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In-Source Laser Spectroscopy of Po

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Introduction/Motivation

Shape coexistence at low excitation energy in nuclei is a phenomenon which has continuously shown much interest on both the experimental and theoretical fronts [1–3]. The region around the neutron mid-shell, N= 104, and closed proton shell, Z= 82, is especially prolific. For example, in the Pt isotopes (Z=78), excited, strongly prolate, deformed structures ($\beta \sim 0.25$) coexists at low energy with the weakly deformed oblate deformed configuration ($\beta \sim 0.15$) in nuclei between A<176 and A>188. Furthermore, the former configuration becomes the ground state in 176≤A≤188 isotopes (N=98-108). The coexistence and mixing of these two configurations is clearly reflected in the strong deviation of the Pt charge radii from the droplet model values in vicinity of the neutron mid-shell at N=104. Figure 1 shows the systematics of the charge radii as a function of the neutron number in the Z=82 region.

A similar effect has been known for some time in the Hg isotopes (Z=80), in which a large isotope shift for the low spin $3/2^-$ state between ^{185}Hg and ^{187}Hg was observed along with

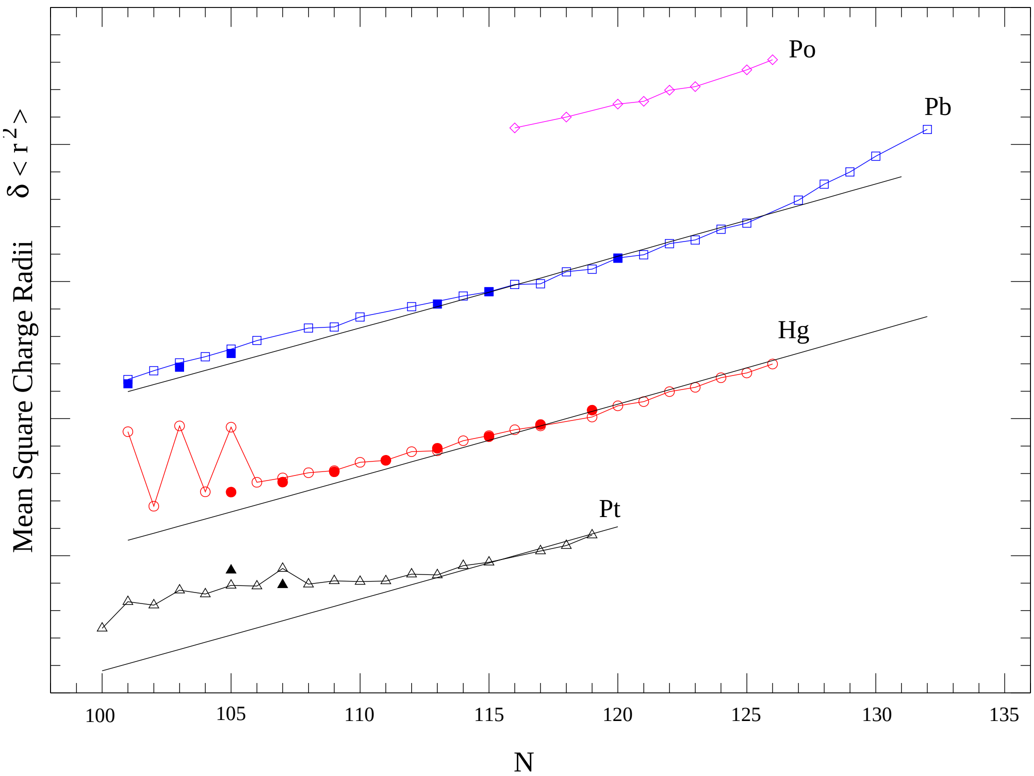

FIG. 1: Neutron number vs. mean square charge radii for Platinum (Z= 78) [4–6], Mercury (Z= 80) [7], Lead (Z= 82) [7, 8] and Polonium (Z= 84) [9]. The solid line is the droplet model [10].

a large isomer shift between the $3/2^-$ and $13/2^+$ states in ^{185}Hg [11]. This was interpreted as a change in shape from the weakly oblate ($\beta \sim 0.15$) $3/2^-$ ground state in ^{187}Hg to the strongly deformed prolate ($\beta \sim 0.25$) $3/2^-$ ground state in ^{185}Hg.

