CERN-INTC-2008-027 / INTC-P-247
21/04/2008

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

Proposal to the INTC Committee

Shape coexistence measurements in even-even neutron-deficient Polonium isotopes by Coulomb excitation, using REX-ISOLDE and the Ge MINIBALL array.

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Abstract

The neutron-deficient polonium isotopes with two protons outside the closed Z=82 shell represent a set of nuclei with a rich spectrum of nucleus structure phenomena. While the onset of the deformation in the light Po isotopes is well established experimentally, questions remain concerning the sign of deformation and the magnitude of the mixing between different configurations. Furthermore, controversy is present with respect to the transition from the vibrational-like character of the heavier Po isotopes to the shape coexistence mode observed in the lighter Po isotopes. We propose to study this transition in the even-mass neutron-deficient ^{198,200,202}Po isotopes by using post-accelerated beams from REX-ISOLDE and "safe"-energy Coulomb excitation. Gamma rays will be detected by the MINIBALL array. The measurements of the Coulomb excitation differential cross section will allow us to deduce both the transition and diagonal matrix elements for these nuclei and, combined with lifetime measurements, the sign of the deformation in Po isotopes. We require **27 shifts** to reach the aims of the experiment.

1 Physics motivation

In the region around Z=82 shell closure with neutron number around the midshell between N=82 and N=126, shape coexistence occurs at low excitation energy. This phenomenon is well-established in the neutron-deficient polonium isotopes [1-3]. The proton-pair excitations across the magic Z=82 along with the strong proton-neutron interaction in the vicinity of the neutron midshell are considered as a driving mechanism for shape coexistence in this region [4-5]. The strong perturbation of the level systematics in the very light Po isotopes is also interpreted as arising from the interaction between regular and intruder structures [3][6].

Extensive studies of the level structure and properties along the even-mass Po isotope chain have been performed by in-beam γ-ray spectroscopy, α decay, β^+/Electron-capture decay and laser spectroscopic studies [2][7-21].

The energy systematics of the Po isotopes in the mass range 190-210 are presented in Fig.1.A. In ^{210}Po, which has a close neutron shell configuration (N=126), a high 2_1^+ state energy and a quasi-degenerency in energy for the 4_1^+, 6_1^+ and 8_1^+ are observed. The excited levels for this nucleus can be understood in terms of a simple two-proton $\pi 1h_{9/2}$ configuration. By removing 2 neutrons, the yrast 2_1^+ and 4_1^+ drop in energy. While the 2_1^+ state energy stays rather constant down to ^{200}Po, the 4_1^+, 6_1^+ and 8_1^+ states show smooth increases in energy. The ^{200}Po nucleus appears as a transition point. It marks the end of a "regular seniority-type regime" [23], which is replaced, starting with ^{198}Po, by an abrupt downsloping trend for nearly all the states. From ^{200}Po, the near-degeneracy the 6_1^+ and 8_1^+ states is lifted. The B(E2;$8_1^+ \rightarrow 6_1^+$) reduced transition probability and g-factor of the 8_1^+ state in ^{198,200}Po have been measured in reference [24] (see Tab. 1). The sudden change of B(E2;$8_1^+ \rightarrow 6_1^+$) from 655(35) e^{2}fm^4 in ^{200}Po to 137(10) e^{2}fm^4 in ^{198}Po, reveals that the 6_1^+ state changes from a predominant two-proton structure to likely vibrational character, while the 8_1^+ state still keeps its mainly two-proton character as deduced from the g-factor.

		^{198}Po	^{200}Po
$T_{1/2}(8_1^+)$	[ns]	29(2)	61(3)
$E_\gamma(8_1^+ \rightarrow 6_1^+)$	[keV]	136.1(2)	12.2(2)
B(E2;$8_1^+ \rightarrow 6_1^+$)	[e^{2}fm^4]	137(10)	655(35)
g(8_1^+)		+0.91(3)	+0.93(2)

TAB. 1 – Half-lives $T_{1/2}$, energies E_γ, transition probabilities B(E2) and g-factors of ^{198}Po and ^{200}Po published in reference [24].

Moreover, the preliminary results on the change in the mean square charge radii by (in-source) laser spectroscopy perfomed at ISOLDE [15] show a deviation from the predictions of the spherical droplet model, starting from ^{199}Po. This supports the idea that ^{200}Po is a transition nucleus.

