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Single-particle behavior at $N = 126$: Isomeric decays in neutron-rich ^{204}Pt

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The four proton-hole nucleus ^{204}Pt was populated in the fragmentation of an $E/A = 1$ GeV ^{208}Pb beam. The yrast structure of ^{204}Pt has been observed up to angular momentum $I = 10\hbar$ by detecting delayed γ-ray transitions originating from metastable states. These long-lived excited states have been identified to have spin-parities of $I^{\pi} = (10^{+})$, (7^{-}), and (5^{-}) and half-lives of $T_{1/2} = 146(14)$ ns, 55(3) μs, and 5.5(7) μs, respectively. The structure of the magic $N = 126$ ^{204}Pt nucleus is discussed and understood in terms of the spherical shell model. The data suggest a revision of the two-body interaction for $N = 126$, $Z < 82$, which determines the evolution of nuclear structure toward the r-process waiting point nuclei.

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The evolution of the properties of atomic nuclei with respect to neutron and proton numbers is a key question of nuclear physics. The study of unstable, neutron-rich nuclei represents one of the foremost pursuits of modern nuclear physics. Over the coming decade new radioactive ion beam facilities are being built with the main objectives being to probe neutron-rich nuclei. Within recent years surprising phenomena have been observed in neutron-rich nuclei such as neutron skins, halos, and dramatic changes in the ordering and spacing of energy levels [1].

While the stability of the $N = 82$ shell gap is an active topic of research [2,3], an open question is whether or not there is a quenching of the $N = 126$ shell gap as protons are removed from doubly magic ^{208}Pb. The proton dripline has been experimentally reached up to heavy elements [4], our present knowledge of the neutron dripline is limited to light species. The part of the nuclear chart with the least information on neutron-rich nuclei is the $_{76}$Os to $_{82}$Pb region, with experimental knowledge on only a few isotopes. This mass region is, however, an ideal testing ground of nuclear theories. With the removal of just a few protons and neutrons the landscape evolves from spherical to elongated prolate through disk-shaped oblate and triaxial forms [5]. Consequently the information gained on neutron-rich, $N = 126$ nuclei is essential for the understanding of nuclear structure in heavy nuclei. From a longer-term perspective, experiments in this region pave the way toward the proposed

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nuclear-astrophysical r-process waiting point nuclei along the $N = 126$ shell closure [6,7]. Studies of magic nuclei are of fundamental importance in our understanding of nuclear structure because they allow direct tests of the purity of shell model wave functions. Information on the single particle energies and two-body residual interactions can be derived from the experimental observables such as energies of the excited states and transition probabilities.

Experimental information on the neutron-rich, $N = 126$ nuclei is very scarce. Information has been obtained on excited states for only two isotones with $Z < 82$: ^{207}Tl [8] and ^{206}Hg [9–11]. In the case of ^{205}Au only the ground state is known [12]. The lack of information on nuclei "below" ^{208}Pb is due to difficulties in populating these neutron-rich nuclei. Fragmentation has proven to be an efficient tool in producing exotic nuclear species. When projectile fragmentation is combined with high-sensitivity γ-detection arrays, structural information can be gained for otherwise inaccessible nuclei. The highest sensitivity is achieved with both isomeric and β-delayed γ-ray spectroscopy techniques; delayed γ rays are time-correlated with individually identified ions, thereby minimizing the associated background radiation. Information on the excited states populated in this way can be obtained when producing only a few hundred nuclei of interest [13,14].

In this Rapid Communication the first spectroscopic information on the structure of the four proton-hole nucleus ^{204}Pt is presented. Preliminary results were published in conference proceedings [15,16].

