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Citation: [AIP Conference Proceedings](#) **1681**, 050007 (2015); doi: 10.1063/1.4932282

View online: <http://dx.doi.org/10.1063/1.4932282>

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β -decay properties of neutron-deficient Pt, Hg, and Pb isotopes

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Abstract.

Neutron-deficient isotopes in the lead region are well established examples of the shape coexistence phenomenon in nuclei. In this work, bulk and decay properties, including deformation energy curves, charge mean square radii, Gamow-Teller (GT) strength distributions, and β -decay half-lives, are studied in neutron-deficient Pt, Hg, and Pb isotopes. The nuclear structure involved is described microscopically from deformed quasiparticle random-phase approximation calculations with residual interactions in both particle-hole and particle-particle channels, performed on top of a self-consistent deformed quasiparticle Skyrme Hartree-Fock basis. The sensitivity to deformation of the GT strength distributions in those isotopes is proposed as an additional complementary signature of the nuclear shape. The β -decay half-lives resulting from the GT strength distributions are compared to experiment to demonstrate the ability of the method.

INTRODUCTION

Shape evolution and shape coexistence in the region of β -unstable nuclei with $Z \approx 82$ have been experimentally studied along the years by isotope-shift measurements, γ -ray spectroscopy, and lifetime measurements (see [1] for a general review). Low-lying excited 0^+ states have been experimentally observed at excitation energies below 1 MeV in all even Pb isotopes between $A = 184$ and $A = 194$. Maybe the most singular case corresponds to ^{186}Pb , where two excited 0^+ states below 700 keV have been found. Excited 0^+ states below 1 MeV have also been found in neutron-deficient Hg isotopes from $A = 180$ up to $A = 190$. Their ground states are found to be weakly deformed and of predominantly oblate nature, while the excited 0^+ states exhibit a larger deformation. Similarly, low-lying states in light Pt isotopes, still show shape coexistence of states with different deformation.

Within a mean-field description of the nuclear structure, the energy of the different shape configurations is evaluated from constrained calculations, resulting in deformation-energy curves (DECs). The presence of several minima at close energies in the DECs is understood as due to the coexistence of various collective nuclear shapes corresponding to different 0^+ states.

It has also been shown [2, 3] that the decay properties of β -unstable nuclei may depend on the nuclear shape of the decaying nucleus. In particular, the Gamow-Teller (GT) strength distributions corresponding to β^+ /electron capture (EC) decay of proton-rich nuclei in the mass region $A \approx 70$ have been studied systematically [4, 5, 6] as a function of the deformation by using a deformed quasiparticle random-phase approximation (QRPA) approach built on a self-consistent Hartree-Fock (HF) mean field with Skyrme forces and pairing correlations. The sensitivity of the GT strength distributions to deformation has been exploited to determine the nuclear shape in neutron-deficient Kr and Sr isotopes by comparing theoretical results with β -decay measurements using the total absorption spectroscopy technique (TAS) [7]. In this work we study the decay properties of neutron-deficient Pt, Hg, and Pb isotopes, aiming to show the extent to which GT strength distributions may be used as fingerprints of the nuclear shapes in this mass

region [8, 9, 10]. The general purpose is to identify possible signatures of the nuclear shape in the decay patterns. This study is timely because there is a program to carry out measurements of the GT strength distributions in the lead region with TAS techniques. $^{188,190,192}\text{Pb}$ and $^{182,184,186}\text{Hg}$ isotopes have been already measured at ISOLDE/CERN and are being currently analyzed [11].

Theoretical method

The theoretical formalism used to describe the β -decay properties can be found in Refs. [2, 3]. In summary, the method starts with a self-consistent calculation based on a deformed Hartree-Fock mean field obtained with effective two-body density-dependent Skyrme interactions, SLy4 in this work. The method also includes pairing between like nucleons in the BCS approximation with fixed gap parameters for protons and neutrons, which are determined phenomenologically. Assuming time-reversal and axial symmetry, the solution of the HF equation is found using an expansion of the single-particle wave functions in terms of the eigenstates of an axially symmetric harmonic oscillator in cylindrical coordinates using twelve major shells. From these calculations we obtain energies, occupation probabilities, and wave functions of the single-particle states. Constrained HF calculations are performed to obtain the DEC's, which are analyzed as a function of the quadrupole deformation parameter. Calculations for GT strengths are performed subsequently at the equilibrium shapes of each nucleus; that is, for the solutions (in general deformed) for which minima are obtained in the DEC's.

FIGURE 1. Experimental β^+ / EC decay half-lives in Pt, Hg, and Pb isotopes compared with the results of QRPA calculations with SLy4 for various nuclear shapes.

