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Short Note

Spectroscopy of the neutron-deficient nuclide ^{171}Pt

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Abstract. A number of previously unobserved γ-rays emitted from the neutron-deficient nuclide ^{171}Pt have been identified using the recoil decay tagging technique. The level scheme has been updated using information from γ-γ coincidences and angular distribution measurements. To further confirm the assignments of the γ-rays to ^{171}Pt, the events were correlated with the alpha-decay of the daughter nucleus ^{167}Os.

PACS. 23.20.Lv Gamma transitions and level energies – 27.70.+q $150 \leq A \leq 189$

1 Introduction

The region near the proton drip line around $A = 170$ has been an object of intense investigation in the last few years [1–11]. Studies have revealed a richness in physical phenomena like shape coexistence and vibrational structures. The study of the lightest nuclides in the region presents a difficult challenge. The production cross-sections in suitable fusion-evaporation reactions using stable beams and targets lie in the μb or sub-μb region. Furthermore, these weakly populated nuclear species have to be detected and identified in an intense γ-ray background from fusion-evaporation channels closer to stability, fission, transfer reactions, Coulomb excitation, etc., as well as radioactivity.

The experimental access to excited states in this region of the nuclear chart relies on the predominance of alpha (or proton) unstable ground- or low-lying excited states. The highly selective and efficient recoil decay tagging (RDT) technique [12,13] has thus provided a crucial experimental tool for structural studies of heavy neutron-deficient nuclei. In this method the characteristic particle decay energies are measured in a focal-plane detector of a recoil mass filtering device and correlated with the prompt γ-rays detected near the target.

The platinum isotopes exhibit collective bands which indicate underlying structural changes as the proton drip line is approached [1]. Near the stability line their ground states are characterised by near-oblate shapes with rather small quadrupole deformations. The yrast levels in the odd isotopes have been assigned to $\nu i_{13/2}$ configurations and have spacings very similar to the corresponding levels in the even isotopes, indicating a decoupling of the odd $i_{13/2}$ neutron from the core. This situation is drastically changed as we approach the neutron mid-shell. Here ($100 \leq N \leq 108$), the similarity of level spacings is lost, pushing the lowest excited states for the odd isotopes up in energy relative to those in the even isotopes. This can be interpreted as a transition into a region of strongly coupled configurations, characterised by a prolate core and a high Ω-value for the odd $i_{13/2}$ particle. As we continue towards the proton drip line, the situation changes again. For $N \leq 98$, a prolate band and a weakly deformed triaxial band are predicted to coexist. Indeed, the ground-state bands of ^{176}Pt [14,15] and ^{174}Pt [16] show strongly perturbed rotational patterns.

When comparing the level energies of ^{171}Pt and ^{172}Pt [1] ($N = 93$ and $N = 94$), the pattern changes once again. Here, the similarity of level spacings between

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odd and even isotopes has reappeared with a pattern that is reminiscent of a vibrational structure. Using total Routhian surfaces and quasi-particle random phase approximation calculations, this has indeed been interpreted as a transition from a collective rotational structure into a new region with predominantly collective vibrational character [1]. King *et al.* [2] have extended the platinum systematics to include excited states in ^{168}Pt and ^{170}Pt, confirming this scenario.

This article presents new γ-ray spectroscopic data on ^{171}Pt, extending the information on excited states from a previous study [1]. A large number of newly observed γ-rays have been unambiguously assigned to ^{171}Pt by means of daughter decay (^{167}Os) correlations and the previously suggested level scheme is extended by means of γ-γ coincidence spectroscopy. In addition, multipolarity assignments deduced from angular-distribution measurements are made for the strongest γ-ray transitions.