The SIS-18 accelerator at GSI provided a ^{208}Pb beam at $E/A = 1$ GeV. The average beam intensity was $\sim 4 \times 10^8$ ion/s and the total operating time was $\sim$105 h. The ^{208}Pb ions impinged on a target of ^{9}Be of thickness 2.5 g/cm^2. The nuclei of interest were selected and identified in flight by the FRagment Separator (FRS) [17]. The FRS was operated in standard achromatic mode using an Al wedge-shaped degrader of thickness 4.9 g/cm^2, positioned at the intermediate focal plane. To maximize the number of fully stripped ($q = Z$) nuclei passing through the FRS, niobium foils of 221 and 108 mg/cm^2 thicknesses were, respectively, placed after both the target and the intermediate focal plane degrader. According to the charge state calculations (using the GLOBAL code [18]), 93.7% of the ^{204}Pt ions were fully stripped exiting the target and 76.6% were stripped after the intermediate focal plane. The identified ions were slowed in an Al degrader and halted in a 7-mm-thick plastic stopper, positioned at the final focal plane of the FRS. Scintillation detectors placed before and after this Al degrader allowed suppression of events where the fragments of interest were destroyed in the slowing down process ($\approx$18%) and in cases where they did not implant in the stopper ($\approx$0.2%). The stopper was surrounded by the RISING array in the "Stopped Beam" configuration [19,20], consisting of 15 former EUROBALL HPGe cluster detectors [21]. The photopeak efficiency of this array was measured to be 15% at 661 keV [22]. These detectors recorded the delayed γ-ray transitions associated with the implanted nuclei.

The identification of the fragments is demonstrated in Fig. 1. The calibration of the particle identification is confirmed by the detection of previously identified γ rays that follow

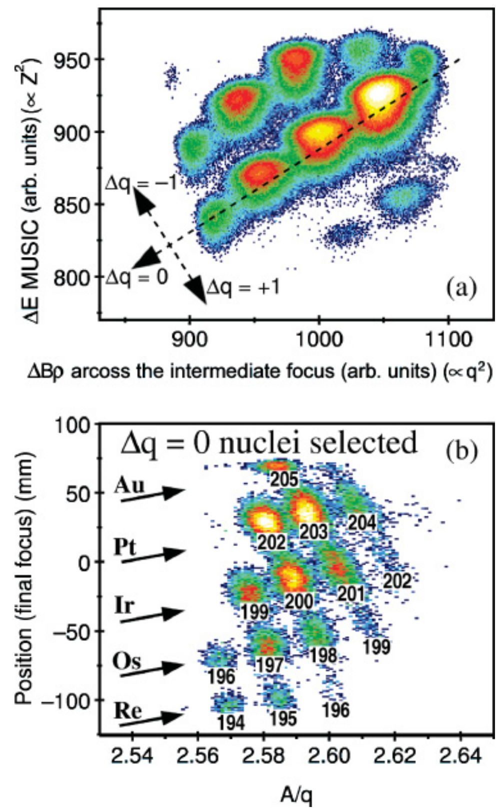

FIG. 1. (Color online) Identification of the fragmentation products in the FRS setting optimized for ^{203}Ir transmission. (**a**) Energy loss at the final focal plane vs change in magnetic rigidity, $\Delta B\rho(\propto q^2)$, at the intermediate focal plane. This distinguishes which nuclei change charge state in the middle of the FRS (approximately all $\Delta q = 0$ correspond to $q = Z$ for the entire FRS flight time). (**b**) Position in the final focal plane versus A/q for fully stripped ($\Delta q = 0$) nuclei.

the deexcitation of the $I^\pi = 7^-$ isomer in ^{202}Pt [23,24]. The identification process is described in more detail in Ref. [25].

The results for ^{204}Pt were obtained from four different magnetic rigidity settings of the FRS. A total of 9.3×10^4 ^{204}Pt ions was implanted in the stopper. Most of the data, $\sim$70% (in 24 h), were recorded in a setting optimized for the transmission of ^{203}Ir. In this setting the delayed γ rays were measured over a range of $0 \rightarrow 80$ μs following implantation. In the other settings, the γ rays were detected over a range of $0 \rightarrow 380$ μs.