To describe properly the GT transitions, a spin-isospin residual interaction is added to the mean field and treated in a deformed proton-neutron QRPA. This interaction contains two parts, particle-hole (ph) and particle-particle (pp), which are expressed in a separable form. The technical details to solve the QRPA equations have been described in Refs. [5, 12]. β -decay half-lives are obtained by summing all the allowed transition strengths to states in the daughter nucleus with excitation energies lying below the corresponding Q_{EC} energies, which are weighted with appropriate phase-space factors. Our results for half-lives include a standard quenching factor $(g_A/g_V)_{\text{eff}} = 0.77(g_A/g_V)_{\text{free}}$.

FIGURE 2. Accumulated GT strength as a function of the excitation energy in the daughter nucleus for the various equilibrium shapes in Pt, Hg, and Pb isotopes.

Results

We first calculate the DEC's for neutron-deficient Pt, Hg, and Pb isotopes. We obtain in most cases several energy minima (oblate/prolate for Pt and Hg isotopes and oblate/spherical/prolate for Pb isotopes), revealing a generalized shape coexistence in these isotopes. Results are similar for different Skyrme interactions. We get in most cases well defined energy minima close in energy, and separated by energy barriers in the axial degree of freedom. These findings are in qualitative agreement with recent calculations including nonrelativistic self-consistent treatments with either Skyrme or Gogny interactions, as well as relativistic mean-field approaches. On the other hand, triaxial mean-field studies of structural changes with the Gogny interaction for Pt isotopes [13, 14] show that the (axial) prolate and oblate minima, which are well separated by high-energy barriers in the axial degree of freedom, are in some cases softly linked along the γ direction. Indeed, some axial minima become saddle points when triaxiality is included in the analysis. However, the differences found with the present HF + BCS approach for the axial equilibrium values are not significant, although the topology of the surfaces are somewhat different. There are robust features common to all calculations, such as the existence of oblate and prolate minima in Pt and Hg isotopes, located at similar deformations and separated by spherical barriers, or the isotopic evolution from oblate shapes in the heavier isotopes to prolate shapes in the lighter ones. But there are also particular features that change according to the different calculations, such as the height of the barriers or the relative energies between the minima that finally determines the exact isotope where the shape transition takes place. Obviously, the exact location of the shape transition is very sensitive to small details of the calculation because the shape transition occurs precisely around the region where the energies of the competing shapes are practically degenerate. Nevertheless, for the purpose of this work, the exact location at which the shape transitions occur is not of relevance. The important aspect in this work is that a shape competition takes place and that the sensitivity of the $B(GT)$ profiles to deformation can be used as a fingerprint of the nuclear shape.

Next, we perform QRPA calculations of the GT strength for those configurations where energy minima are obtained in the DEC's. In Figure 1 we compare the experimental half-lives [15] with our QRPA calculations for those nuclear shapes. The total experimental half-lives contain contributions from the competing α decay. We have extracted

β -decay half-lives by using the experimental percentage of the β^+ /EC involved in the total decay. The agreement with experiment is somewhat better for the spherical shapes in the heavier Pb isotopes and for the prolate shapes in the lighter Pt isotopes. In general we obtain a quite reasonable agreement that validates the quality of our results. We show in Figure 2 the accumulated GT strength calculated in QRPA for the equilibrium nuclear shapes corresponding to the Skyrme interaction SLy4. The arrows indicate the Q_{EC} energies showing the range of energies relevant for the calculation of the half-lives. Clearly Q_{EC} increases as we move to lighter (more exotic) isotopes. No quenching factors are included in this figure. The profiles of the GT responses are different depending on the nuclear shape. In most cases we observe a strong peak at low excitation energy for prolate shapes and a more fragmented structure in the case of oblate shapes that can be tested experimentally. For Pb isotopes the spherical distributions show a peak at about 2 MeV, which is at higher energy than the low-lying excitation energies for prolate and oblate profiles. This feature can be used as a distinct characteristic of the spherical shape.

Conclusions

We have studied bulk and decay properties of neutron-deficient Pt, Hg, and Pb isotopes using a deformed pnQRPA formalism with spin-isospin separable residual interactions. The quasiparticle mean field is generated from a deformed HF approach with the SLy4 Skyrme effective interaction. The formalism includes pairing correlations in the BCS approximation. The equilibrium deformations in each isotope are derived self-consistently within the HF procedure obtaining various coexisting shapes in most isotopes. The main objective in this work is the study of the decay properties of these isotopes, paying special attention to the deformation dependence of their decay patterns in a search for fingerprints of nuclear shapes that would complement the information extracted by other means. We have evaluated the energy distributions of the GT strength for the possible equilibrium shapes and have shown their energy profiles to be compared with upcoming experiments. The β^+ /EC half-lives have been calculated and compared to the available experimental information. These calculations contribute to extend our knowledge of this interesting mass region characterized by shape coexistence by describing their decay properties in terms of the deformation.

ACKNOWLEDGMENTS

This work was supported by Ministerio de Economía y Competitividad (Spain) under Contract No. FIS2011–23565 and by the 7th European Community Framework Programme Marie Curie IOF ELECTROWEAK (O.M.).

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