

Experimental report

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Proposal: 3-16-11

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Title: Coherent scattering length measurements of lithium isotopes by neutron interferometry

Research area: Physics

This proposal is a new proposal

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Samples: Aqueous solutions of ${}^6\text{Li}$ ${}^7\text{Li}$ and natLi

Instrument	Requested days	Allocated days	From	To
S18	10	10	30/05/2023	13/06/2023

Abstract:

Experimental report on experiment 3-16-11

Coherent scattering length measurements of lithium isotopes by neutron interferometry

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Objectives

The bound coherent scattering length $b_c(j)$ of a nucleus j is an important quantity in neutron sciences, which is determined experimentally. The ILL PhD project titled “*Determination of accurate bound coherent neutron scattering lengths, b_c , of lanthanide, cadmium, thallium and lithium isotopes*” aims for a systematic investigation of b_c values lacking accuracy. Neutron powder (NPD) diffraction is well suited and reaches 0.5 to 1.0 % precision (experiments 1-10-46, 1-10-48 and 1-10-50). This experiment aims at applying neutron interferometry known to reach precisions of 10^{-4} [1] to the isotopes of lithium, which have already been investigated with NPD.

Experimental Details

The measurements were carried out on liquid samples in silica glass *Hellma* cells of $D = 1.00(1)$ mm as described by Fischer et al. [2] for a previous interferometry experiment, using the differential experimental setup shown in figure 1:

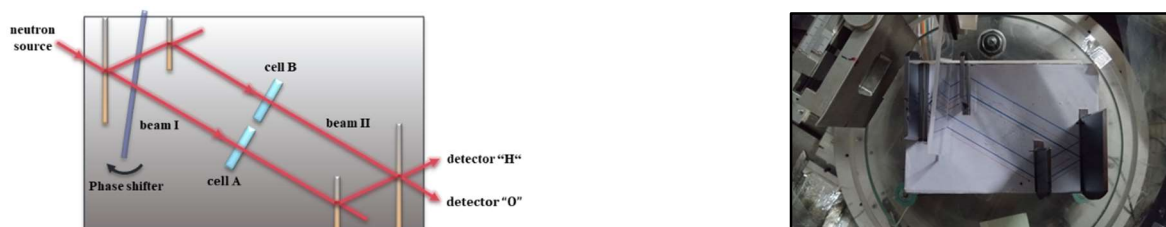


Figure 1: Experimental setup with beam paths for the conducted interferometry experiment. Left side schematic and right-side photograph

Samples were prepared by dissolving ${}^{6/7}\text{natLi}_2\text{SO}_4 \cdot \text{H}_2\text{O}$ in pure water to obtain three Li solutions with concentrations of $c(\text{Li}^+) = 5.00(2)$ mol/l (5M) and three of $2.50(1)$ mol/l (2.5M). Six acquisition series were made for each solution concentration, where Li_2SO_4 solutions were measured with cell A in beam I and cell B in beam II, and then *vice versa*. In addition, 5M solutions of ${}^7\text{Li}$ and ${}^6\text{Li}$ were measured against H_2SO_4 solution of $c(\text{H}^+) = 5.000(1)$ mol/l.

The intensities at the detectors “O” and “H” were measured at 31 different phase shifter positions in the range of $109.3 - 114.7^\circ$ for 30 s each; in each case with and without the cells in the beam path. The additional measurement of the phase shift of the empty interferometer, i.e. with the sample cells moved out, at each phase shifter position enables real-time correction of any phase shifts caused by

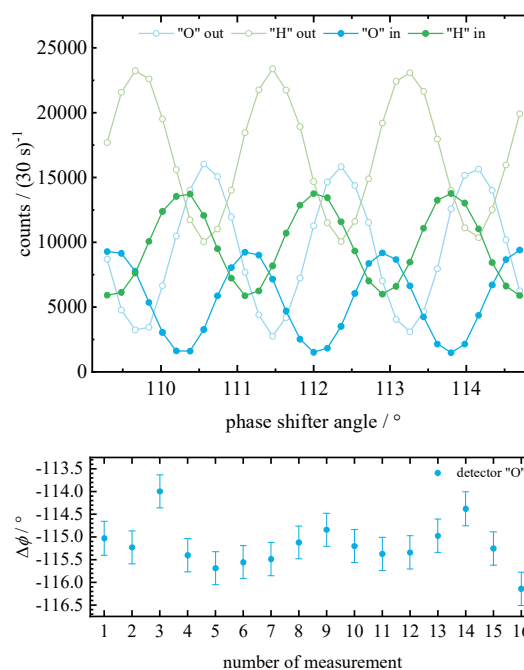


Figure 2: Top -- Typical interferograms as a function of phase shift angle, measured for 5M ${}^6\text{Li}$ and ${}^7\text{Li}$ solutions. Data points are neutron events recorded at the “O” detector (blue) and “H” detector (green) with samples in (dots) and samples out (circles). Bottom -- The phase shift $\Delta\phi$ is the mean from 16 interferograms each recorded consecutively for approximately 30 min.

external interference during the measurement series.

