EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Report to the ISOLDE and Neutron Time-of-Flight Committee

Report on Decay Spectroscopy and In-Source Laser Spectroscopy Studies on Heavy Nuclei at ISOLDE

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Abstract

We report on the experimental campaigns on decay-spectroscopy and in-source laser-spectroscopy on the heavy nuclei performed at ISOLDE. These involve the following ISOLDE experiments:
- IS456: Study of polonium isotopes ground state properties by simultaneous atomic- and nuclear-spectroscopy
- IS466: Identification and systematical studies of the electron-capture delayed fission (ECDF) in the lead region - Part I: ECDF of 178,180Tl and 200,202Fr isotopes
- IS511: Shape coexistence in the lightest Tl isotopes studied by laser spectroscopy
- I86: Development of astatine ion beams with RILIS

1. Introduction and Physics Motivation

- Shape coexistence:

The region of the heavy, neutron-deficient lead region (with Z~82 and N<126) is characterized by the manifestation of shape coexistence. Optical spectroscopy studies, decay- and in-beam studies have resulted in a wealth of experimental data [see e.g. 1,2]. The most notorious example is the ^{186}Pb nucleus (Z=82, N=104 midshell between N=82 and 126) whereby the three lowest nuclear states all have spin and parity equal to 0^+ [1]. It has been advocated that these states are characterized by a spherical, oblate and prolate configuration. Note however that the latter statement has not yet been firmly experimentally proven.

- Beta-delayed fission:

Another interesting feature that can be studied in these light neutron-deficient isotopes around Z=82 is beta-delayed fission (BDF). Prior to our work, only one example was reported in the literature (^{180}Tl), however some doubt were risen as the obtained result for the branching ratio of the BDF (P_{BDF}) was more than two orders of magnitude lower compared to the known systematic trend in the trans-actinide region [4]. Studying BDF in the neutron-deficient region around Z=82 is interesting for two main reasons: i) this region is characterized by and N/Z value around 1.25 which is different from the typical value of 1.4-1.6 where the vast majority of all fission studies have been performed, moreover, depending on the Q_{EC} and fission barrier (B_f) BDF is a low-energy fission process, and ii) the BFD process is believed to be responsible for the so-called fission cycling at the end of the r-process nucleosynthesis.

2. Status Report

- In-Source Laser Spectroscopy of the light lead and polonium isotopes

The mean square charge radii and nuclear moments of the lead (down to ^{182}Pb) and polonium (down to ^{191}Po) have been deduced using in-source laser spectroscopy. For the latter, the polonium atomic level structure had to be investigated and extensive atomic theory was used to deduce the charge radii [5-11]. The data have been compared to theoretical calculations (e.g. beyond mean-field calculations) and the main conclusions from this work are:

- the lead isotopes (Z=82) stay essentially spherical in their ground state even at and beyond N=104. It was very important to prove this statement with model independent experimental data as this will be the basis on which many other interpretations of the nuclear structure in this region will be based.

- the polonium isotopes (Z=84) exhibit a swift onset of collective behaviour when going from N=126 to lighter mass nuclei. This effect happens much earlier compared to the mercury (Z=80) or platinum (Z=78) isotopes. The odd-mass polonium isotopes follow the trend of the even-mass neighbours and no strong staggering is observed. This appears to emphasize the importance of the proton-neutron interaction when they occupy similar orbitals (between N,Z=82 and 126).

- Beta-delayed fission studies of neutron-deficient thallium, francium and astatine isotopes

The BDF of ^{178,180,182}Tl, ^{200,202}Fr and ^{196}At has been studied using the pure beams produced at ISOLDE using, amongst others, the laser ion source. P_{BDF} values as well as in certain cases the mass distribution of the fission products has been determined. The main conclusions from this work are:

- the P_{BDF} value for ^{180}Tl has been deduced to be 3.6(7)10^{-5} (instead of the literature value of 3 $10^{-(7\pm1)}$ [4]) and agrees with the systematic trend of the P_{BDF} values for the actinide region [16]. These experimental values will reveal information about the fission barrier in this region of the nuclear chart.

- an asymmetric mass distribution of the fission fragments has been observed with maxima around ^{80}Kr and ^{100}Ru, instead of a symmetric mass split into two ^{90}Zr (Z=40, N=50) nuclei naively expected from simply energy considerations [16]. The recently measured mass distribution after the BDF of ^{202}Fr (experiment took place in May 2011) showed a broadened structure indicating either an asymmetric distribution or a broad symmetric distribution. Further analysis is needed. These puzzling observations are now being interpreted by different theoretical approaches and complementary experiments using different approaches, e.g. populating the nuclei at higher excitation energy and different angular momenta, are underway at JAEA (Tokai, Japan) and at GSI (Darmstadt, Germany).
The paper on ^{180}Tl has been cited and discussed in various scientific newspapers and journals.

- the new development of laser ionization of astatine allowed to observe the BDF of ^{194,196}At. The experiment took place in May 2011 and the data will reveal a reliable value for the P_{BDF}. This value, together with the values on ^{192,194}At from GSI, will allow to study the variation of P_{BDF} over a wide range (about three orders of magnitude) while changing the Q_{EC}-B_f from about -1 to 3.5 MeV. With the new astatine beams now available at ISOLDE mass distribution measurements of fission fragments will be possible for ^{194}At and ^{196}At. The study of the mass distribution after BDF cannot be performed with the SHIP-GSI system (as the radioactive ions are implanted in the silicon array) and thus these studies are unique to these studies at ISOLDE.