Delayed γ rays associated with ^{204}Pt nuclei are shown in Fig. 2. In the sub-microsecond regime three γ-ray transitions with energies of 97, 1061, and 1158 keV, together with characteristic platinum x rays have been identified, all showing similar decay characteristics. The measured half-life is $T_{1/2} = 146(14)$ ns; see inset to Fig. 2 (top). Two additional γ rays with energies 872 and 1123 keV have been observed over a longer time range, see Fig. 2 (middle). However, their decay curve cannot be fitted with a single decay component. Two components must be considered, resulting in one half-life of $T_{1/2} = 5.5(7)$ μs, populated by a higher lying isomer with a longer half-life of $T_{1/2} = 55(3)$ μs.

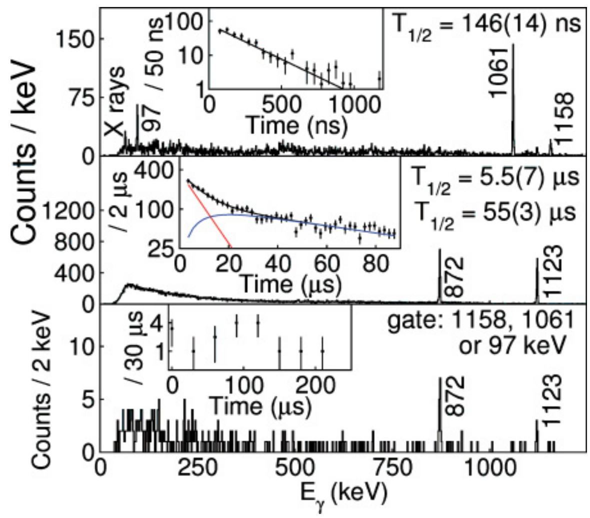

FIG. 2. (Color online) γ-ray spectra associated with ^{204}Pt. (Top) γ rays detected between 50 and 850 ns after implantation. (Inset) Decay curve of 1061 and 1158 keV γ rays. (Middle) γ rays observed between 2.5 and 80 μs after implantation. (Inset) Decay curve of the 872 and 1123 keV γ rays. (Bottom) Time-differentiated $\gamma\gamma$ coincidence. Shown are γ rays detected from 2.5 to 380 μs following implantation, after a $T_{1/2} = 146$ ns associated γ ray (97, 1061, 1158 keV) has been observed over the range 50 to 850 ns. (Inset) Time difference between detection of $T_{1/2} = 146$ ns associated γ rays and the later observed 872 and 1123 keV transitions.

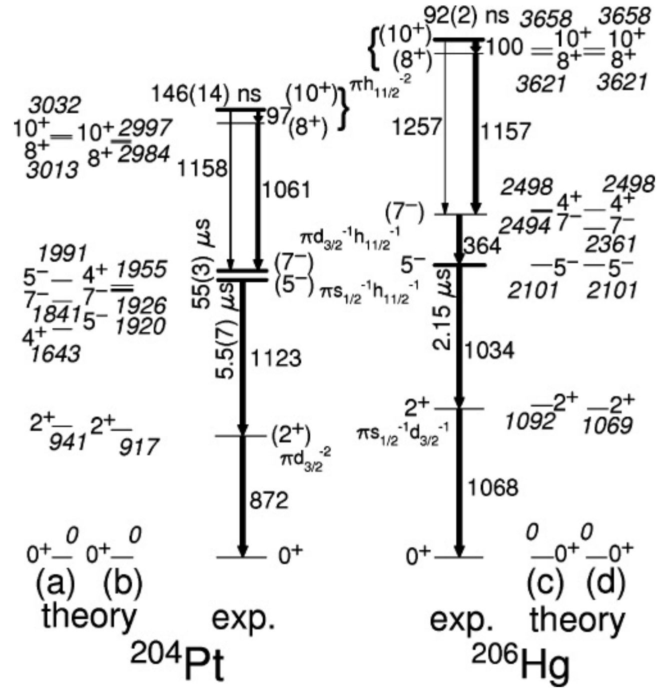

FIG. 3. Experimental and calculated partial level schemes of the $N = 126$ ^{204}Pt and ^{206}Hg [9] nuclei. Arrow widths denote relative intensities of parallel decay branches. The dominant state configurations are indicated. (a) and (d) are calculations using the Rydsrtöm matrix elements, while (b) and (c) are with the modified ones, as described in the text.

