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Precise determination of the neutron scattering length of lead isotopes ^{204}Pb, ^{207}Pb and ^{208}Pb by neutron interferometry

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Abstract. The neutron scattering length of lead isotopes ^{204}Pb, ^{207}Pb and^{208}Pb are determined by a set of neutron interferometry experiments. The obtained values $b_{(208)} = 9.494(30)$ fm, $b_{(207)} = 9.286(16)$ fm, $b_{(204)} = 10.893(78)$ fm have much higher accuracy then current table data. Together with the precise value of b for natural lead, these results represent a complete set of data and allow one to calculate $b_{(206)} = 9.221(69)$ fm, which is in the very good agreement with the present day experimental value.

1 Introduction

For more than a decade isotopes of lead have been a subject of great interest for nuclear physics. These have been found to be important both for studies of the neutron nucleus interaction and for the determination of the electrical structure of the neutron. For example, the effect of parity non-conserving rotation of the neutron spin in the natural lead observed in 1982 [1] could not be explained by the compound-nuclear model of mixing resonance levels with opposite parities for the known energy levels in lead isotopes. A possible explanation using the valence model has also to be rejected of the lack of an observed effect in experiments with ^{207}Pb [2]. At present, efforts are focused on the isotope ^{204}Pb, which can provide such an effect because of the existence of a still unknown negative low-energy resonance level [2].

Another example is the study of the electromagnetic structure of the neutron, i.e. the determination of such parameters as the mean square electric charge radius and the polarizability of the neutron, by investigation of the neutron interaction with atoms of heavy elements [3–7]. It is commonly accepted at present that the most suitable isotope for this purpose is ^{208}Pb, because its nucleus has only two resonance levels that significantly contribute to the total neutron cross section [8]. This fact allows a correct evaluation of the contribution of the resonance scattering to the total cross section $\sigma_{tot}(E)$. However, at small energies ($E \sim 0$) the total cross section is strongly influenced by interference effects (connected with the aggregate state of the sample), which cannot be calculated with sufficient precision [9]. However, $\sigma_{tot}(0)$ can be determined from the neutron scattering length b measured by thermal neutrons ($E \sim 10^{-3}$ eV).

To achieve sufficient (about 2%) accuracy in the determination of the neutron-electron interaction amplitude, which in turn determines the mean square electric charge radius of the neutron, one has to know b of ^{208}Pb with very high precision, of about 0.01% [10]. Determination of the neutron scattering length at this level of accuracy is achievable by the recently developed neutron interferometry technique [11, 12]. However, this accuracy is limited by the isotopic purity of the particular sample used in the measurement. In spite of a high degree of the enrichment of lead samples used in experiments they nevertheless contain an admixture of isotopes ^{207}Pb, ^{206}Pb and ^{204}Pb. Therefore, the measured value of the neutron scattering length $b_{meas}^{(208)}$ must be corrected for the isotopic composition of the sample:

$$b_{208} = \frac{1}{c_{208}} \cdot \left[b_{meas}^{(208)} - b_{207} \cdot c_{207} - b_{206} \cdot c_{206} - b_{204} \cdot c_{204} \right] \quad (1)$$

where c_i is isotopic concentrations of i-th isotopes with the neutron scattering length b_i ($i = 204$, 206, 207, 208). Therefore, to achieve an accuracy of the determination of b_{208} of about 0.01%, uncertainties of terms corresponding to the isotopic corrections in (1) should also be within 0.01%.

Values of b for the lead isotopes obtained by Christiansen filter method [13] are in good agreement with the-