- Beta- and alpha-decay studies of the neutron-deficient Tl, Po, At and Fr isotopes

A series of decay studies have been performed as by product from the in-source laser spectroscopy and the BDF studies [7,10,13]. Over the last three years decay data have been collected on ^{178,180,182}Tl, ^{195}Po, ^{200,202}Fr and ^{196}At. Part of the alpha-decay studies have been published [10], but most is currently under analysis. The beta-decay of the thallium isotopes has resulted in an important extension of the level scheme of the respective even mercury isotopes and is ready to be submitted for publication [13]. The main results are:

- Discovery of the excited 0^+_2 and 2^+_2 states in ^{180}Hg [13]. This confirms that the assumed prolate deformed band in the mercury isotopes indeed reaches its minimum in ^{182}Hg and that the 2^+_2-2^+_1 transition is strongly converted (total conversion coefficient = 3.5(4)). The latter hints to strong mixing between these two states combined with a large difference in their initial deformation. These findings were confirmed by an in-beam electron spectroscopy study performed at JYFL (a paper [14] will be submitted back-to-back to [13]).

- No evidence for the existence of a low-spin isomer in ^{180}Tl was found. This is an important conclusion for the BFD fission study of this nucleus and essential to extract reliable P_{BDF} values.

- the detailed decay study of ^{182}Tl revealed the conversion coefficient of the 2^+_2-2^+_1 transition (=4.1(7)). This value forms a crucial ingredient for the analysis of the Coulomb excitation experiments on ^{182}Hg that have been performed at ISOLDE to study shape-coexistence in the light mercury isotopes [15].

- Development of an efficient ionization scheme for astatine (in collaboration with TRIUMF)

A new efficient ionization scheme for astatine has been developed on-line based on the only two atomic transitions that were known in the literature. The ionization potential was determined for the first time and different excitation paths were found and tested for efficiency and sensitivity to isotope shifts and/or hyperfine structure at TRIUMF at ISOLDE. This resulted in new, pure and intense beams of neutron-deficient and neutron-rich astatine isotopes. Production tests and the isotope shift were preliminary measured for ^{196}At, ^{205}At and ^{218}At. These developments to further optimise the production of astatine beams will also allow to studying even more exotic nuclei like ^{192}At (measured production rate in May 2011: ~ 0.02 atoms/second

3. Future outlook

The in-source laser spectroscopy studies combined with efficient detection set-ups for beta- and alpha-decay studies will allow to explore further the region of the most neutron-deficient isotopes in the lead region. These data will be essential to understand the phenomena of shape-coexistence and low-energy fission. The following campaigns are planned.

- In-source laser spectroscopy studies on the neutron-deficient thallium isotopes in order to pin down the spin values and study the charge radii (approved and scheduled experiment [17]). A by product will be a beta-decay study of ^{184}Tl revealing data essential for the interpretation of the Coulomb excitation data on ^{184}Hg. Preparatory work has been performed at Gatchina on longer-lived thallium isotopes and isomers to obtain the mass shift and electronic factors for the atomic transition that will be used.
- The newly developed ionization scheme for astatine will allow beta-decay studies of ^{198,200,202}At feeding levels in the polonium daughter nuclei. These data will be necessary for the analysis of the Coulomb excitation experiments on the neutron-deficient polonium isotopes (approved experiment [18]). Moreover, the BDF studies of the astatine isotopes will allow to link the mass region studied at ISOLDE with the GSI fission data induced by electromagnetic excitation. In-source laser spectroscopy measurements are planned to identify, amongst others, the properties of the isomer and ground states necessary for the BDF studies.
- In-source laser spectroscopy of highly excited atomic states in astatine is a logical extension of the ionization scheme development. Through measurements of Rydberg and autoionizing states the first ionization potential can be defined with a high precision and even more efficient ionization paths could be found.
- The improved sensitivity of the in-source laser spectroscopy technique at ISOLDE will allow to extend the measurements to the very neutron-deficient mercury isotopes even beyond the region where strong staggering between isomer and ground state is observed.

The combination of Coulomb excitation, beta-decay, in-beam data and charge radii will form stringent tests for state-of-the-art calculations and will improve our understanding of shape coexistence and of nuclear structure as a whole. The unique tool to study low-energy fission (through BDF) in a region of the nuclear chart with an unusual N/Z~1.25 should give essential information for a better, microscopic, description of the fission process.

4. Publications

References [5-10,16] result from this work and a number of papers are in the final stage of submission [11-13]. Several further publications are to be expected as a significant part of the obtained data set is still under analysis and work on the characterization of the silicon detectors at SCK-CEN (Belgium) and ILL-Grenoble (France) is ongoing. For the latter beam time has been approved at the Lohengrin separator. Moreover, intensive discussions on the BDF results with theory groups are underway but have not yet converged to a comprehensive message (contacts have been established with W. Nazarewicz, P.-H. Heenen, M. Bender, P. Möller and others). Also contacts with the atomic theory has been established related to the astatine and polonium work (S. Fritsche and others).

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