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Study of the neutron deficient $^{182–190}$Pb isotopes by simultaneous atomic- and nuclear-spectroscopy

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Abstract Mean-square charge radii and magnetic moments have been measured for the neutron deficient lead isotopes, $^{182–190}$Pb. The measurement was performed at the ISOLDE online mass separator, using the in-source resonance ionization spectroscopy technique.

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The wavelength of the first excitation step for the resonance ionization laser ion source (RILIS) was scanned over the resonance(s) whilst the α- and γ-ray spectra from the decay of the Pb isotopes were recorded as a function of the wavelength. The isotope shift and, in the case of odd-A isotopes, the hyperfine splitting were deduced. The rms-charge radii of the very neutron deficient Pb isotopes follow the smooth trend of the heavier isotopes. This finding indicates a spherical shape for the lead ground states at the neutron mid-shell (N=104), where the excitation energy of the oblate 0^+ state in the even isotopes reaches its minimum.

Key words laser spectroscopy · nuclear structure · resonance ionization · laser ion source · isotope shift · hyperfine structure · nuclear charge radius · nuclear magnetic moment

1 Introduction

In the region of neutron deficient lead isotopes, intruder states and shape coexistence phenomena have been widely investigated around neutron mid-shell at N=104. In ^{186}Pb at N=104, it has been found that the three lowest lying states have 0^+ as spin and parity values [1]. They have been associated with different shapes in the nucleus: spherical and deformed (oblate and prolate). In a shell model picture these states can be described as 0p–0h, 2p–2h and 4p–4h states, respectively [2]. Significant mixing of the deformed states into the spherical ground state would result in an increased nuclear charge radius. It is therefore of great interest to extend the study of nuclear radii in the lead chain to the very neutron deficient isotopes around neutron mid-shell.

2 Experimental method and set-up

The study of isotopes lying far from β-stability is dominated by the need for an increase in experimental sensitivity. For example, at ISOLDE the Pb ion yield drops by six orders of magnitude from ^{187}Pb to ^{183}Pb [3]. For this reason we used the in-source photoionization spectroscopy technique, which is one of the most sensitive laser spectroscopy methods. The use of the RILIS (Resonant Ionization Laser Ion Source) for atomic spectroscopy studies of exotic nuclei was pioneered at the Leningrad/Petersburg Nuclear Physics Institute (Gatchina, Russia), where it was applied to short lived $^{154–156}$Yb isotopes [4, 5]. At ISOLDE studies of short-lived Be, Cu, Pb isotopes by in-source RILIS laser spectroscopy have been also implemented (see reviews [6, 7] and references therein). These experiments have shown the high sensitivity of the method. Following the upgrade of the laser system a new series of such experiments have been performed at the ISOLDE facility at CERN.

The Pb nuclei were produced in spallation reactions induced by a 1.4 GeV proton beam impinging on a UC_x target (50 g/cm^2 of ^{238}U and ≈10 g/cm^2 of carbon) connected to the ISOLDE mass separator. The spallation products diffuse out of the high temperature target (T≈2,050°C) and effuse as neutral atoms into the laser ion source cavity. The cavity is a niobium tube of 30 mm length and 3 mm internal diameter and is heated to approximately 2,100°C. The laser beams were focused inside the cavity and the ionization of Pb isotopes was performed with a three-step ionization scheme (Fig. 1). The same scheme was used for earlier Pb experiments [8]. Laser light for the resonant excitation of the first two atomic