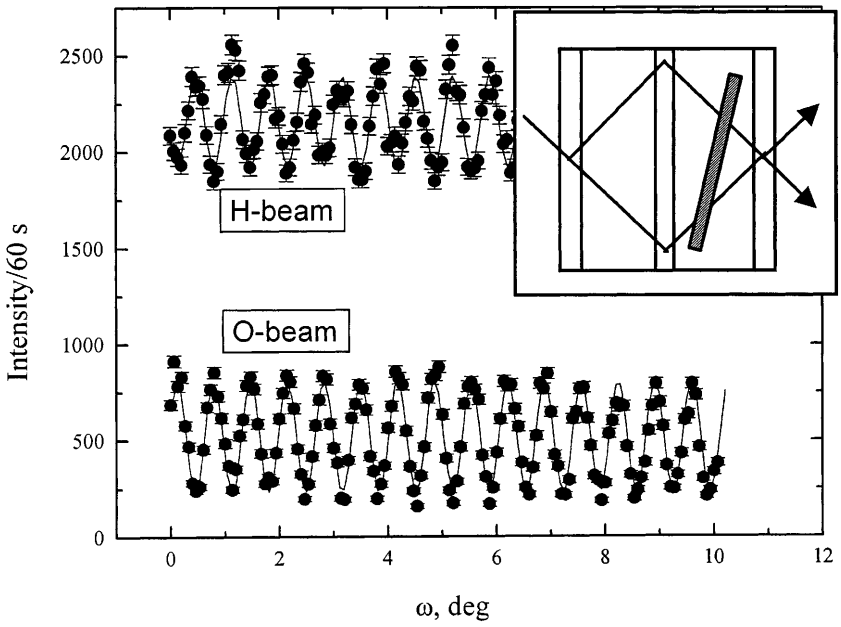

Fig. 1. Interference curves taken for the rotating sample of ^{207}Pb that overlaps both of the interferometer's beams. Solid lines represent best fit by mean least square procedure. Inset shows the experimental arrangement

oretical expectations, but do not have sufficient accuracy for our purpose. It was the aim of this research to improve values of the neutron scattering length for all lead isotopes. We used a neutron interferometry method and a number of highly enriched samples for lead isotopes 208, 207 and 204. Together with precise knowledge of the b of the natural Pb [14] it provides us with a complete set of data that allows an accurate determination of neutron scattering length of all lead isotopes.

2 Experimental procedure

We use a traditional procedure for neutron interferometry experiments, whereby the rotating sample overlaps both of the interferometer's coherent beams (see inset in Fig. 1). The intensity distribution in this case is

$$I = I_0 \cdot \{1 + V \cdot \cos(N \cdot b \cdot \lambda \cdot t_{eff} + \varphi_0)\} \qquad (2)$$

where V is the interference pattern visibility, I_0 is the incident beam intensity and φ_0 is an initial phase. The argument of the cosine function in (2) is the phase introduced by the sample with the effective thickness t_{eff}, which in our case is

$$t_{eff} = t_0 \cdot \left\{ \frac{1}{\cos(\vartheta_B - \omega)} - \frac{1}{\cos(\vartheta_B + \omega)} \right\} \qquad (3)$$

where ω is the angle of the sample rotation and ϑ_B is the Bragg angle for the neutrons with wavelength λ. Thus, fitting the experimental data to the function (2) with known parameters t_0, λ and N (the atomic density) it was possible to obtain the value of b.

In order to determine the neutron wavelength l we use as our sample plane parallel plates made from a perfect crystal of silicon. The thickness of the plates is either 9.987(1) mm or 5.239(1) mm. Then using the same formula (1) and the well-known parameters of silicon $N = 4.9943 \cdot 10^{22}\,\mathrm{cm}^{-3}$, $b = 4.149(1)$ fm, we determine the wavelength value within an accuracy of 10^{-3}. The thermal drift of the instrument causes changes of the angle of incidence of the neutron beam on the interferometer and, therefore, changes in λ. To correct for this drifts, we alternated measurements of the interference pattern for the Si plate and for the lead sample in turn (an experimental cycle would be Si – Pb – Si). During data analysis we took the average value of λ obtained from the two surrounding measurements.

The total time of data collection for each sample (Si or Pb) was about 20 hours.

2.1 Samples

Samples enriched in isotopes ^{208}Pb, ^{207}Pb and ^{204}Pb are prepared from lead isotope mixtures by vacuum melting and pressing. This procedure allowed us to obtain plane parallel samples, the density of those was determined by the picnometry method and agreed with the theoretically calculated bulk density to within the experimental uncertainties error has coincided. Sample thickness are 3.298(5) mm, 6.660(5) and 4.877(5) mm for samples of ^{204}Pb, ^{207}Pb and ^{208}Pb, respectively. The isotopic abundances of the samples used in this research was determined using mass-spectroscopy during the sample preparations and is presented in Table 1.