2 Experimental details

The experiment was performed at the JYFL accelerator facility in Jyväskylä, Finland. The JYFL K130 cyclotron accelerated ^{78}Kr ions, produced in the 14.5 GHz ECR ion source from isotope-enriched krypton gas, to an energy of 370 MeV. The ^{78}Kr projectiles were used to bombard a target consisting of a 500 μg/cm^2 thick self-supporting metallic foil made from isotope enriched (96.52%) ^{96}Ru. The centre-of-target beam energy was approximately 363 MeV. The target was surrounded by the germanium γ-ray detector array JUROSPHERE [17], consisting of fifteen EUROGAM [18] type detectors, five NORDBALL [19] type detectors, and five TESSA [20] type detectors. In this configuration, JUROSPHERE had a total photo-peak efficiency of about 1.5% at 1.3 MeV. The gas-filled recoil separator RITU [21,22] was used in conjunction with JUROSPHERE in order to separate the fusion-evaporation products from the beam particles and from the fission background. RITU selected the reaction products, transmitting about 40% of the recoils to the focal plane. After passing through RITU, the recoils were implanted in a focal-plane detector consisting of 16 silicon strips, each with an area of 5×35 mm^2 and with a total area of 80×35 mm^2. Each strip is position sensitive along the strip, in order to enable correlation by distance between two signals detected at different times in one strip. The recoil signals can therefore be correlated with a subsequent alpha-decay as long as the count rate is low enough in comparison to the half-life of the alpha-decay. The length of the recoil trajectory from the target position to the focal plane of RITU is approximately 5 metres. For a recoil velocity of 0.04c, as in the present experiment, the flight time will be around 0.4 μs. If the recoil signal is detected in delayed coincidence with the JUROSPHERE data, the prompt γ-rays emitted from a nucleus with known alpha-decay energy can be correlated (*tagged*) with the subsequent alpha-decay of the recoil nucleus. In this manner, a γ-ray energy spectrum belonging to a specific nuclide can be constructed. Since an implanting recoil deposits more energy in the strip detector than an alpha-particle emitted from a decaying nucleus, and less energy than a scattered beam particle, recoil implants can be singled out by selecting events within a certain energy interval. An additional criterion for a recoil event is a signal in the multi-wire proportional avalanche counter (MWPAC), placed in front of the strip array. Alpha events containing the MWPAC signal are vetoed out in order to suppress the background due to alpha-particles escaping from the silicon strip detector. A second silicon detector is placed behind the strip detector. An additional criterion for accepting an alpha event is that no signal is found in this second detector. This reduces the effect of light particles flying through the recoil separator, leaving a signal when punching through the silicon strips. The system has been described in detail by Kettunen *et al.* [23]. In order to enable the correlation between recoils and alpha-decay events, a microsecond clock time stamps every event. Suitable criteria for the correlation in time and position are set during the off-line analysis. In order to enable detection of γ-rays emitted from isomeric states, as well as γ-rays and X-rays from daughter products, a single germanium detector was placed behind the focal plane. The acquired data were written to magnetic tapes and sorted off-line.

3 Results

The nuclide ^{171}Pt was produced with an approximate cross-section of 50 μb using the reaction ^{96}Ru(^{78}Kr, 2pn)^{171}Pt. A γ-ray energy spectrum tagged by the characteristic alpha-decay of ^{171}Pt ($E_\alpha = 6.453$ MeV, $T_{1/2} = 43$ ms [24]) is shown in fig. 1a. The search time between a recoil implant and its alpha-decay is limited to 130 ms, corresponding to approximately three half-lives of the ^{171}Pt ground-state alpha-decay. The assignment of the newly identified γ-rays to ^{171}Pt is confirmed in fig. 1b, which shows a spectrum obtained by demanding, in addition, the detection of an alpha-decay of the daughter nuclide ^{167}Os ($E_\alpha = 5.853$ MeV, $T_{1/2} = 840$ ms [24,6]) at a nearby position within the silicon strip. The maximum alpha-alpha correlation time was set to 2.5 seconds. In table 1 we have listed the energies and intensities extracted from the spectrum in fig. 1a. By identification of the same peaks in fig. 1b, the assignment of these γ-ray transitions to ^{171}Pt is confirmed. A measurement of the intensity variation of γ-ray transitions between different angles of the JUROSPHERE detector system enabled us to study the angular distribution of the strongest γ-rays. The result is presented in fig. 2. Here, the intensities of the 445 keV, 605 keV, and 669 keV lines are plotted *versus* the detector angles $\Theta = 78°$, 101°, 133.6°, and 157.6°, relative to the beam axis. The intensities are normalised to the detector efficiency in the respective angle. The experimental values are compared to calculated angular distributions:

$$P(\Theta) = 1 + \alpha_2 A_2 P_2(\cos(\Theta)) + \alpha_4 A_4 P_4(\cos(\Theta)), \quad (1)$$

where the parameters A_2 and A_4 are adopted from Yamazaki [25] using the spins assigned in fig. 4 below. The

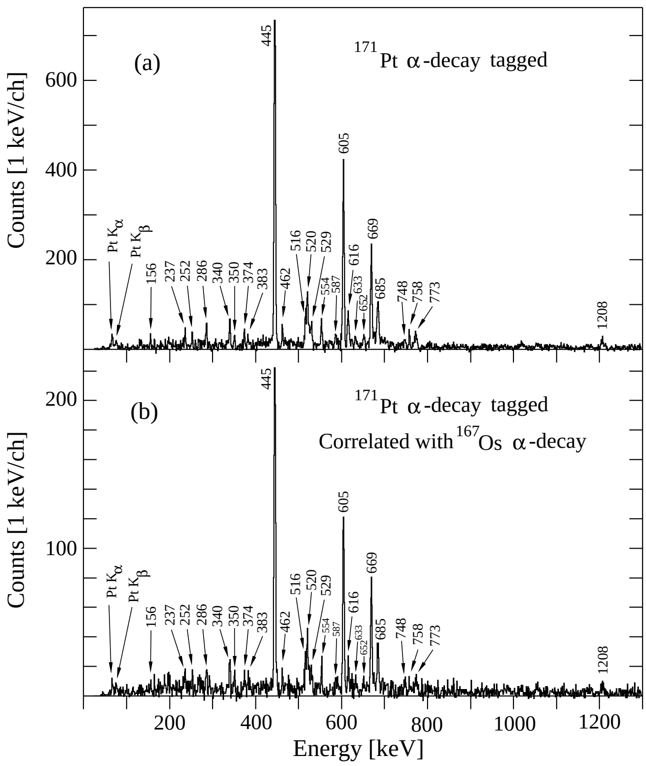

Fig. 1. Gamma-ray spectra from the decay of excited states in ^{171}Pt. A smooth background has been subtracted from both spectra. Panel (a) shows the recoil decay tagged spectrum using a search time limit of 130 ms between a recoil implant and a 6.453 MeV alpha-decay. Selecting the events that, in addition, are followed by a subsequent alpha-decay of the daughter nucleus ^{167}Os ($E_\alpha = 5.853$ MeV, $T_{1/2} = 840$ ms), produces the spectrum in panel (b). The alpha-alpha search time limit was set to 2.5 seconds.

Table 1. Observed γ-rays, in order of energy, assigned to ^{171}Pt. Intensities are adjusted for detector efficiencies and normalised to the intensity of the strongest transition in the spectrum (445 keV). Gamma rays observed in a previous study [1], are marked by stars.

