In-beam γ-ray spectroscopy of the neutron-rich platinum isotope $^{200}\text{Pt}$ towards the $N=126$ shell gap


1 Dipartimento di Fisica e Astronomia, Università di Padova, I-35131 Padova, Italy
2 Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
3 Istituto di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy
4 School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom
5 Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany
6 Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain
7 Department of Physics, University of Surrey, GU2 7XH Guildford, United Kingdom
8 Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
9 Istituto Nazionale di Fisica Nucleare, Sezione di Milano, I-20133 Milano, Italy
10 Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany
11 Dipartimento di Fisica, Università di Firenze, I-50019 Sesto Fiorentino (Firenze), Italy
12 Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, I-50019 Sesto Fiorentino (Firenze), Italy
13 School of Computing, Engineering and Mathematics, University of Brighton, Brighton BN2 4GJ, United Kingdom
14 Institut de Recherche sur les lois Fondamentales de l’Univers IRFU, CEA/DSM, Centre CEA de Saclay, F-91191 Gif-sur-Yvette Cedex, France
15 Department of Physics, Faculty of Science, Istanbul University, Vezneciler/Fatih, TR-34134, İstanbul, Turkey
16 Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse CSNSM, CNRS/IN2P3 and Université Paris-Sud, F-91405 Orsay Campus, France
17 Institut Rudjer Bošković, HR-10000 Zagreb, Croatia
18 Dipartimento di Fisica Teorica, Università di Torino, I-10125 Torino, Italy
19 Istituto Nazionale di Fisica Nucleare, Sezione di Torino, I-10125 Torino, Italy
20 Département de Physique, Université libre de Bruxelles, B-1050 Bruxelles, Belgium
21 Department of Physics and Astronomy, Uppsala University, SE-75120 Uppsala, Sweden

(Dated: April 3, 2017)

The neutron-rich nucleus $^{200}\text{Pt}$ is investigated via in-beam γ-ray spectroscopy in order to study the shape evolution in the neutron-rich platinum isotopes towards the $N=126$ shell closure. The two-neutron transfer reaction $^{198}\text{Pt}^{(80}\text{Se}, 80\text{Se})^{200}\text{Pt}$ is used to populate excited states of $^{200}\text{Pt}$. The Advanced Gamma Ray Tracking Array (AGATA) demonstrator coupled with the PRISMA spectrometer detects γ rays coincident with the $^{80}\text{Se}$ recoils, the binary partner of $^{200}\text{Pt}$. The binary partner method is applied to extract the γ-ray transitions and build the level scheme of $^{200}\text{Pt}$. The level at 1884 keV reported by Yates et al. [Phys. Rev. C 37, 1889] was confirmed to be at 1882.1 keV and assigned as the $(6^+_1)$ state. An additional γ ray was found and it presumably de-excites the $(8^+_1)$ state. The results are compared with state-of-the-art beyond mean-field calculations, performed for the even-even $^{190–204}\text{Pt}$ isotopes, revealing that $^{200}\text{Pt}$ marks the transition from the γ-unstable behaviour of lighter Pt nuclei towards a more spherical one when approaching the $N=126$ shell closure.

PACS numbers: 21.10.Re, 21.60.Jz, 23.20.Lv, 27.80.+w

---

a Corresponding author: philipp.john@ikp.tu-darmstadt.de
Present address: Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany

b Present address: Department of Physics, University of Oslo, P. O. Box 1048 Blindern, N-0316 Oslo, Norway
Finite many-body systems such as molecules, many
man made nano-materials and atomic nuclei exhibit non-
spherical (deformed) ground states, representing a sponta-
neous symmetry breaking \[1\]. In atomic nuclei the de-
formed shape is due to the complex interplay between the
residual nucleon-nucleon interactions driving towards de-
formation and the shell gaps which tend to restore the
spherical shape. The study of the nuclear shape evolution
along an isotopic chain opens a window on the underly-
ing microscopic force and is an important testing ground
for nuclear models \[2\].