The sum energy of the 97 and 1061 keV transitions is equal to that of the third transition (1158 keV). Therefore it is likely that they form a parallel branch. Considering that the 97 and 1061 keV transitions should have identical intensity after allowing for electron conversion of the transition branches, we conclude that the 97 keV transition is of $E2$ or $M1$ character. The 872 and 1123 keV γ-ray peaks have equal intensities within experimental uncertainties. The data allow the extraction of coincidence relationships. The 97 and 1061 keV transitions, as well the 872 and 1123 keV pair, are in mutual coincidence. The spectrum in Fig. 2 (bottom) shows the transitions following the decay out of the short-lived isomer (gating on 97, 1061, and 1158 keV), together with the time difference between the transitions associated with the shorter lived and longer lived isomeric states. This demonstrates that the shorter lived ($T_{1/2} = 146$ ns) isomer decays into both of the longer lived ones. This is in agreement with the extracted relative population at the time of implantation of the isomeric states: 1:4.5:1.4 for $T_{1/2} = 146$ ns, 55 μs, and 5.5 μs, respectively. The implantation rate of ^{204}Pt nuclei is 0.4 nuclei/s; thus the number of chance coincidences in Fig. 2 (bottom) is negligible.

Based on these experimental data the level scheme has been constructed and has been compared with the two proton-hole $N = 126$ isotone ^{206}Hg in Fig. 3. It is established from experiment, except the tentative spin assignments and also the sequence of the 97, 1061 keV and the 872, 1123 keV pairs of transitions, which are respectively taken from comparison with ^{206}Hg and theoretical considerations.

Shell model calculations have been performed in the $s_{1/2}, d_{3/2}, h_{11/2}, d_{5/2}, g_{7/2}$ ^{208}Pb proton-hole space with the OXBASH code using single particle energies from ^{207}Tl and two-body matrix elements (TBME) from Ref. [26]. These are based on the Kuo-Herling interaction including core polarization, but the decisive elements for the then known 2^+ and 5^- states of ^{206}Hg had been adjusted. The resulting states and their main configurations are included in Fig. 3. The 2^+ and 5^- states in ^{206}Hg are trivially well reproduced, but also the 8^+ and 10^+ fit well, while the 7^- is off by 100 keV.

In ^{204}Pt the highest lying 146 ns isomer is without any doubt assigned to the calculated $(h_{11/2})^{-2}10^+$ level and also the 8^+ and 7^- states populated in its decay are certain. The two other lifetimes measured in ^{204}Pt give the proposed spin sequence (moving upward) of 5^-, 7^-, and an unobserved 4^+, while the calculations give 7^- below 5^- and a 4^+ state below both, incompatible with experiment. By this proposal the 7^- to 5^- $E2$ transition has the astonishingly large $T_{1/2} = 55$ μs, and the 5.5 μs is ascribed to the 5^- to 2^+ $E3$. If the 4^+ is below the 5^- the possible $E1$ decay would destroy the isomerism and if the 7^- is below the 5^- it could only decay by a much slower low-energy $E3$ to 4^+ or by $E5$ to 2^+. The $B(E2, 10^+ \rightarrow 8^+)$ and $B(E3, 10^+ \rightarrow 7^-)$ agree within errors with those measured in ^{206}Hg [9].

The 872 and 1123 keV γ rays are assigned as the decays from the 5^- isomeric state. It is expected that the 2^+ energy of ^{204}Pt, with a predominantly $(d_{3/2})^{-2}$ orbital configuration, is smaller than that of ^{206}Hg, with a mainly $(d_{3/2})^{-1}(s_{1/2})^{-1}$

TABLE I. Transition strengths for experiment, the Rydström [26] shell model (SM), and the new TBMEs (SM_{mod}) (see text) in ^{204}Pt. Effective charges of 1.5 and 2.0 *e* for $E2$ and $E3$, respectively, were assumed, which were chosen to reproduce the ^{206}Hg $10^+ \to 8^+$ $E2$ and $10^+ \to 7^-$ $E3$ transitions [9].