Energy (keV)	Relative intensity
156.4(4)	19(3)
236.5(3)	25(3)
252.4(3)	22(3)
285.8(3)	49(4)
340.0(3)	66(7)
350.5(3)	19(3)
374.5(3)	43(4)
382.7(3)	18(3)
⋆445.0(2)	1000(37)
462.2(3)	45(4)
515.6(3)	86(13)
⋆520.5(3)	234(19)
528.8(4)	123(11)
554.0(2)	82(6)
586.5(3)	52(5)
⋆604.7(2)	727(24)
⋆615.9(2)	145(8)
633.0(4)	58(7)
651.7(3)	48(5)
⋆669.4(2)	371(13)
⋆684.9(2)	201(11)
747.8(3)	49(5)
⋆758.2(3)	63(6)
⋆772.7(3)	140(9)
1208.0(5)	107(9)

attenuation coefficient of the spin alignment, α_2, was chosen as 0.75, giving an α_4 value of 0.4 [25]. The curves in fig. 2 correspond to a stretched quadrupole (solid curve) distribution and a stretched dipole (dashed curve) distribution. All three γ-ray transitions are assigned to be of stretched quadrupole character, and are therefore assumed to be of $E2$ multipolarity.

The recoil decay tagged data were also used to study γ-γ coincidences. Gates on two γ-ray energies are shown in fig. 3. Based on these and other E_γ gates, and on the relative γ-ray intensities, the level scheme of ^{171}Pt is constructed in fig. 4. The assignments of the three lowest states made in a previous study [1] are confirmed, and two new levels are added. The yrast cascade is extended by a 685 keV transition, and the 616 keV decay to the (tentative) $17/2^+$ level might indicate the existence of a sideband similar to the negative-parity sidebands that have been observed in, *e.g.*, the lighter $N = 93$ isotones [26, 27]. Spin and parity are assigned in agreement with the angular-distribution measurements.

The assignment of spin and parity for the ground state is based on a total Routhian surface calculation [28], using a Woods-Saxon potential. Energy surfaces at zero rotational frequency revealed minima at low quadrupole deformation ($\beta_2 \approx 0.15$, $\gamma = 10°$–$20°$) for both the positive- and negative-parity configurations. A comparison between the energy values at these minima shows that the positive-parity configuration has a slightly lower energy compared to the negative-parity configuration. The only suitable positive-parity configuration for $N = 93$ at this deformation is $\nu i_{13/2}$, and we therefore assign the ground state to have spin and parity $I^\pi = 13/2^+$.

In order to interpret the present data there are two main features that need to be accounted for. The first observation is the similarity in relative excitation energies between the odd-mass nucleus and its even-even neighbour. The other observation that can be made is the vibrational-like pattern, especially at the top of the deduced level structure. Two alternative scenarios could reproduce these features. The first scenario involves the $i_{13/2}$ neutron weakly coupled to a vibrational core. The other interpretation would imply a decoupled ($\nu i_{13/2}$) rotational band in ^{171}Pt, based on a weakly deformed γ-soft rotor. The latter scenario requires, in addition, a 2–quasi-particle alignment of $i_{13/2}$ neutrons in order to explain the upbend in the experimental alignment plot. In reference [27] it was shown that the interaction strength for the BC $(i_{13/2})^2$ quasi-neutron alignment deduced in the $N = 93$ isotones is reduced with increasing proton number for ^{163}Yb, ^{165}Hf, ^{167}W, and ^{169}Os. This trend seems to be broken by the