One region of the nuclear chart, where oblate, prolate,
\(\gamma\)-soft and spherical shapes are observed and predicted is
the tungsten-osmium-platinum region with \(A \approx 190\). A
prolate-to-oblate shape transition is predicted to appear
when moving towards the \(N = 126\) shell closure, where
the spherical shape should be restored. For platinum
and osmium isotopes such a shape transition occurs while
passing through nuclei having a \(\gamma\)-soft potential. How-
ever, the path to sphericity is not yet fully expounded.

This region has been studied from a theoretical point
of view via microscopic self-consistent mean-field ap-
proaches (Hartree-Fock-Bogoliubov, HFB) with a variety
of interactions \[3\] revealing the importance of triax-
ial deformation. An other approach has been the inter-
acting boson model, either purely phenomenological \[10\]
or based on potential energy surfaces (PES) mapped to
those obtained with HFB calculations with energy den-
sity functionals (EDF) \[11\] \[12\]. State-of-the-art beyond-
mean-field calculations based on energy density function-
als have been successfully applied to reproduce the col-
lective character of the ground-state bands in the os-
mium isotopic chain \[13\]. Such a theoretical framework,

\[\text{symmetry conserving configuration mixing (SCCM) method, includes simultaneous particle number\]
and angular momentum projections and axial and non-
axial shape mixings \[13\] \[16\] and provides information on
both intrinsic deformations and the properties of excited
levels in a natural manner.

The intrinsic deformation of the atomic nucleus is not
a direct observable. In order to deduce the nuclear shape,
in addition to the study of reduced electromagnetic tran-

I. EXPERIMENTAL SETUP AND DATA
ANALYSIS

To produce neutron-rich isotopes around \(^{198}\text{Pt}\) in ex-
cited states, a \(^{82}\text{Se}\) beam was accelerated by the XTU
Tandem-ALPI accelerator combination at the Laboratori
Nazionali di Legnaro to an energy of 426 MeV. The beam
impinged on a 2 mg/cm\(^2\) thick self-supporting \(^{198}\text{Pt}\) tar-
get with an energy \(\approx 11\%\) above the Coulomb barrier.
Beam-like fragments were unambiguously identified in
PRISMA by their atomic number, charge state and mass.

The time-of-flight range and the gas pressure of the ioni-
sation chamber of PRISMA were optimised for the study
of neutron-rich nuclei around \(^{198}\text{Pt}\). The target was tilted
by \(5^\circ\) in order to allow the target-like and beam-like re-
colls to exit the target. The binary partner of the ion
identified in PRISMA was stopped by the target cham-
ber walls after a time-of-flight of around 10 – 15 ns.
Gamma rays in coincidence with an ion detected at the focal plane of PRISMA were measured by the AGATA demonstrator, that was placed at a distance of 15.5 cm from the target and opposing PRISMA with an angle of 180° to its optical axes. The setup of the experiment is drawn schematically in Fig. 1.

At the time of the experiment the AGATA demonstrator, from now on called AGATA, was in its full configuration of 5 triple clusters. Each cluster consists of 3 differently hexagonal tapered coaxial HPGe detectors with 36 electrical-separated outer segments and a common inner core contact. In order to reduce the counting rate in the first segments, a 600 µm thick Sn absorber was installed in front of AGATA. In this configuration, AGATA had an angular coverage of 15% of 4π. The relative and absolute efficiency curve was derived using the 133Ba, 152Eu and 60Co standard calibration sources. The efficiency after using the γ-ray tracking algorithm was ≈ 4% at 1332.5 keV. The average rate per crystal was kept between 20 and 30 kHz during the whole experiment. The trigger was the coincidence of an ion arriving at the focal plane of PRISMA with at least one AGATA crystal (inner core). The signals were digitised and the energy and the waveform of the initial 1 µs were written to disk.

The position of each interaction in an AGATA segment is deduced by passing the digitised signals to a pulse shape analysis algorithm. The interaction positions together with their energies are used to reconstruct the γ rays by the Orsay Forward Tracking algorithm (OFT). The emission time of the γ rays is deduced from the signal of the first interaction point, as identified by the tracking algorithm. The signals of the segments are aligned in time to the core signal. The time depending fully digitised signals are summed and the intersection between the baseline and the interpolated linear slope defines the time signal.

