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Addendum to Experiment IS407: Study of the Neutron Deficient Lead and Bismuth Isotopes by Simultaneous Atomic and Nuclear Spectroscopy

Andrei Andreyev[*], Nathalie Barré[‡], Anatolii Barzakh[#], Sarah Dean[†], Hilde De Witte[†], Dima Fedorov[#], Valentine Fedosseev[++], Serge Franchoo[+,++], Gerhard Huber[+], Mark Huyse[†], Ulli Köster[++], Peter Kunz[+], Jens Lassen[*], François Le Blanc[‡], Ivan Mukha[†], Rainer Neugart[+], Brigitte Roussière[‡], Jocelyne Sauvage[‡], Maxim Seliverstov[+], Piet Van Duppen[†], Yuri Volkov[#]

Spokesperson: Serge Franchoo
Contact person: Serge Franchoo

Abstract

We summarize the results of Experiment IS407 that were obtained on the ground-state properties and long-lived isomeric states in $^{183\text{-}190}$Pb. Having achieved improved stability, precision and reproducibility, we have extended the lead systematics below mid-shell at N=104. It appears that the ground states remain spherical and that mixing by the low-lying deformed 0^+ states in the even isotopes is limited. We propose to extend the measurements to ^{182}Pb, using a dedicated short UC target to achieve faster release of the activity, and devote more effort to ^{189}Pb with an improved tape station. We ask for 8 shifts of additional beamtime.

[†] Instituut voor Kern- en Stralingsfysica, University of Leuven, B-3001 Leuven, Belgium
[+] Institut für Physik, University of Mainz, D-55099 Mainz, Germany
[‡] Institut de Physique Nucléaire, F-91406 Orsay, France
[#] Petersburg Nuclear Physics Institute, RU-188350 Gatchina, Russia
[++] Cern, CH-1211 Geneva 23, Switzerland
[*] Triumf, V6T 2A3 Vancouver BC, Canada

1. Introduction

With the Resonance Ionisation Laser Ion Source at Isolde, isobaric beam contamination is greatly suppressed and previously unavailable, neutron-deficient lead isotopes far from stability have become available for study [Fed03, Kös03]. Moreover, due to the inherently large optical isotope shift of 2 GHz/amu in the lead region and a magnetic hyperfine splitting of the order of 10 GHz, it is feasible to use the laser ion source also for direct atomic spectroscopy. Indeed, the first step of the ionisation process is sensitive to the isotope shift and the hyperfine structure. Hence the change in the nuclear mean square charge radius and, for non-zero nuclear spin, the magnetic moments can be deduced. If one measures along extended isotopic chains, systematic trends in the nuclear structure can be extracted.

Of particular interest is the extension of our knowledge of charge radii and nuclear moments for the magic lead isotopes across mid-shell at N=104, subject of this experiment. Next to the evolution and the role of 0^+ intruder states and the phenomenon of shape coexistence [Hey83, Woo92, And00, Van03], it will allow to directly test the predictions of nuclear models such as the Extended Thomas Fermi Strutinski Integral [Buc94, Gor01], the Finite-Range Droplet Model [Buc94, Möl95] or the Relativistic Mean Field approach [Lal99].

2. Status report

During the summer of 2003, experiment IS407 has used 13 of its 15 shifts. At two separate experimental stations, optimized for the detection of alpha respectively gamma radiation, ground state properties and long-lived isomeric states in the neutron-deficient lead isotopes were measured.

In order to certify the validity of the in-source laser spectroscopy method, we measured the known isotope shift of ^{190}Pb. Our result of $\delta\langle r^2\rangle^{208,190}$ = 0,839(10) fm^2, deduced from the measurement of the isotope shift in the 283 nm transition $6p^2\ (1/2, 1/2)_0 \rightarrow 6p7s\ (1/2, 1/2)^0{}_1$, nicely agrees with the earlier result at GSI of $\delta\langle r^2\rangle^{208,190}$ = 0,840(10) fm^2, obtained from the isotope shift in the 723 nm transition $6p^2\ {}^1D_2 \rightarrow 6p7s\ {}^3P_1$ [Dut91]. Next the radii were