2.2 Instruments

The present measurements of the coherent scattering length were performed by neutron interferometers installed at the reactor BER-II of the Berlin Neutron Scattering Center (Hahn-Meitner Institute, Berlin, Germany)

Table 1. Experimental results for the samples enriched in isotopes ^{208}Pb [17], ^{207}Pb and ^{204}Pb (lines 1 to 3) and isotopic abundance of these samples (line 4)

j		c_{208}	c_{207}	c_{206}	c_{204}	$b^{(i)}_{meas}$, fm
1	Sample of ^{208}Pb	0.973	0.0206	0.0064	0.000	9.488(29)
2	Sample of ^{207}Pb	0.0908	0.883	0.0261	0.0001	9.303(14)
3	Sample of ^{204}Pb	0.196	0.132	0.306	0.366	9.895(23)
4	Natural Pb	0.524	0.221	0.241	0.014	9.4017(20)

Table 2. The coherent scattering lengths of lead isotopes obtained in present research in comparison with results obtained by Christiansen filter method [5]

Lead isotope	Results of present experiement	Results obtained by Christiansen filter method [5]
^{208}Pb	9.494(30) fm	9.500(60) fm
^{207}Pb	9.286(16) fm	9.280(40) fm
^{206}Pb	9.221(69) fm	9.220(50) fm
^{204}Pb	10.893(78) fm	10.60(2.00) fm

[16] and the reactor LWR-15 of the Nuclear Physics Institute (Rez near Prague, Czech Republic) [15]. These interferometers are operating at different wavelengths, $\lambda = 2$ Å and $\lambda = 1$ Å, respectively. This approach allows us to avoid possible systematic errors, connected with intrinsic features of one of the instruments.

3 Results and discussions

Experimental results are presented in Table 1, where lines 1 to 3 contains results obtained for the samples enriched in isotopes ^{208}Pb [17], ^{207}Pb and ^{204}Pb and the isotopic abundance of these samples. The line 4 contains the high accuracy value $b^{(nat)}_{meas}$ for the natural Pb [14]. All together they represent a closed system of four linear equations $\sum_i c_i \cdot b_i = b^{(i)}_{meas}$:

$$\begin{cases} 0.973 \cdot b^{(208)} + 0.0206 \cdot b^{(207)} + 0.0064 \cdot b^{(206)} \\ \quad +0.000 \cdot b^{(204)} = 9.488 \\ 0.0908 \cdot b^{(208)} + 0.883 \cdot b^{(207)} + 0.0261 \cdot b^{(206)} \\ \quad +0.0001 \cdot b^{(204)} = 9.303 \\ 0.196 \cdot b^{(208)} + 0.132 \cdot b^{(207)} + 0.306 \cdot b^{(206)} \\ \quad +0.366 \cdot b^{(204)} = 9.895 \\ 0.524 \cdot b^{(208)} + 0.221 \cdot b^{(207)} + 0.241 \cdot b^{(206)} \\ \quad +0.014 \cdot b^{(204)} = 9.4017 \end{cases} \quad (4)$$

An analytical solution of the system of (4), $b_i = \sum_i a_i \cdot b^{(i)}_{meas}$, gives us the relation between the coherent scattering length b_i of the pure lead isotopes and the measured values of the coherent scattering length $b^{(i)}_{meas}$ of the samples enriched in i-th isotope.

In order to evaluate uncertainties Δb_i of the values b_i obtained by such way we use the fact that experimental errors for different isotopes are independent, because the measurements have been done by different instruments and at different times. Therefore, the error bars can be calculated by the conventional method of the propagation of errors $\Delta b_i = \sqrt{\sum_i [a_i \cdot b^{(i)}_{meas}]^2}$. Final results are presented in Table 2. By comparing with results obtained by the Christiansen filter method [13] presented in the same table for convinience, one can conclude that both results are in very good agreement, however interferometric measurements resulted to the at least twice the accuracy for the isotopes ^{208}Pb, ^{207}Pb. As to the isotope ^{204}Pb, the overall accuracy is increased by a factor of 25.

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