PRISMA provides the momentum vector of the beam-like recoil. This information is used together with the position of the first interaction inside AGATA for the Doppler correction for the γ rays emitted by the beam-like recoils. The momentum vector of the target-like recoils is deduced event-by-event assuming a relativistic binary reaction without particle evaporation. However, the evaporation of neutrons is likely for excitation energies above the neutron-separation energy. Therefore, the deduced mass of the binary partner is just an upper limit. The energy loss of the reaction products in the target material is estimated for each event employing the Northcliffe-Schilling approximation. The FWHM of the Doppler corrected γ-ray peaks are well below 1% for both beam-like and target-like recoils.

Since the momentum and the angle of the beam-like recoils are measured simultaneously, the Q value of the reaction can be approximately reconstructed for each event. The reconstructed Q value has in this experiment an uncertainty that can reach up to 30 MeV due to the thickness of the target that is much higher than the neutron-separation energy of the neutron-rich platinum isotopes.

### II. RESULTS

In the γ-ray spectrum gated on 80Se and Doppler corrected for the binary partner 200Pt, γ-ray peaks from lighter platinum isotopes appear. In order to reduce the fraction of γ-ray peaks from ions produced by neutron evaporation in the γ-ray spectra, a condition on the low part of the reconstructed Q value is applied. This condi-
tion is the best compromise between statistics and the appearance of additional peaks due to neutron-evaporation.

The two isomeric states, \(7_1^{+}\) and \((12_1^{+})\) are populated in this reaction. Both have short half-lives of 17.0 (5) ns and 13.9 (10) ns \([32]\), respectively. In order to enhance the true prompt events a condition on the initial 20 ns part of the prompt \(\gamma\)-ray peak is placed.

Fig. 2 (a) shows the Doppler corrected \(\gamma\)-ray spectrum gated on \(80\)Se, the binary partner of \(200\)Pt. The most intense \(\gamma\)-ray peak in this spectrum is the \(2_1^{+} \rightarrow 0_8^{+}\) (666 keV) transition of \(80\)Se. The Coulomb excitation of the \(82\)Se is reduced by placing a tight condition on the mass selection. However, peaks belonging to \(82\)Se can not be completely suppressed leading to a small \(\gamma\)-ray peak at 655 keV. The wrongly Doppler corrected \(\gamma\)-ray transitions belonging to the platinum isotopes appear as broad structures in the spectrum. In Fig. 2 (b) the same spectrum is drawn, where the Doppler correction is performed for \(200\)Pt. Gamma-ray peaks from \(200\)Pt and lighter platinum isotopes produced after the evaporation of neutrons are labelled by their energy and with different symbols, respectively. Due to the lifetime of the isomeric states, these \(\gamma\) rays are emitted mostly not at the target position. Hence, these peaks possess a tail in the Doppler corrected \(\gamma\)-ray spectrum.

Besides the previously reported \([31, 32, 34, 35]\) ground state band transitions at 469 keV and 633 keV, two \(\gamma\)-ray peaks at 780 keV and 869 keV appear in this spectrum that are assigned to the ground-state band of \(200\)Pt. An energy level at 1884.0 keV was reported by \textit{Yates et al.} \[34\] which decays to the \(5_1^{−}\) and \(4_1^{−}\) states via \(\gamma\) rays of 317.4 keV and 780.8 keV having relative intensities of 29 (9) and 36 (5), respectively. This experiment confirms the \(\gamma\)-ray transition observed by Yates et al. \[34\] at 780 keV. The \(\gamma\)-ray peak that we observe in our spectra at 317.9 keV is a doublet composed of two transitions, the 317.4 keV de-exciting the \((6_1^{−})\) level at 1882 keV (corresponding to the 1884 keV level of Ref. \[34\]) to the \(5_1^{−}\) level at 1565 keV and the transition at 318.4 keV feeding the \(7_1^{+}\) isomeric state \([31, 32]\). The relative intensities of the 317.4 keV and 780.8 keV reported in \[34\], has been used to extract the intensity of the 317.4 keV transition in the doublet and, as a consequence, the one of the 318.4 keV transition.

