EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Nuclear moments and transition probabilities in the vicinity of the doubly magic ^{208}Pb. ^{210}Po and ^{210}Pb studies during the LS2.

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Abstract

We propose to perform Coulomb excitation of the very-long lived isotopes ^{210}Po and ^{210}Pb in order to study transition probabilities, magnetic-dipole and electric-quadrupole moments of the first 2^+ excited states. ^{210}Po ($t_{1/2}$ = 138 d) and ^{210}Pb ($t_{1/2}$ = 22 y) have two protons or two neutrons, respectively, away from the doubly magic ^{208}Pb. The structure of these isotopes has been studied for many years, however, the long-lived 6^+ and 8^+ states have hampered obtaining reliable information for the lowest-lying excited states (e.g. 2^+ and 4^+ states). The possibility of Coulomb exciting these states, using radioactive ion beams, provides a unique opportunity for gaining nuclear structure information and testing textbook concepts such as the extreme single-particle shell model, the additivity relation of nuclear magnetic moments and the seniority scheme. The proposed measurements are analogous to measurements on the related nuclei ^{134}Te and ^{134}Sn in the vicinity of neutron-rich doubly magic ^{132}Sn [Stuc13, Been04, Radf05], and are needed for critical comparisons of nuclear structure and nucleon-nucleon interactions in the ^{132}Sn and ^{208}Pb regions.

Standard Coulomb excitation of the first-excited states in ^{210}Po and ^{210}Pb would be used to obtain precise and reliable transition probabilities, B(E2). The Recoil In Vacuum (RIV) technique will be applied to determine the magnetic dipole moments, and the Coulomb reorientation effect would be used to determine their electric quadrupole moments. The methodology would take inspiration from similar measurements on neutron-rich ^{134,136}Te at HRIBF, Oak Ridge [Allm17, Stuc13].

Requested shifts: [x] shifts
Beamline: MINIBALL + CD or MINIBALL + CD + Cologne Plunger or MINIBALL + T-REX

Physics motivation

Our understanding of the structure of atomic nuclei is based on several basic concepts. For example, within the nuclear shell model the nuclear properties are governed by several valence nucleons moving in the field of an inert core [Goep50]. This approach is expected to be most valid in the vicinity of the doubly-magic nuclei and ^{208}Pb is one of the primary pillars of the nuclear shell model. The structure of semi-magic nuclei can be understood in the so-called seniority scheme [Shal63, Talm71]. In this approach, the low-energy excited states with J>0, with *n* particles on a single *j* shell, can be considered as originating from the recoupling of the angular momenta of the ν unpaired nucleons. This results in a number of states, having the same number of unpaired nucleons (seniority) ν. The seniority is considered a good quantum number and the generalized seniority scheme, where more than a single *j* orbital would be considered, represents a truncation of the nuclear shell model.

A particular interest here is to compare the shell structure in the neutron-rich ^{132}Sn region with that in the vicinity of stable ^{208}Pb [Cora09]. While the high-spin structure has been quite thoroughly studied experimentally around ^{208}Pb, the electromagnetic properties of low-excitation, low-spin states associated with a few pairs of valence nucleons outside ^{208}Pb have not. Thus, direct comparisons of the related few-particle states around ^{132}Sn and ^{208}Pb are currently limited by the lack of experimental data on electromagnetic properties near ^{208}Pb rather than near ^{132}Sn.

The gyromagnetic factor of a nuclear state, with a number of valence nucleons residing on the same orbital, should be independent of the number of unpaired nucleons and the total spin to which they are coupled. In that sense, the gyromagnetic factor of the 2^+, 4^+, 6^+ and 8^+ states of the same nucleus should be identical (additivity relation) if no core polarization effects are present. Therefore, an experimental determination of the gyromagnetic factors for a series of states, within the seniority approach, could fine test the robustness of the inert core. In particular, the octupole vibration of ^{208}Pb is known to affect the g factors of the 8^+ states in the N=126 isotones [Stuc93].