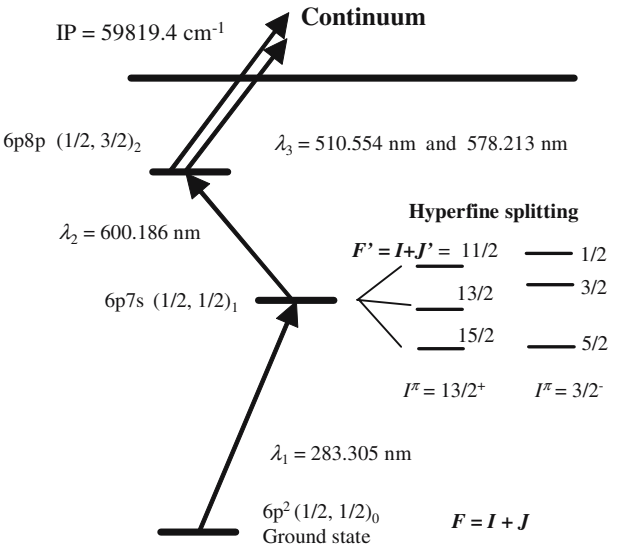

Fig. 1 The three-step laser ionisation scheme for Pb isotopes, applied in this work. Shown are electronic configurations for the levels involved and laser wavelengths for each step. On the right a schematic illustration of the hyperfine structure components in case of the $13/2^+$ and $3/2^-$ isomeric states in odd Pb isotopes is presented. More details are given in the text

transitions (λ_1=283.305 nm and λ_2=600.186 nm) was provided by two tunable pulsed dye lasers. The ultraviolet radiation (λ_1) was obtained by doubling of the fundamental dye laser radiation frequency using a non-linear BBO crystal. For the pumping of the dye lasers and the excitation of the final ionising transition (the third step) into the continuum, copper vapour lasers, operating at a pulse repetition rate of 11 kHz, were used. An ionisation efficiency of about 3% was measured in off-line tests with stable lead isotopes [9].

During the online experiment with radioactive nuclei the laser power of the first excitation step was reduced to avoid additional broadening of the optical line, so we estimate the on-line efficiency for Pb isotopes to be ≈ 1%. The laser ion source is not only a very effective in its normal use as an element-selective tool for producing intense ion beams, but it can be used as a very powerful atomic-spectroscopy tool due to the resonance character of the photoionization.

In contrast to other laser spectroscopic techniques, the scanning procedure is applied directly within the ion source. For atomic spectroscopy measurements, a narrow bandwidth laser (line width 1.2 GHz) was used for the first excitation step. By scanning its frequency over the resonance, together with simultaneous counting of the mass-separated photo-ions, the isotope shifts and hyperfine structure of the atomic spectral lines could be measured. From these data the change in nuclear mean square charge radii and the static nuclear moments (magnetic moments and spectroscopic quadrupole moments) have been determined.

Due to the low production yield for the very neutron-deficient lead isotopes, the direct ion counting was prohibited by a severe isobaric contamination of the ion beam. An isotope and isomer selective registration of the photo-ions was required and could be achieved by the synchronous measurement the α- and γ-ray spectra characteristic for the decay of the Pb isotopes and isomers in question. For this work, the radioactive Pb isotopes were either detected with a α-spectroscopy setup composed of a wind mill system and a passivated implanted planar silicon detector and a γ- or α-γ spectroscopy setup comprising a tape transport system, a planar Ge(HP) X-ray detector, two 70% efficiency coaxial Ge(HP) detectors and an silicon α-detector.

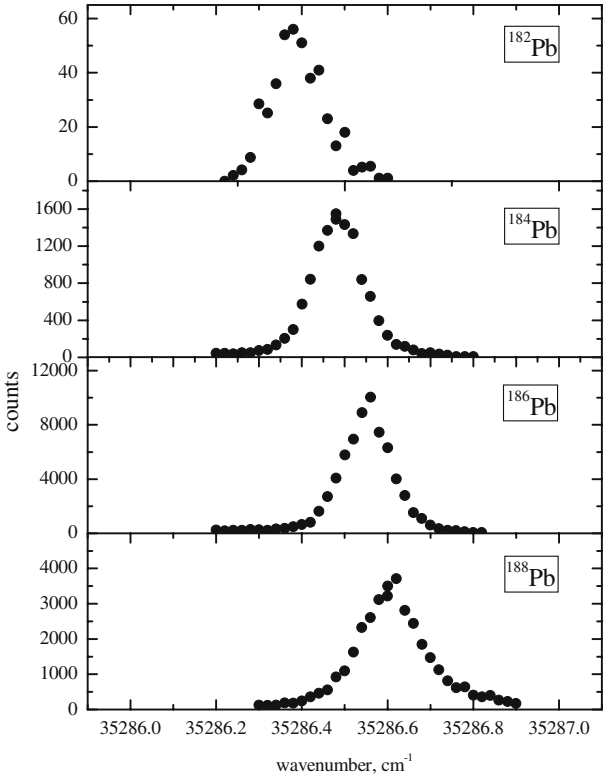

Fig. 2 Typical examples of the collected spectra (α-counts versus laser wavenumber) of the even-mass isotopes of Pb