In order to verify this assignment a \(\gamma\)-\(\gamma\)-coincidence analysis is performed with a \(\gamma\)-\(\gamma\) matrix produced using the same conditions as for the creation of the spectrum in Fig. 2, the \(\gamma\)-\(\gamma\) matrix was constructed placing a gate on the identified \(80\)Se isotopes, on the low reconstructed Q value and on the early part of the prompt peak with a 20 ns wide gate.

The results are shown in Fig. 3. The \(2_1^{+} \rightarrow 0_8^{+}\) and \(4_1^{−} \rightarrow 2_1^{+}\) transitions are in mutual coincidence with each other and the 780 keV and 869 keV \(\gamma\)-ray peaks. A coincidence between the 780 keV and 869 keV \(\gamma\)-ray peaks is not observed. This is expected due to statistical consideration and the efficiency of AGATA. The results are shown in Fig. 3. The \(2_1^{+} \rightarrow 0_8^{+}\) and \(4_1^{−} \rightarrow 2_1^{+}\) transitions are in mutual coincidence with each other and the 780 keV and 869 keV \(\gamma\)-ray peaks. A coincidence between the 780 keV and 869 keV \(\gamma\)-ray peaks is not observed. This is expected due to statistical consideration and the efficiency of AGATA.
To better understand the collective character and the shape evolution in this region, SCCM calculations based on Gogny D1S energy density functionals have been performed for $^{190–204}$Pt isotopes. Nuclear states are defined in this method as linear combinations of particle number and angular momentum projected HFB wave functions with different quadrupole shapes (axial and non-axial). Hence, the coefficients of such configuration mixings are obtained self-consistently by using the generator coordinate method (GCM) [46]. On the other hand, the intrinsic HFB wave functions are found through a variation after particle number projection method (PNVAP) [37] imposing constraints on the quadrupole deformation $\beta_2, \gamma$. Additionally, these intrinsic HFB wave functions do not break either reflection or time-reversal symmetries. Therefore, only positive parity states can be described and a systematic stretching of the theoretical spectra with respect to the experimental data is expected [48]. A detailed description of the present SCCM method can be found in Reference [15].

As a first step, one can analyse qualitatively the shape of a given nucleus by studying its potential energy surface (PES), i.e., the energy as a function of the intrinsic deformations. In Fig. 5, the PESs in the $(\beta_2, \gamma)$ plane for $^{190–204}$Pt isotopes are presented, calculated with a PNVAP method. Here, one observes only one minimum in each PES which evolves rather smoothly from a triaxial deformed shape $\approx (0.15, 40^\circ)$ in $^{190}$Pt, to an axial oblate deformation $\approx (0.10, 60^\circ)$ in $^{196}$Pt, and to a much less deformed oblate $\approx (0.05, 60^\circ)$ in $^{200}$Pt when approaching the $N = 126$ spherical shell closure. Here ($^{204}$Pt), a spherical magic nucleus is found. A similar behaviour of the PESs has been already obtained with other EDFs [6, 10, 11, 49].

A more quantitative analysis of the collective character of the isotopic chain is the study of the ratio of the excitation energies of the ground-state band with respect to the value of the excitation energy of the first $2^+$ state. In Fig. 6, the theoretical results obtained with the SCCM method described above and the available experimental data are represented for $^{190–204}$Pt nuclei. In addition, the predictions for the axial rotor, vibrator and $\gamma$–unstable/triaxial rotor geometrical models are plotted. The experimental data is taken from References [35, 50, 52] and this work for $^{196,198,200}$Pt. The latter limit is reproduced almost perfectly with the microscopic calculations in the isotopes $^{194–199}$Pt, while for $^{190–192}$Pt and $^{200}$Pt tiny deviations from the first limit towards a more axial rotational and vibrational character are observed, respectively. The states $(6^+)$ and $(8^+)$ that have been associated to the $\gamma$–ray peaks at 780 keV and...
FIG. 5. (colour online) Particle number projected potential energy surfaces in the triaxial plane for $^{190−204}$Pt isotopes calculated with the Gogny D1S interaction. Solid and dashed contour lines are separated 1.0 MeV and 0.2 MeV, respectively.

869 keV in $^{200}$Pt, agree well with the SCCM calculations, supporting the spin and parity assignment. For the semi-magic isotope $^{204}$Pt, the predictions lie even below the vibrational limit although for these nuclei explicit quasi-particle excitations not included in the present framework could play a major role in describing low-lying excited states.