For nearly all Po isotopes, second excited 2_2^+ and 4_2^+ states have also been identified. They follow the 4_1^+ and 6_1^+ states trends, respectively. In ^{196,198}Po, they are interpreted by reference [9] as members of a π(4p-2h) deformed oblate band with 4 particles in the $\pi h_{9/2}$ orbital and 2 holes in the $\pi s_{1/2}$ orbital. However, reference [10] offers an other explanation. By making a comparison between the experimental data

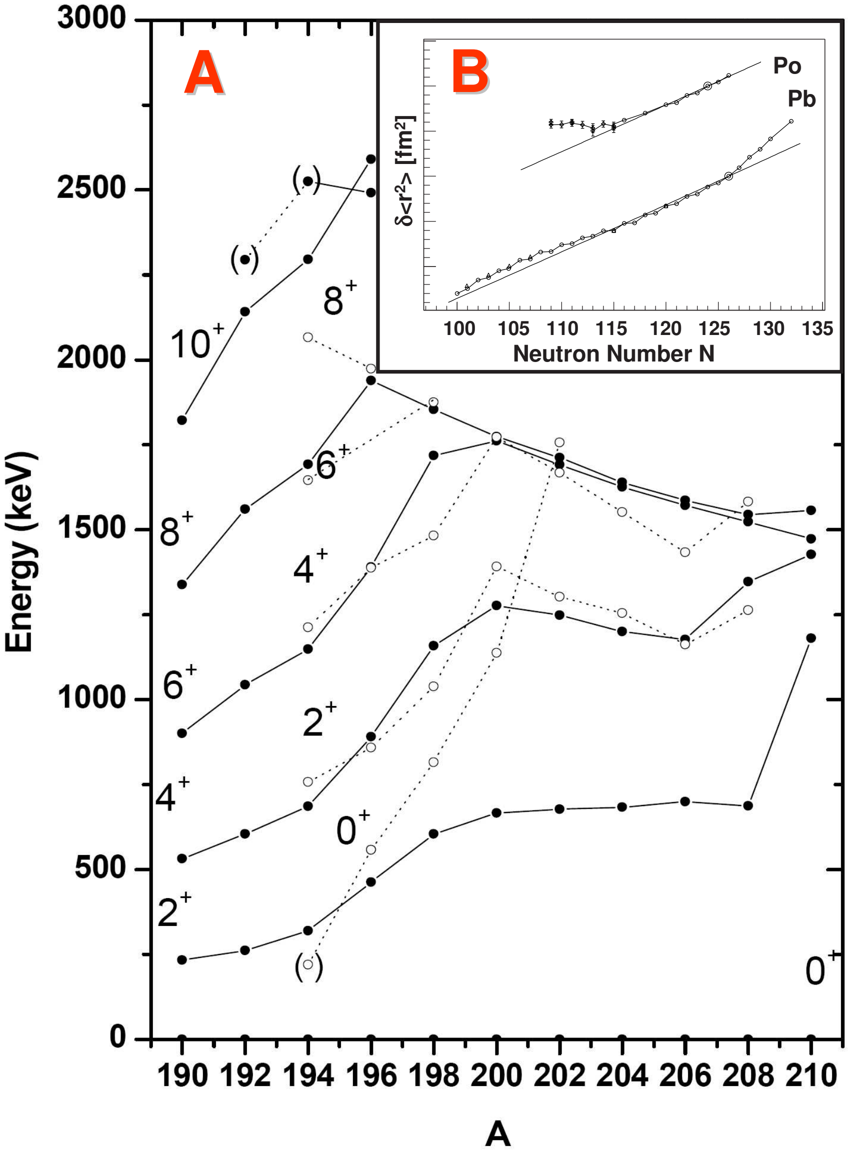

FIG. 1 – ***(A)*** *Systematics of selected yrast (filled circles) and non-yrast (empty circles) states for even-even neutron-deficient polonium isotopes, from N=106 to N=126. The states with same spin and parity are connected by a line. The figure is taken from reference [7]. Experimental data are taken from [2][8-14].* ***(B)*** *Changes of the mean squared charge radii as a function of the neutron number N for the lead and polonium isotopes. Solid lines indicate predictions of the spherical droplet model [22]. Changes are relative to a reference isotope circled for each element. The distance between the different chains is chosen arbitrarily for better display. One minor division on the vertical scale corresponds to 0.1 fm^2. The figure is taken from reference [15]. Preliminary results for $^{193-204}$Po are reported, completing the picture dressed by reference [17]. Experimental data for Pb isopotes are taken from [18-21].*

and vibrational, rotational and "4p-2h" pictures, it seems that the best agreement is found in the vibrational limit. The increasing role of the $\nu i_{13/2}$ and its larger overlap with the $\pi h_{9/2}$ is underlined.