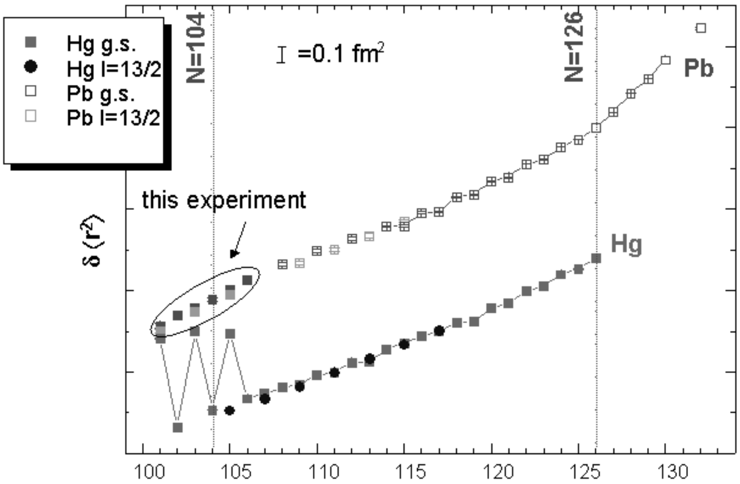

Fig. 1: Variation of the mean square charge radii for mercury and lead. Taken from [Ulm86, Din87, Dut91, Ott88].

measured for the even isotopes ^{184,186,188}Pb. For the odd isotopes ^{183,185,187}Pb, the radii were determined for both the $13/2^+$ and $3/2^-$ states and the magnetic moments derived with higher precision than during the preliminary measurements under IS387 [And02]. These results are shown in Fig. 1 and Fig. 2.

Every two or three measurement points during a given scan were alternated with a reference measurement at a fixed frequency within the same isotope. In this way, fluctuations in the laser power could be corrected for. Wavelength drifts were avoided by means of continuous software monitoring of the laser wavelength with realtime adjustment if necessary. In addition, the isotope shifts of the stable isotopes ^{206,207,208}Pb were measured regularly throughout the beamtime to monitor the long-term stability of the set-up and fix the profiles needed for fitting the obtained data.

Thanks to the improved stability, precision and reproducibility that we achieved for the in-source laser spectroscopy technique, we have been able to extend the lead systematics below mid-shell at N=104. It appears that the ground states of the lead isotopes remain spherical. This should be seen in a context where several 0^+ states with different deformations have been observed throughout the neutron-deficient even lead isotopes and triple shape coexistence at low excitation energy has been ascertained at midshell for ^{186}Pb [And00]. Our measurements firmly establish that mixing of the deformed 0^+ states in the ground state is limited.

The excited 0^+ intruder states that are, in a shell-model picture, described as 2 particle-2 hole and 4 particle-4 hole excitations through the Z=82 closed shell are expected to rise again in energy once the midshell at N=104 has been passed. Recent measurements have shown that the rise of the 0^+_2 state is less than expected, which may be due to the specific nature of the underlying structure [Van03]. It is therefore significant to determine how this trend evolves for ^{182}Pb, the lightest isotope that is still within reach of our technique.

3. Proposed addendum

We have measured the hyperfine structure of ^{183}Pb with a count rate of 10 atoms/s at resonance. Extrapolating from Fig. 3, we expect a yield that is about 10 times lower for ^{182}Pb. Because of the 0^+ nuclear spin, the hyperfine structure only has one peak instead of the three

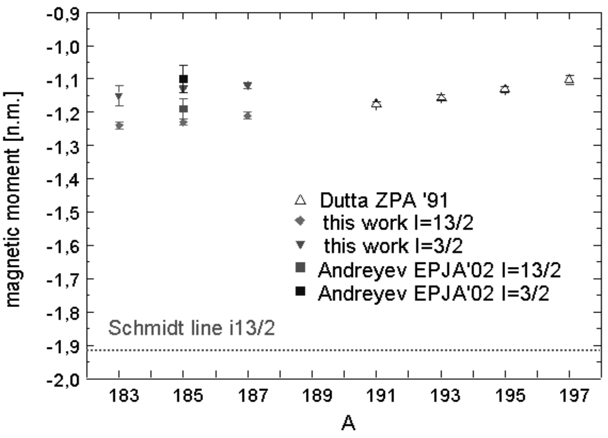

Fig. 2: Magnetic moments of neutron-deficient lead isotopes. Taken from [Dut91], [And02] and this work.

peaks in ^{183}Pb, somehow compensating the lower yield. For ^{184}Pb, where the hyperfine structure comprises only one peak, the count rate was 70 atoms/s at resonance. Extrapolation of this value results in an expected yield for ^{182}Pb of 0.7 atoms/s. It would therefore be reasonable to put forward a yield of 1 atom/s for ^{182}Pb.

However, the foregoing assumption does not take into account the much shorter half-life of 55^{+40}_{-35} ms for ^{182}Pb [Tot87] with respect to 535(30) ms for ^{183g}Pb, 415(20) ms for ^{183m}Pb [Jen02] and 550(60) ms for ^{184}Pb [Sch80]. Fast release of the activity becomes particularly important, which can be achieved with a shorter target heated to higher temperatures. We therefore request a dedicated 2 cm short UC_x/graphite target for this measurement with about 5 g/cm^2 ^{238}U.