A stringent test of the above-mentioned rules in the immediate vicinity of the textbook doubly-magic nucleus ^{208}Pb has still not been achieved experimentally. The idea that we would like to put forward with this LoI is that such a study could be performed at ISOLDE in an off-line mode since both ^{210}Po and ^{210}Pb have very long lifetimes. Thus, their post-acceleration can be done a few months, up to a few years, after a target has been irradiated.

A summary of the presently available experimental data.

The ^{210}Po case.

The low-energy structure of ^{210}Po, with 2 $\pi h_{9/2}$ protons above ^{208}Pb, is expected to be dominated by the j^2 coupling of those, giving rise to excited states of 2^+, 4^+, 6^+ and 8^+. Indeed, this is what is observed experimentally (see Fig. 1). The lifetimes (thus transition probabilities) are known for all 4 excited states. However, the lifetime of the 2^+ state, as quoted at NNDC [NNDC], is almost an order of magnitude different from the prediction of the seniority scheme. A recent DSAM study [Koch17] reports a value that is a factor of 3 shorter, giving better agreement with the theoretical expectations but still several factors too long.

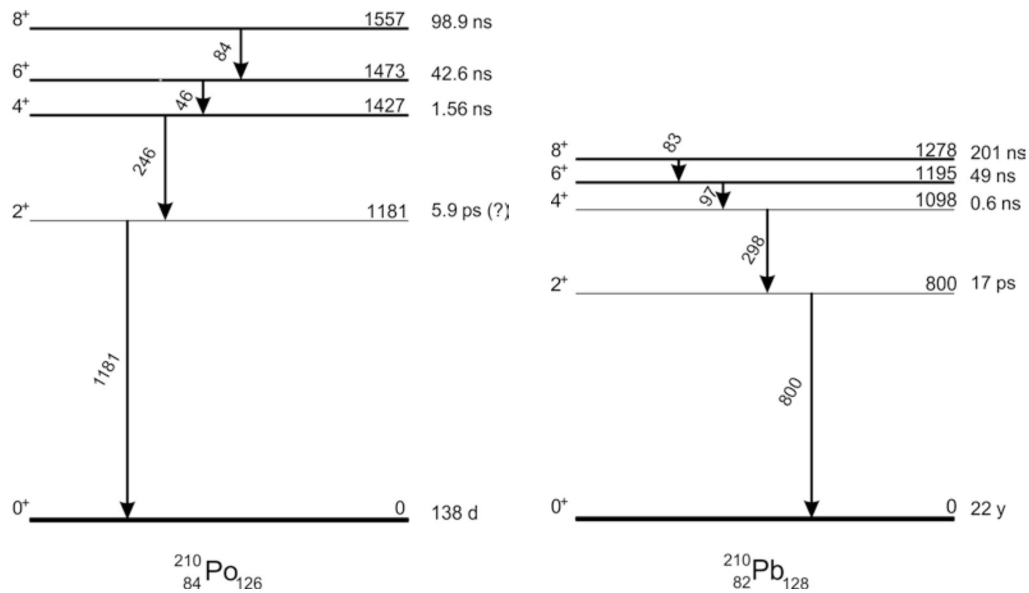

Fig. 1. Experimental level schemes (low-energy part) of ^{210}Po and ^{210}Pb.

The unusual behaviour of ^{210}Po is evident in Fig. 2, which compares B(E2) values in the nominal $\pi(j)^2$ multiplets in ^{50}Ti, ^{54}Fe, ^{134}Te (where $j=f_{7/2}$) and ^{90}Mo and ^{210}Po (where $j=g_{9/2}$) with $\pi(j)^2$ scaling expectations; see Ref. [Stuc13a]. The case of ^{210}Po stands out, even with the new data, as having a B(E2;2$\rightarrow$0) value well below expectations. It contrasts with cases like ^{54}Fe and ^{92}Mo, where there can be strong collective effects from core excitations, resulting in an increased B(E2). Therefore, a new, *more precise and independent value for the lifetime of the 2⁺ state in ²¹⁰Po is needed*.