During each laser scan an α- or γ-ray spectrum was recorded. In the data analysis the characteristic lines were integrated for every laser frequency setting. The optical photo-ionization spectra (number of photo-ions versus laser frequency) were obtained. Typical examples of the collected optical spectra are shown in Figs. 2 and 3. Isotopes $^{182–188}$Pb were studied with the α- detection, ^{189}Pb with the γ-ray and α-detection and ^{190}Pb with the γ-ray detection.

A multiparameter servo-control for the laser frequency scanning was implemented for this experiment. The new control system incorporates controls for the narrowband laser etalon and diffraction grating positions, a frequency read-out with feed back control and also communication to the data acquisition system using the RS232 or TCP/IP protocols. The long-term stability of the laser control system enabled laser scans in excess of two hours to be performed. This is essential for the measurement of the radioactive isotopes at low production yield.

Throughout the experimental period, measurements of radioactive Pb isotopes at the scanning frequencies were, at regular time intervals, combined with measurements at a fixed reference frequency in order to monitor the stability of the experimental system. For an absolute wavelength scale calibration, spectra of stable Pb isotopes were recorded regularly. For these isotopes, the photo-ion current was directly measured with a Faraday cup.

For heavy elements such as Pb, with large isotope shift and hyperfine structures, the Doppler limited RILIS spectroscopy is particularly advantageous. Using an optical setup with a high long term stability and isobaric-background free ion detection, an extremely high sensitivity can be obtained and is essential in such a study.

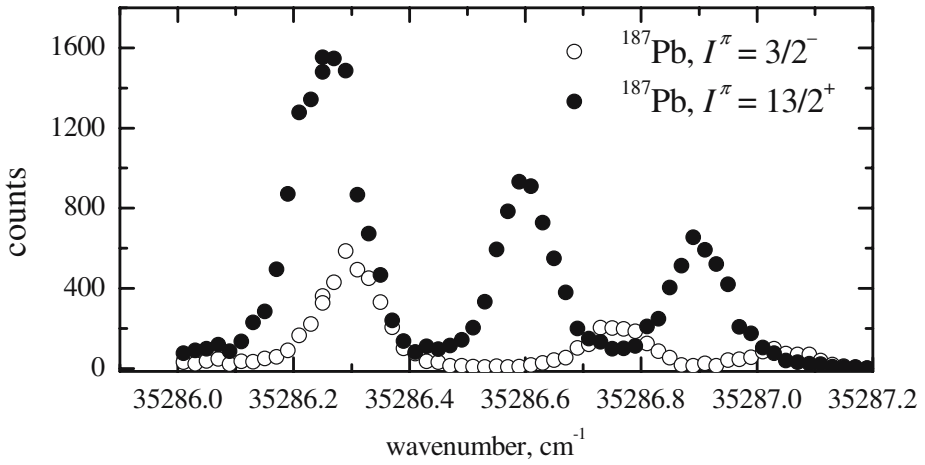

Fig. 3 Spectra for the high spin isomer ($I^{\pi} = 13/2^{+}$, $E_{\alpha} = 5.993$ MeV) and the low spin isomer ($I^{\pi} = 3/2^{-}$, $E_{\alpha} = 6.194$ MeV) of ^{187}Pb collected in a single scan

3 Results and discussion

The isotopic change of the charge radius $\delta\langle r^2\rangle_{A,A'}$ was evaluated through the standard formula:

$$\delta\nu_{A,A'} = F \cdot \lambda_{A,A'} + M\frac{A' - A}{A \cdot A'}, \tag{1}$$

where $\delta\nu_{A,A'}$ is the isotope shift between isotopes with mass numbers A and A', F is the electronic factor, M is the mass shift constant, $\lambda_{A,A'}$ is the nuclear parameter [10]:

$$\lambda = \delta\langle r^2\rangle + C_2\delta\langle r^4\rangle + C_3\delta\langle r^6\rangle + \ldots = C\delta\langle r^2\rangle. \tag{2}$$

The following values of constants were used [11]:
F=20.26 (0.18) GHz fm^{-2},
M=0.19(0.25) × N (here N is the normal mass shift constant),
C=0.93.