Also in this region, the lead isotopes arguably represent the most interesting case of the shape coexistence at low energy, since the coexistence of three configurations (spherical, oblate, prolate) is observed in the vicinity of the neutron mid-shell [12].

Alpha-decay was shown to be a very sensitive tool to study the shape coexistence. Extensive α-decay campaigns have been undertaken by the members of the present collaboration on the Po and Pb isotopes close to and beyond the neutron mid-shell using LISOL at Louvain-la-Neuve, ISOLDE at CERN, the velocity filter SHIP at GSI, and the RITU gas-filled recoil separator at the University of Jyväskylä. Some recent results can be found in Refs. [12–16]. Through these α decay studies, structures in both the mother and daughter nuclei have been studied including excitation energies, decay patterns and state configurations of lowest states. Complementary to this, in-beam γ-decay work has been used to characterize the band structures built on the low-lying states (Ref. [3] and references therein). However, the interpretation of decay and in-beam results is often model dependent and direct measurements of the deformation of the modelled states are most wanted.

To further study the effects of mixing of a deformed configuration in the ground-state of Pb isotopes, we recently performed the Pb charge radii measurements in the experiment IS407 [18] where $\delta < r^2 >$ values of Pb isotopes down to A=183 were measured (Fig. 1). From these measurements it was deduced that the mixing of the deformed intruder configurations in the spherical ground state of lead remains very weak and the ground states of the neutron-deficient Pb isotopes remain essentially spherical throughout the isotopic chain [8]. Still, some deviation from the droplet model prediction does exist and a theoretical work is underway to elucidate the possible reasons.

The recent α decay and in-beam studies mentioned above proved that there is a gradual transition from the spherical ground state in $^{196-210}$Po, to the oblate ground state in ^{190,192}Po and finally to a prolate ground state in ^{186,188}Po. As in Hg and Pt nuclei, one would expect to see this change in charge radii measurements. As a relevant example of such complementary studies we briefly discuss the case of ^{191}Po, in which two α-decaying isomeric states were observed in our experiment at the RITU gas-filled separator. In particular, it was observed that despite the α-decay energies of the strongest decays in ^{191m,g}Po are different only by 40 keV, their half-lives differ by a factor of ~ 4 (22 ms vs 93 ms) as shown in Figure 2. On these grounds, it was concluded, that there is a shape staggering between the nearly spherical $3/2^-$ isomeric state and oblate-deformed $13/2^+$ isomeric state in ^{191}Po. In a subsequent dedicated in-beam study [16], this conclusion was further confirmed by observing the low-lying excited states built on top of these two isomers, which clearly demonstrate a gradual transition towards the strongly-coupled scheme in the $13/2^+$ isomer ^{191}Po. Recently such studies were extended up via α-decay of the new isotopes ^{186,187}Po [17] and in-beam studies of ^{190,192,194}Po [3].

ISOLDE is suited to investigate the expected shape coexistence in the Po isotopes using in-source laser spectroscopy. We would like to study the isotope/isomer shifts measurements, which can provide information both on the charge radii and magnetic moments of the nuclei under study. In polonium nuclei these isotope shifts are only known in ^{200}Po, ^{202}Po and $^{204-210}$Po [9] but not for the neutron-deficient polonium isotopes of interest, in which the effects of shape coexistence should be more pronounced.