Summarising, the even-even $^{190−200}$Pt exhibit a $\gamma$-soft potential energy surface and the excited states lie close to the $\gamma$-unstable/triaxial rotor geometrical model. The deformation decreases approaching the $N = 126$ subshell closure and the nucleus $^{200}$Pt marks the transition towards a more spherical behaviour. Hence, for $^{204}$Pt, the potential energy surface is purely spherical and the excited states, as stated before, go even below the vibrational limit. For the $^{202}$Pt isotope the potential energy surface follows the general trend where the minimum tends towards sphericity. However, the ratio shown in Fig. 6 g) shows a slightly more $\gamma$-soft behaviour than in $^{200}$Pt, changing the trend towards the spherical $^{204}$Pt.

The reason for this anomaly has to be found in the subtle evolution of the shape of the excited states individually. While for $^{200}$Pt the excited states evolve towards the triaxial degree of freedom with an almost constant $\beta_2$ value of 0.07, for $^{202}$Pt the excited states remain axial oblate deformed with a small increase in deformation as a function of the angular momentum from $\beta_2 = 0.05$ (almost spherical) for the $0^+_1$ state to $\beta_2 = 0.10$ for the $8^+_1$ state. Therefore, the observed increased in the $E(J^+_1)/E(2^+_1)$ ratio in $^{202}$Pt reflects the slight increase in the deformation of the excited states and not the return towards $\gamma$-unstable/triaxial rotor. In fact, this theoretical limit only has a well-defined meaning when the deformation remains constant for all the states, which is not the case for the $^{202}$Pt.

The comparison with the experimental data is rather good although a slightly less rotational character than the theoretical predictions is shown in $^{190,198}$Pt. Nevertheless, the evolution from triaxial collective character towards a vibrational spectrum when approaching the $N = 126$ shell gap is well reproduced.

IV. SUMMARY

Medium-high ground state band states in $^{200}$Pt have been studied via in-beam $\gamma$-ray spectroscopy using the AGATA demonstrator coupled with the large acceptance PRISMA magnetic spectrometer employing the $^{198}$Pt($^{82}$Se, $^{80}$Se)$^{200}$Pt reaction. Two additional states were assigned to the ground-state band extending the yrast band up-to the $(8^+_1)$ level. The nuclear shape evolution of the even-even $^{190−204}$Pt isotopes was studied via state-of-the-art SCCM calculations. The theoretical predictions agree well with the experimental data. In particular the ground-state band of $^{200}$Pt is well reproduced, revealing its nature as a transitional nucleus between the lighter $\gamma$-unstable platinum isotopes and the presumably spherical $N = 126$ platinum isotope $^{204}$Pt.
FIG. 6. (colour online) Yrast band excitation energies, normalised to the corresponding $2_1^+$ energies, for $^{190-204}$Pt isotopes. Blue dots and black boxes are the experimental points and theoretical beyond mean-field predictions respectively. Theoretical limits for axial rotor (red continuous line), vibrator (magenta dashed line) and $\gamma$-unstable/triaxial rotor (green dotted line) geometrical models are also given. The experimental data is taken from References 35, 50–52 and this work for $^{196,198,200}$Pt.

ACKNOWLEDGMENTS

The authors want to thank the partial funding of this project by the BMBF project numbers 06DA7047I and 05P12PKFNE, the Ministerio de Economía y Competitividad, Spain under Programa Ramón y Cajal 2012, grants AIC-D-2011-0746, FPA2011-29854, FPA-2011-29854-C04-01 and FIS2014-53434-P, the Spanish Consolider-Ingenio 2010 Programme CPAN (CSD2007-00042), the UK Science and Technology Facilities Council (STFC), the Generalitat Valenciana, Spain, under grant PROMETEO/2010/101, the Scientific Research Projects Coordination Unit of Istanbul University under Project No.15539, a Daphne Jackson Fellowship, the IAP program P6/23 Belgian State-BSP, the Polish Ministry of Science and Higher Education (Grant No. DPN/N190/AGATA/2009) and the EC by the ENSAR grant n. 262010.