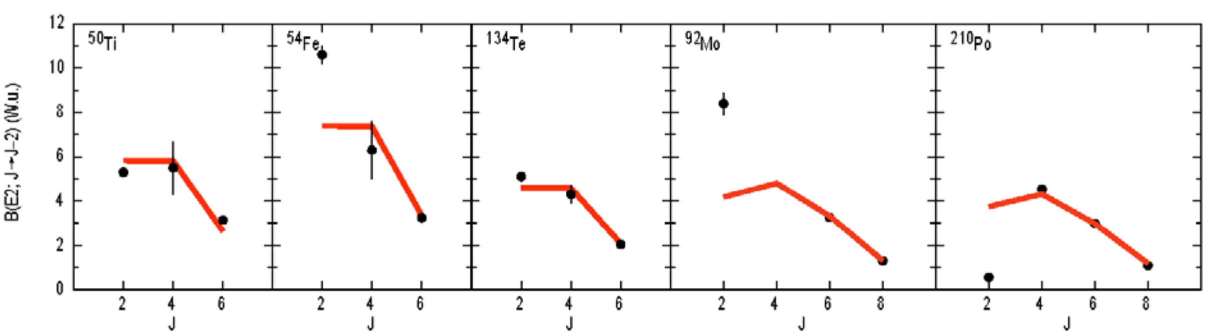

Fig. 2. B(E2) values for nominal two-proton states compared with $\pi(j)^2$ scaling [Stuc13a]. Data are from NNDC, except for ^{134}Te from [Stuc13].

The nuclear moments of the 6^+ and 8^+ states of ^{210}Po have been experimentally determined. Their gyromagnetic factors, $g(8^+) = 0.919(6)$ and $g(6^+) = 0.913(8)$, are identical within the experimental uncertainties. Therefore the determination of $g(2^+)$ and $g(4^+)$ could directly test the validity of the simple the seniority approach.

The ^{210}Pb case.

The low-energy structure of ^{210}Pb is expected to be determined by 2 extra neutrons, residing principally in the $\nu g_{9/2}$ orbital, above the ^{208}Pb core. This is indeed confirmed for the 6^+ and 8^+ states for which gyromagnetic factors are experimentally determined as $g(8^+) = -0.312(8)$ and $g(6^+) = -0.312(15)$. At present, there is no experimental information on the gyromagnetic factors of the 2^+ and 4^+ members of the $\nu(g_{9/2})^2$ multiplet. Our intention is to measure the g factors for both of these states. The relatively short lifetime of the 2^+ state ($t_{1/2} = 17(5)$ ps) will require the application of the Recoil In Vacuum (RIV) technique. The longer lifetime of the 4^+ state ($t_{1/2} = 0.6(1)$ ns) permits a time-integral measurement using the hyperfine field after an implantation in a ferromagnetic material. For example, the hyperfine field of lead in iron is known with high precision, B_{HF}(Pb(Fe)) = 26.2(5) T [Baco72], and the combination between the expected $g(2^+) \sim -0.3$ value and this field should allow for a considerable spin rotation of the spin ensemble (~300 mrad) within the lifetime of the state.

In a way similar to ^{210}Po, the lifetime of the 2^+ state in ^{210}Pb ($t_{1/2} = 17(5)$ ps), measured half a century ago using a (t,p) reaction, was obtained with relatively poor accuracy. Performing the RIV study with Coulomb excitation of the radioactive ion beam would considerably improve the precision of the electromagnetic moment values, enabling a meaningful comparison with theory.

Required experimental conditions and yields.