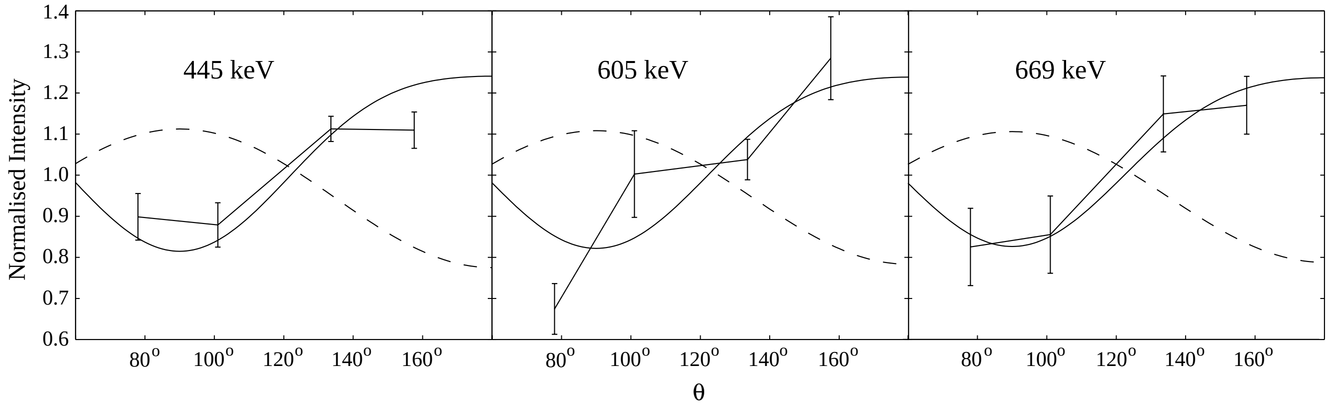

Fig. 2. Angular distributions for three transitions in ^{171}Pt. The experimental distributions are compared to calculated angular distributions [25]. The solid lines correspond to a stretched quadrupole distribution and the dashed lines correspond to the case of a stretched dipole. The spin alignment attenuation coefficient α_2 is chosen as 0.75.

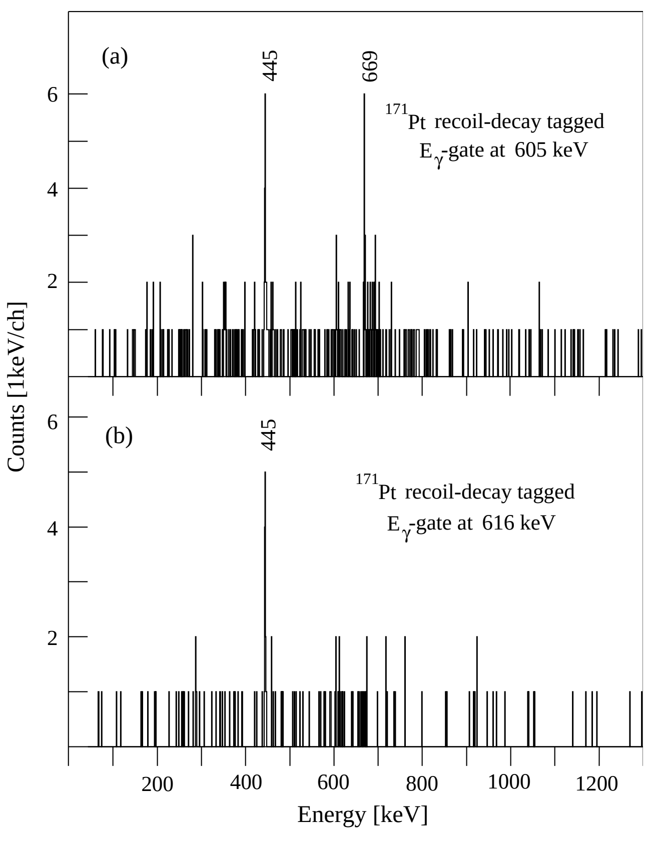

Fig. 3. Selected RDT-gated γ-γ coincidence spectra of ^{171}Pt. Panel (a): 605 keV gate. Panel (b): 616 keV gate. The strongest transitions are marked by their energy in keV.