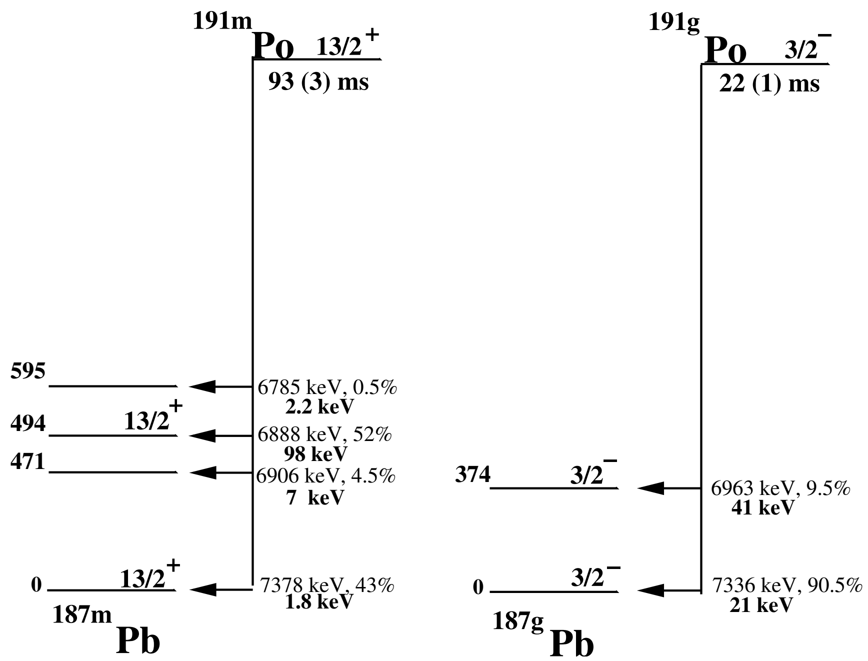

FIG. 2: Alpha-decay schemes for ^{191}Po. Indicated are the α-particle energies, the intensities, and the reduced α-decay widths.

A	σ mb	In-target Yield atoms/s	α branch	Count Rate atoms/s
191	2.00 x 10^{-3}	1.6 x 10^6	$\sim$ 100%	80
192	8.20 x 10^{-3}	6.5 x 10^6	99.5%	320
193	1.61 x 10^{-2}	1.3 x 10^7	$\sim$ 100%	650

TABLE I: Calculated, in-target yields for neutron-deficient polonium isotopes. A 50 $\frac{g}{cm^2}$ target and a 1 μA beam flux was used for the calculations. Count rates were calculated using 50% detector efficiency and 1% ionization efficiency. Please see text for more description.

Experimental Details

Polonium beams between A=193-205 were produced at ISOLDE-SC using a hot plasma ion source and a 9.7 $\frac{g}{cm^2}$, $^{238}UC_x$ target. Yields for these isotopes range from 1.2 x 10^2 atoms/μC in ^{193}Po to 6.0 x 10^7 atoms/μC in ^{205}Po [20]. We believe these values can be improved since two things have changed since these yields were measured: the proton bombarding energy has increased from 600 MeV to 1.4 GeV and improvements can be made on target thickness. By using the selective laser ionization we will obtain a purer beam and suppress contaminants. With these modifications, we can optimize the production rates as done in the Pb yields which were increased by a factor of 10^3 [8, 20]. We anticipate the same results in the polonium isotopes.

Yields for $^{191-193}$Po have been calculated using cross-sections from Ref. [21] (Table I. In reality, there is a certain time in which the polonium remains in the target before it is released. Therefore, we must account for this effect especially when going to the most neutron-deficient isotopes, having short half-life of about 30-100 ms (e.g. ^{191,192}Po). For these reasons, we decreased the yields in Table I by 100 and accounted for branching ratios, ionization and detector efficiency for the count rate calculation. By comparing the cross-sections and count rates of the Pb and Po isotopes we are confident measurement of isotopes down to ^{191}Po are possible, since we were able to measure ^{183}Pb at a countrate of only 10 atoms/s [18].