Transition	EL	$B(EL)$ (W.u.)		
		Exp.	SM	SM_{mod}
$10^+ \to 8^+$	$E2$	0.80(8)	2.64	1.22
$10^+ \to 7^-$	$E3$	0.19(3)	0.21	0.22
$7^- \to 5^-$	$E2$	$0.017 \to 0.0034$[a]	1.21	0.0037
$5^- \to 2^+$	$E3$	0.039(5)	0.713	0.612

[a]Assuming a transition energy between $10 \to 78$ keV.

configuration. It is lower by about 200 keV, taking into account differences in single particle ($(s_{1/2})^{-1}$ vs $(d_{3/2})^{-1}$) and interaction ($(d_{3/2})^{-2}$ vs $(s_{1/2})^{-1}(d_{3/2})^{-1}$) energies. This suggests that the energy of the first excited state is 872 keV. The $E3$ $5^- \to 2^+$ transition proceeds mainly from the dominant $(s_{1/2})^{-1}(h_{11/2})^{-1}$ component of the 5^- state to the weak admixture of the $(s_{1/2})^{-1}(d_{5/2})^{-1}$ configuration in the predominantly $(d_{3/2})^{-2}$ state. The experimental $E3$ transition strength is weak (see Table I).

The transition linking the proposed 7^- and 5^- isomeric states was not observed in the present experiment. The lack of K x rays associated with the long-lived decay suggests a transition energy below the binding energy of the K electron (78.4 keV).

In light of the new ^{204}Pt and updated ^{206}Hg data [9] the Rydström interaction [26] was modified in three points: (i) the $(d_{3/2}h_{11/2})_{7^-}$ TBME was increased by +135 keV as requested by ^{206}Hg; (ii) the $(s_{1/2}d_{5/2})$ monopole was increased by +250 keV, which accounts for the 4^+ level energy and the increased blocking of the $h_{11/2} \otimes 3^-$ coupling lowering the effective $d_{5/2}$ single hole energy; (iii) following a systematic search of the influence of nondiagonal TBME on the $E2$ strength evolution from ^{206}Hg to ^{204}Pt the $(s_{1/2}h_{11/2}; d_{3/2}h_{11/2})_{6^-}$ TBME was changed to +160 keV, close to the value for the responding 5^- TBME. With these minor modifications, the observed excited states within both ^{206}Hg and ^{204}Pt are well reproduced, including the ordering of the $5^-, 7^-$, and 4^+ states (see Fig. 3). The calculated $E2$ and $E3$ strengths with the exception of the $5^- \to 2^+ E3$ agree with experiment (see Table I). The latter discrepancy is common to both ^{206}Hg and ^{204}Pt and most likely due to the 2^+ wave function, which in a pure proton model space is poorly described. Note that $E3$ transitions are mediated by the $h_{11/2} \to d_{5/2}$ conversion, i.e., the weak $d_{5/2}$ content in the wave functions, and any further components such as, e.g., $N = 126$ cross shell excitations, will reduce this contribution in low-spin states. These revised shell model calculations reproduce the measured magnetic and quadrupole moments of the 5^- isomer in ^{206}Hg: $\mu(5^-)_{the} = 5.24\ \mu_N$ with $g_s = 0.7g_{free}$, $\mu(5^-)_{exp} = 5.45(5)\ \mu_N$ [11], $Q(5^-)_{the} = 0.57$ eb, $Q(5^-)_{exp} = 0.65(13)$ eb [10].

It is thus found that small modifications to the two-body interaction, though not unambiguous, significantly improve the description of levels and γ transition rates in ^{204}Pt. Recently new approaches to infer realistic nucleon-nucleon interactions were made, based on the renormalized G matrix [27,28] and the V_{low-k} potential [29]. Further investigations, both experimental and theoretical, are needed to understand the nuclear structure evolution of the $N \sim 126$ region toward the anticipated r-process waiting nuclei at $Z \leqslant 72$.

