporated protons remove more energy than neutrons from the compound system, because of the Coulomb barrier. Assuming that neutrons remove 1.5 MeV, and protons remove 11.5 MeV (approximately the Coulomb barrier), the excitation energies for ^{173}Au and ^{173}Pt are expected to be approximately equal (within the 1 MeV uncertainty in separation energies for these nuclei far from stability), as is also the case for the $A = 175$ and $A = 177$ Pt and Au isobars. Therefore the phase space is expected to be similar for isobars, as is observed for $A = 175$ and $A = 177$ Pt and Au, but in contrast to the data for ^{173}Au compared to ^{173}Pt. Statistical evaporation calculations, performed using the Monte Carlo code PACE [18], predict no differences between the energy-spin distributions for the p2n and 2pn evaporation channels populated by the reactions studied in this work. For the $A = 177$ and $A = 175$ cases this is in agreement with the data presented, whereas the ^{173}Au and ^{173}Pt data contradict the predictions, suggesting that the limited entry distribution of ^{173}Au is a result of the unbound nature of its last proton.

The limited phase space for ^{173}Au may be an indication of proton decay from states which lie immediately above the region dominated by γ emission. If such exotic decays do take place, the decay protons, which are emitted after the last step in (p2n) particle evaporation, would populate states in ^{172}Pt very close to the yrast line. Decay protons from high-spin states

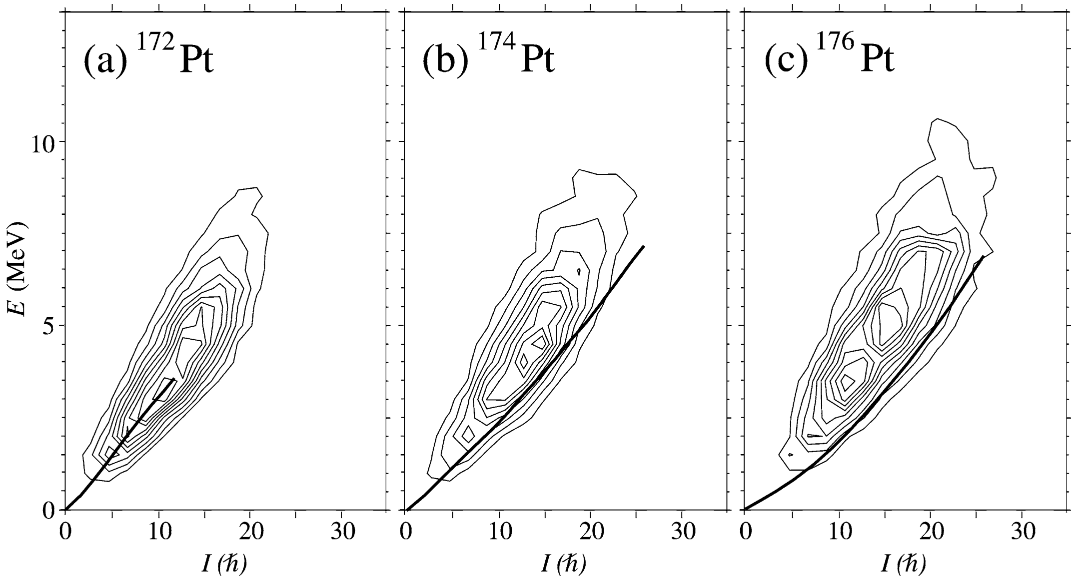

Fig. 3. Two-dimensional entry distributions for (a) ^{172}Pt, (b) ^{174}Pt and (c) ^{176}Pt. Contours represent changes of 10% of the maximum value. The yrast lines [19–22] are presented as thick lines. The excursion of the entry distribution below the yrast line is due to the finite instrumental resolution, which remains after the (H, K) distribution is unfolded.

can remove up to $5\hbar$ in angular momentum and several MeV in excitation energy [4], considerably more energy than for ground-state proton emission. The centrifugal barrier depends strongly on the orbital angular momentum ℓ of the decaying state [1] and is greater for high-spin states ($\ell > 0$) than for proton decay from an $\ell = 0$ ground state. However, the additional barrier is more than compensated for by the increased Q-value for such a decay.

The effect of proton decay from a highly-excited, hot state in ^{173}Au would be expected to manifest itself in the entry distribution of ^{172}Pt, displayed in Fig. 3 along with the distributions for the less proton-rich even–even ^{174,176}Pt isotopes. All of the even–even Pt isotopes are populated very close to their respective yrast lines [19–22], which is expected for four-particle (2p2n) evaporation at the bombarding energies used in the present study. The possible enhanced feeding of ^{172}Pt following proton emission from excited states in ^{173}Au would only contribute a small fraction (approximately 20%) of the total population, dominated by regular 2p2n evaporation from the ^{176}Hg compound nucleus, and would therefore be difficult to observe with the current data.

In summary, entry distributions populating several proton-rich isotopes of Pt and Au with $172 \leqslant A \leqslant 177$ have been measured, using ^{84}Sr + ^{92,94,96}Mo reactions. This is the first systematic study of such distributions for nuclei near and beyond the proton drip line. Significant differences have been observed in the energy-spin phase space of the proton-unbound ^{173}Au system and its more stable ^{173}Pt isobar, and the first experimental evidence has been presented for a limit in the energy and spin which a nucleus beyond the proton drip line can sustain. This limited phase space cannot be explained by simple calculations based on Q-values or by statistical model calculations, both of which predict similar distributions for isobars.

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