The magnetic dipole moments were evaluated from the scaling relations, based on the known magnetic moment μ_0, magnetic coupling constant A_0 and nuclear spin I_0 of a stable ^{207}Pb isotope (μ_0=0.592583(9), I_0=1/2, A_0=8,807.2(3.0)) [11, 12]):

$$\mu = \frac{A \cdot I \cdot \mu_0}{A_0 \cdot I_0}. \tag{3}$$

This expression disregards any hyperfine anomaly, which was found to be less than ≈10^{-3} for $^{190-197}$Pb isotopes studied in [13].

In Fig. 4 our data are shown along with the data for the neighboring Hg (Z=80) and Pt (Z=78) chains [14–17]. The observed slope of the charge radii as a function of the mass follows the smooth trend of the heavier isotopes down to and even below the neutron mid-shell, where the excitation energy of the oblate 0^+ state in the even isotopes reaches its minimum. This finding indicates a spherical shape for the Pb ground states. The charge radii follow rather closely the droplet model prediction. This is in contrast with the Hg isotopes

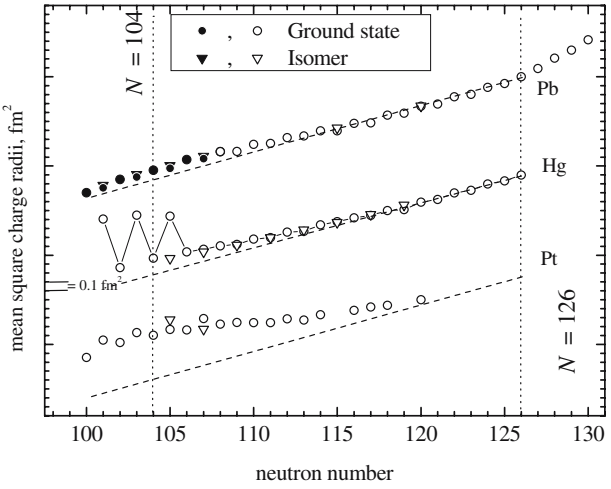

Fig. 4 Change of the mean square charge radii for Pb, Hg and Pt isotopes, compared to the predictions of the spherical droplet model. The *experimental error bars* are smaller than the symbol size. Our data are shown as *filled symbols*, the literature data are shown as *open symbols*. The distance between the different chains is chosen arbitrarily for ease of display. Each minor division on the vertical scale corresponds to 0.1 fm^2

where a large odd–even staggering and shape isomerism set in at N=105. In the Pt series an overall deviation from the linear trend for heavier isotopes indicates the influence of deformation near the mid-shell. Such an effect is absent or at least considerably smaller in the Pb isotope chain, confirming their spherical nature.

The magnetic moments of the high spin isomers ($I^{\pi} = 13/2^{+}$) also follow a smooth trend from A=197 to A=183 with a slight down-sloping towards the Schmidt line.

4 Conclusions and outlook

Substantial improvements in the frequency stabilization for the RILIS laser system have been achieved. With its improved precision and reliability, the in-source laser spectroscopy technique at ISOLDE has been combined with synchronous nuclear decay spectroscopy. The high sensitivity and isomer selectivity enabled measurement of very short-lived neutron deficient Pb isotopes down to ^{183}Pb ($T_{1/2}$=300 ms) and ^{182}Pb ($T_{1/2}$=55 ms) which are produced at very low yield.

The laser spectroscopy investigation of the Pb isotope chain has been extended beyond the neutron mid-shell at N=104. The behavior of charge radii indicates that in this region the ground states of the Pb isotopes remain essentially spherical. Beyond mean-field calculations are underway to compare directly with the experimental data reported in this paper [18, 19].

The in-source laser resonance ionization spectroscopy technique has become a very efficient tool for atomic spectroscopy of rare isotopes approaching the driplines.

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