The Data Acquisition System and detector set-up will be the same as used in IS407 [19]. For the short lived ($t_{1/2}$ < 5 s) α emitters the Leuven windmill set-up will be used as described in Ref. [8]. For longer-lived isotopes, the ISOLDE tape system will be used. Therefore, it is not necessary to develop new DAQ or detector techniques for this experiment.

Laser Development

Since polonium has no stable isotopes, the study of its atomic spectrum is difficult. Nevertheless, approximately 150 lines were observed in the spectral range of 192 - 938 nm in Ref. [22]. Only about one third of these lines have been classified, and the table of Po atomic levels includes just 27 levels [23]. The value of ionization threshold is known as 8.4168 eV, therefore, a three-step laser excitation could be applied for resonance ionization of Po atoms at ISOLDE RILIS. For the first step transition, there are only two possibilities:
$\mathbf{6p^4\ {}^3P_2 \rightarrow 6p^37s\ {}^5S_2}$ (255.801 nm), and $\mathbf{6p^4\ {}^3P_2 \rightarrow 6p^37s\ {}^3S_1}$ (245.011 nm).

The required wavelengths for these transitions can be generated by tripling the frequency of the dye laser pumped by the copper vapor laser. There are only a few known atomic levels, which can be excited at the second step, and only two transitions are feasible with the CVL-pumped dye laser. Both these transitions require using at the first step, the transition 245.011 nm, and for the third step, the CVL beam can be used similar to many other ionization schemes at RILIS. Thus, there are two ionization schemes of polonium that can be tested without searching for new atomic levels:

1. $\mathbf{6p^4\ {}^3P_2 \rightarrow 6p^37s\ {}^3S_1 \rightarrow 6p^38p \rightarrow continuum}$
   λ_1 = 245.011 nm, λ_2 = 538.89 nm, λ_3=510.6 nm;
2. $\mathbf{6p^4\ {}^3P_2 \rightarrow 6p^37s\ {}^3S_1 \rightarrow 6p^38p \rightarrow continuum}$
   λ_1 = 245.011 nm, λ_2 = 532.34 nm, λ_3=510.6 nm;

Unfortunately, the isotope shifts (IS) and hyperfine structure (HFS) of some Po isotopes ($^{200,202,204-210}$Po) has been studied only for the 255.801 nm transition [9]. Using the proposed ionization schemes we can carry out HFS and IS measurements at the first step or at the second step as it would be better to apply the narrow-band scanning laser at the second step transition. Since both IS and HFS are mainly defined by the intermediate state with excited 7s-electron the accuracy of such a measurement will be higher roughly by a factor of 3.

Development of RILIS ionization scheme usually includes a measurement of the ionization efficiency using a sample of stable isotopes. Polonium has no stable isotope and the handling of large amounts of the long-lived alpha-emitting isotopes ^{206,208,209,210}Po would require this to be done in a radioactive "class A" laboratory. Instead of such a complicated off-line experiment it is better to measure the RILIS efficiency for Po on-line.

Spallation cross-sections for protons onto ^{238}U have been measured precisely in inverse kinematics at GSI-FRS [24] and can be used as good reference for the in-target production rates when using a standard UCx graphite target. From the isotopes with known production cross-sections $^{194-213}$Po the more neutron-rich ones are not useful due to abundant background from isobaric francium, but the isotopes $^{194-201}$Po are easily detectable without excessive background by alpha-, beta- or gamma-spectroscopy respectively.

A proton beam energy of 1.0 GeV would be ideal for this test as the cross-sections have been measured at 1.0 GeV. Accepting an increased uncertainty (by scaling the cross-sections with the energy dependence given by various nuclear reaction models), 1.4 GeV would also be acceptable.

Conclusion

We would like to measure the isotope shifts and magnetic moments of the neutron-deficient polonium isotopes at the ISOLDE facility. Through the proposed experiment, we would gain new insight into shape-coexistence in the region of interest. In order to realize this experiment, we **request the development and testing of ionization schemes of polonium.**

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