The low-energy excitations in $^{200-208}$Po can be associated with quadrupole vibrations or single-particle motion. They have been described in the Particle-Core Model with the two valence protons coupled to a vibrating Pb core [24-25][6]. The evolution of the yrast and yrare 4_2^+ and 6_2^+ states is well reproduced. The 2^+ and 4^+ levels could be explained as pure 1 and 2 phonon states. As for the 6^+ and 8^+ levels, they could be interpreted as pure 0 phonon excitations. However, low-energy excitations for mass numbers below A=200 and the 0^+ excited levels are not described at all. A drop in the 0_2^+ energy by 600 keV between ^{202}Po and ^{200}Po is observed experimentally. The 0_2^+ becomes even the second excited state in ^{200}Po.
In order to describe the level structure for A<198 within the PCM, one needs to introduce a sharp rise in the proton-core interaction parameter [24-25]. Oros et al. argued against this unphysical sharp increase in the proton-core interaction strength [6]. They concluded that one cannot describe the level energy systematics from ^{198}Po down to ^{192}Po using an anharmonic vibrator framework by keeping the PCM parameters in a physically meaningful range [6].

Smirnova and collaborators show, by their calculations, that the lowest 0^+ states do not have a well defined deformation, and oblate, spherical and prolate shapes are strongly mixed, both in the ground and the excited 0^+ states [3].

This low lying 0_2^+ has the interesting consequence that they become accessible to α decay. Extensive studies of the level structure and α-decay properties (A.N. Andreyev *et al.*) of the long chain of even-mass Po isotopes show that the nuclei down to ^{198}Po can be considered as nearly spherical anharmonic vibrators. With decreasing neutron number, a presumably deformed oblate configuration intrudes into the low-energy part of the excitation spectrum and becomes the ground state in ^{190}Po. The lighter Po isotopes are predicted to become prolate in the ground state, with coexisting spherical and oblate configurations expected at a low excitation energy.

Recent beyond mean-field calculations confirm the onset of the strong prolate deformation for the lightest Po isotopes [27-29] and suggest a soft character with respect to deformation for the intermediate mass Po isotopes (194<A<200).

To conclude, the onset of the deformation in the lightest Po isotopes is well established experimentally. However, important questions remain concerning the transition from the 'vibrational' mode to the oblate or prolate deformed structure, the sign of deformation (that has never been experimentally determined) and the magnitude of the mixing between different configurations, eventually confirming the shape coexistence interpretation. To date, the experimental B(E2 ; $2_1^+ \rightarrow 0_1^+$) value has been extracted only for ^{194}Po from lifetime measurements, using the recoil-decay tagging technique [27-28]. This experiment has confirmed the high collectivity of the intruder states in this region.

We propose to study the shape coexistence in the even-mass neutron-deficient ^{198,200,202}Po isotopes, where the intruder structures lie higher in energy, by using post-accelerated beam from REX-ISOLDE followed by "safe"-energy Coulomb excitation. This experiment would be complemented by the lifetime measurements of the excited states in ^{198,200,202}Po. The proposal is in preparation.

The obtained reduced transition matrix elements will be compared to beyond mean field models [3][27-29] and will serve as important test of the model and interactions used.

2 Experimental set-up

2.1 Yields and contaminations

T.E. Cocolios and collaborators have recently measured the polonium isotopes yields at ISOLDE [16]. The isotope chain $^{193-198,200,202,204}$Po was produced with the 1.4 GeV CERN-PS Booster proton beam impinging on a UC$_x$ target (50 g.cm^{-2}). Some of the values obtained are presented in Tab. 2 (the even-even isotopes cases).

Isotope	Half life [s]	Yields [ions/μC]
^{194}Po	0.392	2.7×10^3
^{196}Po	5.8	4.8×10^5
^{198}Po	105	1.2×10^7
^{200}Po	690	6.4×10^6
^{202}Po	2682	1.7×10^7
^{204}Po	12708	1.1×10^7

TAB. 2 – Polonium yields published in reference [16].