The measurements finally lead to four interferograms, as shown as an example in figure 2, from which the required phase shift $\Delta\phi$ is then determined. In order to increase the statistical significance of these determinations, the measurement procedure described above was repeated 10 - 20 times for each sample configuration (figure 3). The mean value of all results of such a measurement series is then the phase shift to be determined from which the coherent scattering lengths can be determined. The neutron wavelength λ was determined to be 190.7(7) pm using the [200] Bragg reflection from one of the blades of the silicon interferometer crystal

Preliminary results

Phase shifts obtained are given in table 1 in comparison to shifts calculated using values of $\tilde{b}_c(^6\text{Li})_{\text{NPD}} = 2.01(2)$ fm, $\tilde{b}_c(^7\text{Li})_{\text{NPD}} = -2.28(2)$ fm and $\tilde{b}_c(^{\text{nat}}\text{Li})_{\text{NPD}} = -1.95(2)$ as obtained from previous NPD experiments on samples with the same isotopic composition and equation 1, where \sim denote the scattering length for enriched samples composition e.g. not converted to pure isotopes. $\Delta\phi = \lambda N \Delta \tilde{b}_c D$ (1) where $N \Delta \tilde{b}_c$ denotes the sample scattering length density difference which may be interpreted as the scattering length difference of a Li sample pair for identical Li concentration, sample containers and wavelength. From mean results $\overline{\Delta\phi_{exp}}$ $|\Delta b_c|$ may be calculated using equation (1), and $\tilde{b}_c(^{6/7/\text{nat}}\text{Li})$ values using the corresponding NPD result given above as reference to result in the values given table 2.

Table 1: Calculated and measured phase shift differences for sample pairs. The term $A_i \leftrightarrow B_{ii}$ implies cell A situated in beam I and cell B in beam II and *vice versa* for $B_i \leftrightarrow A_{ii}$. $\overline{\Delta\phi_{exp}}$ is the average of both.

Which shows the phase shift difference expected from the experimentally determined scattering length. Effects of differences in total number density are neglected for the H_2SO_4 solution.

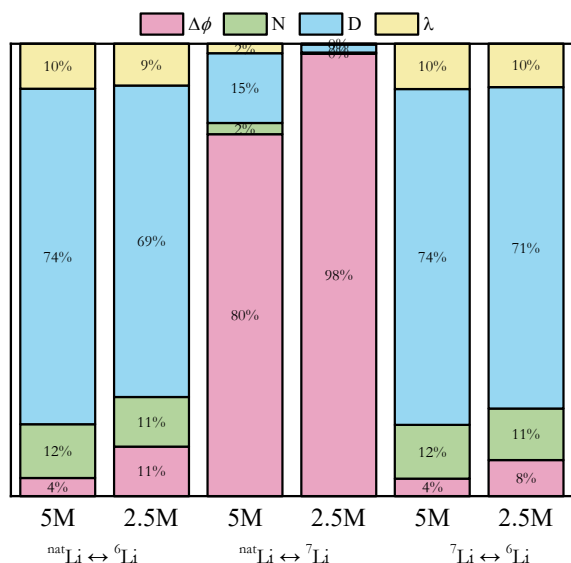
sample	$\Delta\phi_{calc} / ^\circ$	$+\Delta\phi_{exp} / ^\circ$ $A_i \leftrightarrow B_{ii}$	$-\Delta\phi_{exp} / ^\circ$ $B_i \leftrightarrow A_{ii}$	$\overline{\Delta\phi_{exp}} / ^\circ$
$c(\text{Li}^+) = 5.00(1) \text{ M}$				
$^{\text{nat}}\text{Li} \leftrightarrow ^6\text{Li}$	± 130.3	$+128.8(2)$	$-130.7(2)$	$+129.8(3)$
$^{\text{nat}}\text{Li} \leftrightarrow ^7\text{Li}$	± 10.9	$-12.6(2)$	$+11.7(2)$	$-12.2(3)$
$^7\text{Li} \leftrightarrow ^6\text{Li}$	± 141.1	$+142.8(3)$	$-141.7(2)$	$+142.3(3)$
$^6\text{Li} \leftrightarrow ^{\text{nat}}\text{H}^+$	$\pm 189.2^*$	$-189.2(2)$	$+189.3(2)$	$-189.3(3)$
$^7\text{Li} \leftrightarrow ^{\text{nat}}\text{H}^+$	$\pm 48.2^*$	$+26.5(2)$	$+27.1(5)$	$+26.8(5)$
$c(\text{Li}^+) = 2.50(1) \text{ M}$				
$^{\text{nat}}\text{Li} \leftrightarrow ^6\text{Li}$	± 65.2	$+64.9(2)$	$-66.9(2)$	$+65.9(2)$
$^{\text{nat}}\text{Li} \leftrightarrow ^7\text{Li}$	± 5.5	$-5.3(2)$	$+2.9(2)$	$-4.1(3)$
$^7\text{Li} \leftrightarrow ^6\text{Li}$	± 70.7	$+70.6(2)$	$-70.9(2)$	$+70.8(2)$