In summary, we have identified excited states in the four proton-hole nucleus ^{204}Pt. The yrast sequence has been established up to spin-parity $I^\pi = (10^+)$, through the observation of decays from three isomers. The character of the excited states can be understood in terms of the shell model, although to get a consistent description of the experimental level scheme the accepted set of matrix elements has been modified to account for the changing intrinsic shell structure affecting the isomer configuration. The persistence of the isomeric structure, the related transition strengths, and their reproduction in a pure proton space strongly support an unquenched $N = 126$ gap. Due to the crucial role of the $\pi h_{11/2}$ orbit in both allowed and first forbidden β decay of $\nu h_{9/2}$ and $\nu i_{13/2}$ neutrons, respectively [7,30], this study paves the way for examining nuclear structure as both the anticipated pathways for the astrophysical r-process and candidate nuclei for shell quenching are approached.

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[1] A. Klimkiewicz *et al.*, Phys. Rev. C **76**, 051603(R) (2007).
[2] A. Jungclaus *et al.*, Phys. Rev. Lett. **99**, 132501 (2007).
[3] I. Dillmann *et al.*, Phys. Rev. Lett. **91**, 162503 (2003).
[4] P. J. Woods and C. N. Davids, Annu. Rev. Nucl. Part. Sci. **47**, 541 (1997).
[5] P. D. Bond, R. F. Casten, D. D. Warner, and D. Horn, Phys. Lett. **B130**, 167 (1983).
[6] Y.-Z. Qian, Prog. Part. Nucl. Phys. **50**, 153 (2003).
[7] H. Grawe, K. Langanke, and G. Martínez-Pinedo, Rep. Prog. Phys. **70**, 1525 (2007).
[8] D. Eccleshall and M. J. L. Yates, Phys. Lett. **19**, 301 (1965).
[9] B. Fornal *et al.*, Phys. Rev. Lett. **87**, 212501 (2001).
[10] K. H. Maier *et al.*, Phys. Rev. C **30**, 1702 (1984).
[11] J. A. Becker *et al.*, Phys. Rev. C **26**, 914 (1982).
[12] C. Wennemann *et al.*, Z. Phys. A **347**, 185 (1994).
[13] M. Pfützner *et al.*, Phys. Lett. **B444**, 32 (1998).
[14] Z. Podolyák *et al.*, Phys. Lett. **B491**, 225 (2000).
[15] S. J. Steer *et al.*, Acta Phys. Pol. B **38**, 1283 (2007).
[16] Z. Podolyák *et al.*, Eur. Phys. J. Spec. Top. **150**, 165 (2007).
[17] H. Geissel *et al.*, Nucl. Instrum. Methods B **70**, 286 (1992).
[18] C. Scheidenberger *et al.*, Nucl. Instrum. Methods B **142**, 441 (1998).

[19] S. Pietri *et al*., Nucl. Instrum. Methods B **261**, 1079 (2007).
[20] P. H. Regan *et al*., Nucl. Phys. **A787**, 491c (2007).
[21] P. J. Nolan, F. A. Beck, and D. B. Fossan, Annu. Rev. Nucl. Part. Sci. **44**, 561 (1994).
[22] S. Pietri *et al*., Acta Phys. Pol. B **38**, 1255 (2007).
[23] M. Caamaño *et al*., Eur. Phys. J. A **23**, 201 (2005).
[24] Z. Podolyák *et al*., Prog. Theor. Phys. **146**, 467 (2002).
[25] J. Benlliure *et al*., Nucl. Phys. **A660**, 87 (1999).
[26] L. Rydström *et al*., Nucl. Phys. **A512**, 217 (1990).
[27] M. Hjorth-Jensen, T. T. S. Kuo, and E. Osnes, Phys. Rep. **261**, 125 (1995).
[28] B. A. Brown (private communication, 2008).
[29] L. Coraggio, A. Covello, A. Gargano, N. Itaco, and T. T. S. Kuo, Phys. Rev. C **60**, 064306 (1999).
[30] I. M. Borzov, Nucl. Phys. **A777**, 645 (2006).