The yield is defined as the ratio of the ion beam intensity to the primary beam current and is expressed in units of ions/μC :

$$Y = \frac{N_{0i}}{N_p \times 1.6.10^{-19}}.10^{-6}\int_{t=0}^{\infty} P_i(t,\lambda_i)dt \tag{1}$$

with

$$P_i(t,\lambda_i) = exp(-\lambda_i t).P_{\lambda_r,\lambda_f,\lambda_s,\alpha}(t) \tag{2}$$

$$P_i(t,\lambda_i) = exp(-\lambda_i t)[(1-exp(-\lambda_r t)).[\alpha.exp(-\lambda_f t)+(1-\alpha).exp(-\lambda_s t)]] \tag{3}$$

N_{0i} : number of ions created in one proton pulse
N_p: number of protons per pulse
$P_i(t,\lambda_i)$: release fraction [30]
λ_i : the decay constant of the radioactive element i

In our case, unwanted Tl isobaric contaminants are expected with an intensity between 10^6-10^7 ions/μC [31]. To optimize the Po to Tl ratio, we consider the following scenario. As the Tl isotopes are released much faster compared to the Po isotopes a macro-gating procedure can be applied. A yield of 5×10^6 ions/μC is considered for Tl isotopes (see Fig. 2). We consider a typical supercycle of the PS booster with a periodicity of 12×1.2s and N$_p$=2.10^{13} protons per pulse. If we use the first 6 proton pulses of it, the incoming proton beam intensity is $6\times(2\times10^{13})$ $\times(1.6\times10^{-19}$C)/14.4sec=1.3μA. Every supercycle the beam gate will be opened only

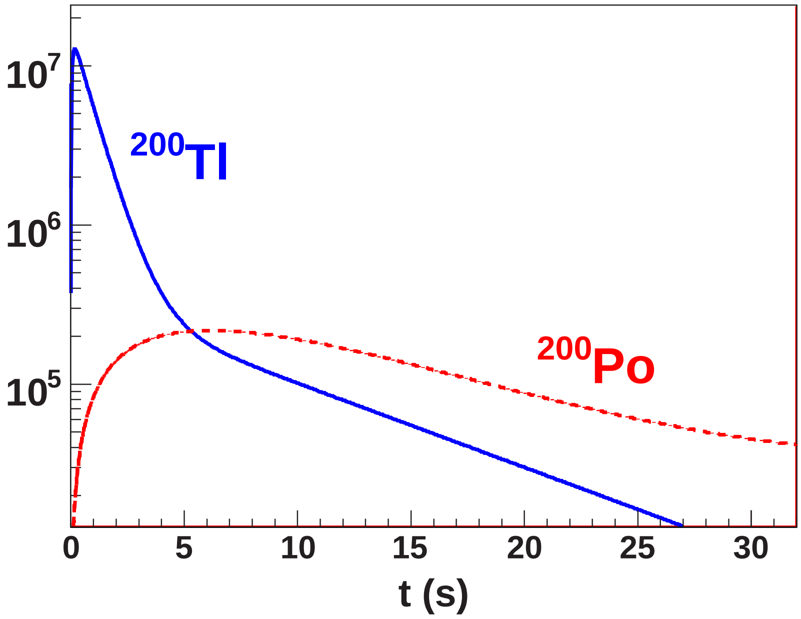

FIG. 2 – *^{200}Po and ^{200}Tl release curves from [30], considering one proton pulse of N_p=2×10^{13} only; where t corresponds to the time since proton impact.*

after 7.4s, 9.7s and 8.6s for ^{198,200,202}Po, respectively. These times have been defined as the moment where the momentary Tl and Po production is equal. By applying this procedure, the expected intensity rates and purity for ^{198,200,202}Po are 2.80×10^{6}pps (81%), 3.70×10^{5}pps (60%) and 8.71×10^{5}pps (70%), respectively.

This calculation assumes no cummulative yields from the previous supercycle and the numbers should therefore be considered as lower limits. Moreover, in case the count rate allows it, we will rather use an off-line software gate to optimise the production rate and contamination level.

Different techniques could be used to estimate correctly the beam contamination fraction during the experiment. A powerful element selective ionisation process is governed by the resonance laser ionisation technique. Using the RILIS, the identification and normalization would be done with the laser on/off method [32-33]. The mass resolving power of HRS is unfortunatly not sufficient (by an order of magnitude) to provide the necessay isobaric mass separation.