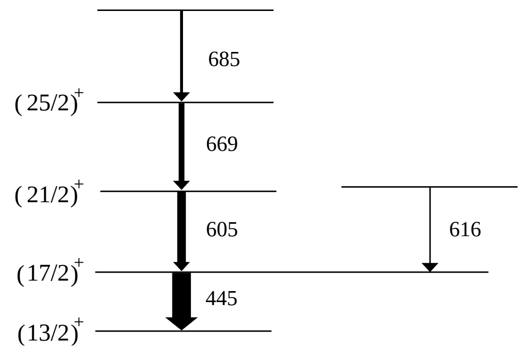

Fig. 4. The tentative level scheme of ^{171}Pt. The proposed ordering of γ-rays is based on the E_γ-E_γ coincidence data and on the measured intensities. The assignments of spin and parity above the ground state are based on the angular-distribution measurements illustrated in fig. 2.

experimental data on ^{171}Pt since, in a rotational picture, the beginning of the alignment due to the 669 keV and 685 keV transitions comes at a lower frequency ($\hbar\omega \approx 0.34$) than in ^{169}Os ($\hbar\omega \approx 0.39$) [27]. Lifetime measurements for the observed states may help to distinguish between the two possible scenarios mentioned above.

4 Summary

A number of previously unobserved γ-rays, emitted from the very neutron-deficient nuclide ^{171}Pt, have been found using the recoil decay tagging technique. In order to confirm the assignment of the γ-ray transitions to ^{171}Pt, the events have been correlated with the decay of the daughter nuclide ^{167}Os. The level scheme has been constructed using γ-γ coincidences, and angular-distribution measurements for the strongest transitions have been used to assign spin and parity to the lowest levels. The theoretical interpretation of the experimental data is not conclusive and may involve vibrational-like as well as rotational-like excitations.

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References

1. B. Cederwall *et al.*, Phys. Lett. B **443**, 69 (1998).
2. S.L. King *et al.*, Phys. Lett. B **443**, 82 (1998).
3. R.A. Bark *et al.*, Nucl. Phys. A **646**, 399 (1999).
4. R.A. Bark *et al.*, Nucl. Phys. A **657**, 113 (1999).
5. S.L. King *et al.*, Phys. Rev. C **62**, 067301 (2000).
6. D.T. Joss *et al.*, Nucl. Phys. A **689**, 631 (2001).
7. R. Julin *et al.*, J. Phys. G **27**, R109 (2001).
8. F.G. Kondev *et al.*, Phys. Lett. B **512**, 268 (2001).
9. F.G. Kondev *et al.*, Nucl. Phys. A **682**, 487c (2001).
10. M.B. Smith *et al.*, Nucl. Phys. A **682**, 433c (2001).
11. D.E. Appelbe *et al.*, Phys. Rev. C **66**, 014309 (2002).
12. E.S. Paul *et al.*, Phys. Rev. C **51**, 78 (1995).
13. R.S. Simon *et al.*, Z. Phys. A **325**, 197 (1986).
14. G.D. Dracoulis *et al.*, J. Phys. G **12**, L97 (1986).
15. B. Cederwall *et al.*, Z. Phys. A **337**, 283 (1990).
16. G.D. Dracoulis *et al.*, Phys. Rev. C **44**, R1246 (1991).
17. R. Julin *et al.*, Acta Phys. Pol. B **32**, 645 (2000).
18. C.W. Beausang *et al.*, Nucl. Instrum. Methods A **313**, 37 (1992).
19. G. Sletten, in *International Seminar on the Frontier of Nuclear Spectroscopy*, edited by Y. Yoshishawa (World Scientific, Singapore).
20. P.J. Nolan *et al.*, Nucl. Instrum. Methods A **236**, 95 (1985).
21. M. Leino *et al.*, Nucl. Instrum. Methods B **99**, 653 (1995).
22. M. Leino, Nucl. Instrum. Methods B **126**, 320 (1997).
23. H. Kettunen *et al.*, Acta Phys. Pol. B **32**, 989 (2001).
24. R.D. Page *et al.*, Phys. Rev. C **53**, 660 (1996).
25. T. Yamazaki, Nucl. Data **3**, 1967.
26. K. Theine *et al.*, Nucl. Phys. A **548**, 71 (1992).
27. D.T. Joss *et al.*, Phys. Rev. C **66**, 054311 (2002).
28. W. Satuła, R. Wyss, Phys. Scr. T **56**, 159 (1995).