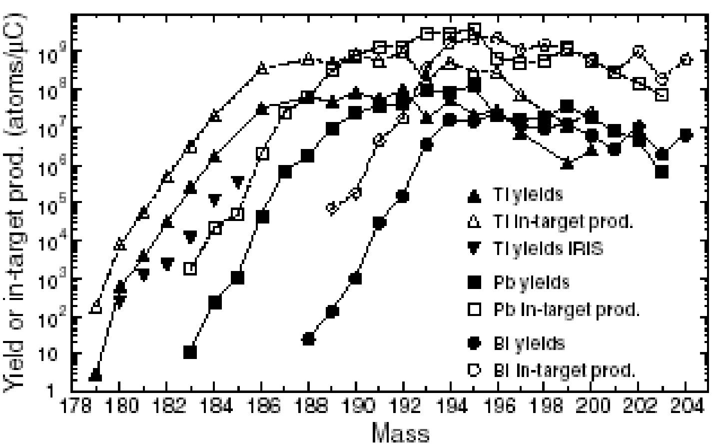

Fig. 3: Ion yields and in-target production rates of neutron-deficient thallium, lead and bismuth isotopes, taken from [Kös03].

We also would like to measure ^{189}Pb, which was singled out as one of the principal goals of experiment IS407 because of the search for an isomeric state in this isotope that would allow to determine the masses of the α-decay chain up to ^{201}Ra. In the original proposal, we wrote: <<The existence of sometimes two or three "long-lived" isomers makes nuclear spectroscopy around Z~82 and N~104 very challenging. It is obvious that the availability of isomerically pure beams is a real breakthrough for nuclear spectroscopy. This we will discuss with the example of ^{189}Pb where only one isomer (with unknown spin) is presently known, while in ^{185}Pb and $^{191-197}$Pb two isomers ($13/2^+$ and $3/2^-$) are known. Here searching for the second isomeric state, is of major interest. Also in ^{189}Pb, which decays by α and β^+/EC respectively, one would expect two isomers ($13/2^+$ and $3/2^-$). By observing the second isomer and establishing the spin for both, the masses and relative positions (via known α decays of parents) of the known $3/2^-$ and $13/2^+$ isomers in the long decay chains Ra-Rn-Po-Pb-Hg can be determined. Recently the masses of the 13/2+ and 3/2- states in ^{185}Hg were accurately measured at Isoltrap [Sch01]. If the α decay of the second isomer in ^{189}Pb could be measured together with the spins of both isomers, then immediately all masses of the 13/2+ and 3/2- isomers in the chain, up to ^{201}Ra, would be determined. We note that ^{201}Ra is the most neutron deficient Ra isotope known and so exotic that a direct mass measurement would be extremely difficult. The proposed studies would complement past and present work on the problem of multiple spin-isomers in neutron deficient isotopes around Z=82 [Bou82, Mac84, Kil87, Sch01].>>

An attempt was made to measure ^{189}Pb during our 2003 beamtime at the γ detection station. We were able to identify previously unknown γ rays that belong to the decay of ^{189}Pb, a necessary condition before scanning could start. During the subsequent scans, unfortunately, friction of the collection tape during its movement induced uncertainty in the position of the sample on the tape. This affected the gamma detection efficiency, finally questioning the reliability of the recorded spectra for this isotope. The most obvious solution that we envisage is the installation of a tape station from our own collaboration (Leuven or Orsay) replacing the existing Isolde station.

We point out that the lower yield of about a factor 10 for this isotope from the proposed short target does not matter much. Indeed, the yields beyond mass 187 are so high that during our experiment last year we were working with a reduced beamgate, which now we can simply open longer.

4. Beam request

The accumulated measurements for ^{184}Pb at the α station last summer took 5 h, those for ^{183}Pb 13 h. We therefore request 4 shifts of beamtime for ^{182}Pb. While the α scans of ^{189}Pb can be done rather quickly, the low α branching of 0.4% being compensated by the high production yield, the measurements at the γ station need higher statistics due to the distribution of the activity into several lines. We thus ask for 4 shifts for ^{189}Pb.

As became clear during our measurements of last year, scans of the stable isotopes are indispensable to achieve reliable results. We hence would need 2 more shifts.

Taking into account that we still have 2 shifts left, we request a total of 8 additional shifts of beamtime. We repeat that the measurements would be done with a dedicated 2 cm short UC_x/graphite target with about 5 g/cm^2 ^{238}U and that we need two separate beamlines for the α and γ detection set-ups, mounted around a windmill system respectively collection tape. The accompanying table summarizes our request.

beam	yield	target	ion source	shifts
stable lead	–	–	–	2 (left from 2003)
^{182}Pb	1 at/uC	2 cm UC	Rilis	4 (requested here)
^{189}Pb	10^7 at/uC	2 cm UC	Rilis	4 (requested here)

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