The ground-state lifetime of ^{210}Po ($t_{1/2} = 138$ d) will allow performing an experiment up to a few months after the production target has been irradiated by a proton beam, assuming the target is kept relatively "cold" during the irradiation in order to minimize any release of the products of interest. ^{210}Po can be produced using a UC_x target either directly or as a decay product from the alpha-decay chain starting from ^{226}U, ^{222}Th etc., since all of those isotopes have lifetimes much shorter than the lifetime of ^{210}Po. An additional contribution to the yield of ^{210}Po would come through the alpha chain starting from ^{226}Pa, which finishes with ^{210}Bi, and populates ^{210}Po via the beta decay of its ground state ($t_{1/2} = 5$ d). Therefore, it might be expected that the in-target production of ^{210}Po is quite abundant. At present, we are discussing an estimation of the ^{210}Po yield with the target-ion-source group at ISOLDE (Th. Storra et al.).

The ground-state lifetime of ^{210}Pb ($t_{1/2} = 22$ y) allows performing off-line experiments with it up to many years after the UC_x target has been irradiated. ^{210}Pb is produced through the alpha decay chain starting with ^{230}U and ^{226}Th. Uranium and thorium isotopes will not be released from the UC_x target independent of the target temperature. The lifetime of ^{230}U ($t_{1/2} = 21$ d) means that the decay products, some of which are of a volatile character, would practically not be populated until the end of the irradiation period (usually 2 to 3 weeks). This means that ^{210}Pb can be extracted from *any* of the "old" ISOLDE UC_x targets from the last few years (i.e. there is no need to irradiate new target in order to perform an experiment with ^{210}Pb).

In order to perform the g-factor measurements of ^{210}Po and ^{210}Pb, we would need a beam intensity of the order of 10^5 to 10^6 pps at energies of about 4 MeV/u for a running period of about one week (per isotope). We are planning to perform the experiments in a "stable-beam like mode" and stop the radioactive nuclei in a plunger stopper foil or thick target. In order to estimate the accumulated radioactivity of this approach, we have considered the lifetime of ^{210}Po and its decay mode: ~100% ground state to ground state decay plus a $1x10^{-5}$ branch to the first excited 2^+ state (E_x = 803 keV) in ^{206}Pb (stable). Because the ^{210}Po ions will be implanted deep into the stopper (target), the 5.3-MeV alpha particles will not escape out of the foil. The 10^{-5} branch of the 803-keV gamma ray will contribute about 1 Bq to the activity, assuming a ^{210}Po beam intensity of 10^6 pps over one week of experiment.

The beta-decay of ^{210}Pb (Q_β = 63.5 keV) to ^{210}Bi goes through a 16% ground state to ground state branch and an 84 % branch with an emission of a 46-keV gamma ray to the ground state. The beta decay of ^{210}Bi (Q_β = 1.16 MeV) to ^{210}Po goes through a 100 % ground state to ground state branch. Considering the 22 years' lifetime of ^{210}Pb and one week of beam intensity of 10^6 pps the activity of the ^{210}Pb stopper would be less than 1 kBq.

Based on the above-calculated activities, we conclude that no important radioprotection issues are expected within the here-proposed experimental program.

Need for stable-beam calibration measurements

For the Recoil in Vacuum measurements, it will be necessary to perform calibration measurements on a stable beam having a near-by atomic number (Z) and known excited-state g factor and lifetime. From the point of view of the field calibration, promising options are the first-excited state of ^{207}Pb (g = 0.320(12), $t_{1/2}$=130.5 ps), or the first-excited state of one of the stable platinum isotopes, e.g. ^{194}Pt (g = 0.300(13), $t_{1/2}$=41.9 ps). Beam intensities and running times similar to the above-mentioned RIB measurements would be necessary.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
MINIBALL + CD or MINIBALL + CD + Cologne Plunger or MINIBALL+T-REX	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + CD, MINIBALL + CD + Cologne Plunger or MINIBALL + T-REX] installation.

Additional hazards: no additional hazards.