Table 2: Calculated phase shift difference between sample pairs and the calculated coherent scattering length of Li isotopes using diffraction given in table 6.

sample	$ \Delta b_c / \text{fm}$	$\tilde{b}_c(^6\text{Li}) / \text{fm}$	$\tilde{b}_c(^7\text{Li}) / \text{fm}$	$\tilde{b}_c(^{\text{nat}}\text{Li}) / \text{fm}$
$c(\text{Li}^+) = 5.00(1) \text{ mol / l}$				
$^{\text{nat}}\text{Li} \leftrightarrow ^6\text{Li}$	3.94(5)	1.99(5)	-	-1.93(5)
$^{\text{nat}}\text{Li} \leftrightarrow ^7\text{Li}$	0.369(9)	-	-2.32(2)	-1.91(2)
$^7\text{Li} \leftrightarrow ^6\text{Li}$	4.32(5)	2.04(5)	-2.31(5)	-
$^6\text{Li} \leftrightarrow ^{\text{nat}}\text{H}^+$	5.75(7)	2.01(7)	-	-
$^7\text{Li} \leftrightarrow ^{\text{nat}}\text{H}^+$	0.815(18)	-	-2.93(3)	-
$c(\text{Li}^+) = 2.50(1) \text{ mol / l}$				
$^{\text{nat}}\text{Li} \leftrightarrow ^6\text{Li}$	4.01(5)	2.06(5)	-	-2.00(5)
$^{\text{nat}}\text{Li} \leftrightarrow ^7\text{Li}$	2.49(2)	-	-2.20(3)	-2.03(3)
$^7\text{Li} \leftrightarrow ^6\text{Li}$	4.30(5)	2.02(5)	-2.29(5)	-

Mean results for each isotope composition give values of $\tilde{b}_c = 2.03(3)$, $-2.28(5)$, and $-1.97(5)$ fm for ^6Li , ^7Li , and $^{\text{nat}}\text{Li}$, respectively, being in quite good agreement with the NPD values, neglecting the H^+ involved measurements. The H_2SO_4 sample was used to take advantage of the well-known scattering length of $^{\text{nat}}\text{H}$ as a reference, but did not give satisfying results, since the number density of H_2SO_4 solution and Li_2SO_4 solution of same concentration was found to differ by about 2% due to different chemical interaction of H^+ and Li^+ with water molecules in the solution. A quantitative determination of the given number density difference could not be performed yet to a reliable precision.

Even though interferometry and NPD results are in good agreement the aim to increase precision compared to the later was not reached. Error analysis found the uncertainty of 0.01 mm in the cell thickness D to be the main source of uncertainty, except for those pairs in particular $^{\text{nat}}\text{Li}$ vs. ^7Li where a quite small phase difference is measured and precision in angle determination is the limiting parameter as illustrated in figure 3. However, since the results are differences of the reference samples scattering length and the measured scattering length differences, their uncertainties are limited to reference samples scattering length uncertainty, which is about 0.02 fm i.e. ca. 1 % of the value in the case of Li.



So far, we conclude that the following conditions have to be fulfilled for precise results in interferometry experiment as conducted: (A) a good reference sample of well-known scattering length, (B) same chemical composition known to high accuracy for reference and probe sample, (C) small scattering length difference $|\Delta b_c|$ compared to the scattering length of the reference sample, which is important to keep the impact of uncertainties in N , D and λ on measured scattering length difference small.

Figure 3: Relative contributions of the square of the parameter uncertainty to the total uncertainty in scattering length difference $|\Delta b_c|$ of sample pairs based on the measured phase shift.

Literature

- [1] A. Ioffe, M. Vrana, *Phys. Lett. A* **1997**, *231*, 319–324. DOI: 10.1016/S0375-9601(97)00334-4.
- [2] H. E. Fischer, J. M. Simonson, J. C. Neufeind, H. Lemmel, H. Rauch, A. Zeidler, P. S. Salmon, *J. Phys.: Condens. Matter* **2012**, *24*, 505105. DOI: 10.1088/0953-8984/24/50/505105.