2.2 Beam intensities on target and Coulex set-up

Considering a REX-ISOLDE efficiency of 1%, we assume to reach 2.9 MeV/u ^{198,200,202}Po beams with resp. 2.80×10^{4}pps, 3.70×10^{3}pps and 8.71×10^{3}pps.

The Coulomb excitation set-up combines the MINIBALL array (8 triple cluster of 6-fold segmented High Purity Ge detectors [34]) and the DSSD CD detector (subtends an angular range 16°- 53° in the laboratory frame). The MINIBALL will provide the de-excitation gamma transition measurements. The CD detector will be used for both scattered projectiles and target recoil detection.

We performed Coulomb excitation cross section calculations using the CLX code [36]. Calculations have been carried out for the Coulomb excitation of the first 2^+ state (at 666 keV) of ^{200}Po projectiles with a beam energy of 2.9 MeV/u on the targets available at MINIBALL. For the ^{200}Po projectiles, we assumed a value of B(E2↑) of 0.79 e^2b^2[36] which is a conservative estimate as can be deduced from a comparison of the value given for ^{194}Po and the experimental data from [27-28]. The energy loss and the center-of-mass scattered angles limits were calculated using SRIM and kinematics programs, respectively. Taking into account MINIBALL efficiencies, it appears that ^{108}Pd (1.6 mg.cm^{-2}) offers the best γ count rates for both the target and the projectile excitation transitions. The energy of the first excited state of ^{108}Pd (434 keV) will not overlap with the 2^+ state energies of ^{198,200,202}Po, which are respectively 605 keV, 666 keV and 677 keV. The other transitions of the ^{108}Pd excitation (497 keV ($2_2^+ \rightarrow 2_1^+$), 614 keV ($4_1^+ \rightarrow 2_1^+$) and 931 keV ($2_2^+ \rightarrow 0_1^+$)) might interfere with 4_1^+ to 2_1^+ transitions (554 keV, 611 keV and 572 keV) or 2_2^+ to 2_1^+ transitions (434 keV, 726 keV and 625 keV) of the Po isotopes, depending on the population probability of the 2_2^+ and 4_1^+ states. In those cases, the complementary use of a ^{120}Sn target (1.7 mg.cm^{-2}) will be considered. For the odd-odd mass ^{198,200,202}Tl contamination, the expected gamma rays transition are of low energy.

In the same way, calculations for ^{198}Po and ^{202}Po, using this target were performed. The results obtained as well as the beam intensity required are presented in the following section. Coulomb excitation cross section calculations for the $2_1^+ \rightarrow 4_1^+$ transition of those nuclei were also estimated.

3 Beam time request

Coulomb excitation cross section calculations for the $0_1^+ \rightarrow 2_1^+$ transition as well as the $2_1^+ \rightarrow 4_1^+$ transition of ^{198,200,202}Po isotopes are presented in Tab.3. Transition probability estimations from [36] and [37] are used. The $2_2^+ \rightarrow 2_1^+$ transition matrix elements depend very strongly on the degree of mixing between these two states. Therefore, a rate estimate for these transition is, at this stage, not possible. Beyond mean field calculations have been performed and the calculated B(E2) are currently being extracted. These values will serve as a guide [27-29].

	Beam intensity on target (pps)	Target	Estimated $\sigma_{0_1^+ \rightarrow 2_1^+}$ (barn)	Estimated $\sigma_{2_1^+ \rightarrow 4_1^+}$ (barn)	Events in the photopeak (counts/shift)		Number of shifts
					$0_1^+ \rightarrow 2_1^+$	$2_1^+ \rightarrow 4_1^+$	
^{198}**Po**	2.80 .10^4	^{108}Pd	0.667	0.061	478	41	3
^{200}**Po**	3.70 .10^3	^{108}Pd	0.461	0.043	43	4	12
^{202}**Po**	8.71 .10^3	^{108}Pd	0.420	0.047	94	9	6
					TOTAL		21+3+3

TAB. 3 – Summary of the expected yields, weighted cross sections, counting rates and shifts required for the nuclei that will be investigated using a 1.6 mg/cm^2 thick ^{108}Pd target.

We request a that a total number of 27 shifts to perform this experiment. The 21 shifts take into account the laser ON-OFF procedure needed to estimate the contamination. 6 (3+3) extra shifts are required for the REX setting up and ascertain the isobaric purity of the beam. Complementary to this experiment, a proposal to measure the life times of the excited states in these Po isotopes is in preparation. The combination of the results will allow us to determine the sign of the deformation as well.

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