THE CONCEPT OF AN EXPERIMENT ON MEASURING THE LENGTH OF COHERENT SCATTERING OF NATURAL GADOLINIUM

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Motivation

Gadolinium is known for the fact that its natural isotope mixture possesses a **record-high neutron radiative capture cross-section, which is ~50 000 barns for thermal neutrons**. This makes it suitable to use as an absorber in diffractometers and polarizers, and as a reference layer in neutron reflectometry to determine the modulus and phase of the reflection coefficient of multilayer nanostructures. For the optimal use of this material, a **knowing of the scattering length is important**.

As the literature analysis shows, at the moment **there is no accurate data of this value:**

Authors/year	Method	Wavelength	Re(b), fm
Watanabe N. et al., 1975 [1]	Diffraction	Epithermal neutrons	9.5 ± 0.2
Korneev D. A. et al., 1982 [2]	Reflectometry	$1-5$Å	18.53
Rauch H. et al., 1985 [3]	Interferometry	1.86Å	5.1 ± 0.4
Frank A. I. et al., 2002 [4]	Reflectometry	$3.5-8$Å	11.5 ± 0.7
Nikova E.S. et al., 2019 [5]	Transmission	$0.6-9$Å	7.6

Measuring the scattering length for gadolinium is associated with significant difficulties. Natural gadolinium consists of a mixture of six stable isotopes, two of which – ^{155}Gd and ^{157}Gd – **have resonances of neutron capture cross-section in thermal region**.

Due to the presence of these resonances, its scattering length has strong dependence on energy of neutrons and is not a constant value. In such a case, it is necessary to **use the Breit-Wigner formula** for calculations:

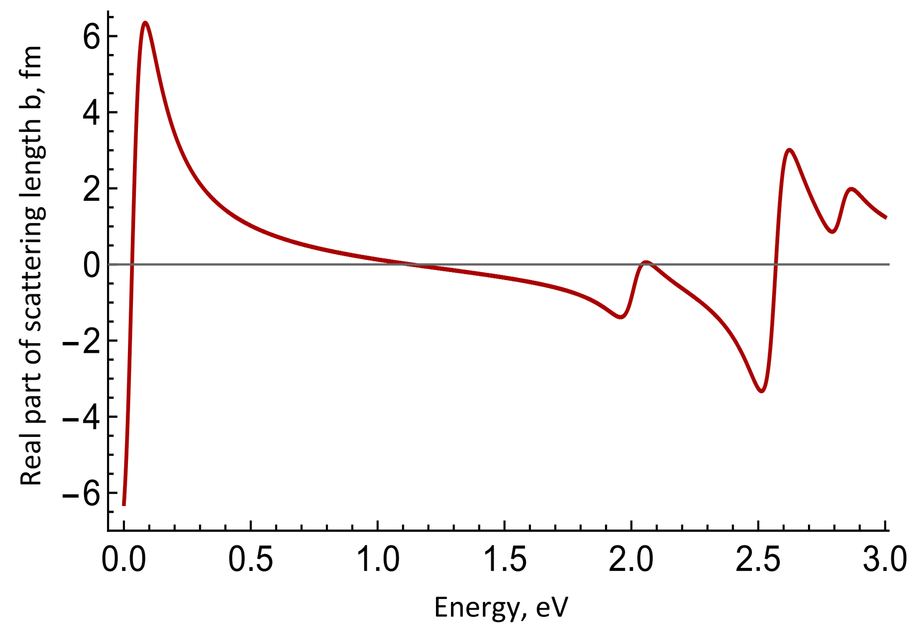


Fig. 1: Dependence of the real part of gadolinium scattering length on energy.

$$b_{coh} = b_0 + \sum \frac{2\lambda_j \Gamma_{nj}(E-E_j)}{4(E-E_j)^2+\Gamma_j^2} + i\sum \frac{\lambda_j \Gamma_{nj}\Gamma_j}{4(E-E_j)^2+\Gamma_j^2},$$

where b_0 **is the constant part of the scattering length**, λ is the reduced wavelength, Γ_j and Γ_{nj} are the total and neutron widths of the j-th resonance, and E_j is the energy at which the j-th resonance occurs.

Systematic analysis of the previous experiment [4]

Since gadolinium is actively oxidized in air, it is necessary to use a protective coating. In the experiment [4], a thin **layer of titanium** was used as such a coating. Measurements were done at the **TOF reflectometer REFLEX (FLNP JINR)**. Experimental reflection curves were compared by theoretical calculations in which the variable parameter was the constant part of the scattering length.

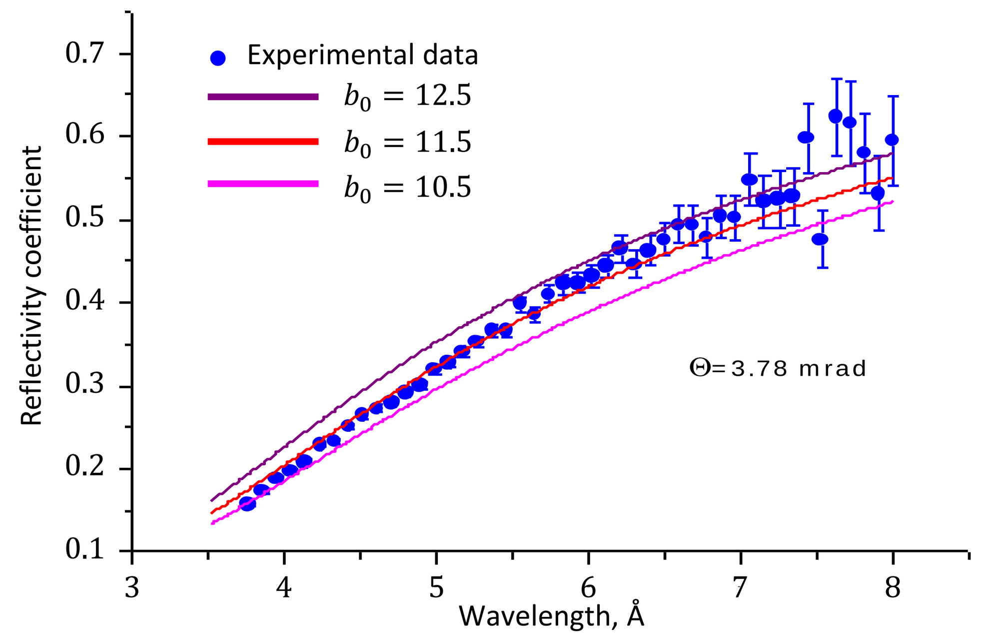


Fig.2: Comparison of experimental and theoretical curves at three values of the constant part of the scattering length [4]

The agreement of the theory with the experiment was not complete. The discrepancy between the empirical and calculated curves is clearly seen. One of the main hypotheses is the **unknown oxidation depth of the titanium protective layer.**

To analyze the role of titanium oxide the calculations from the article [4] were reproduced, considering three scenarios: a fully oxidized titanium layer, one oxidized to half of its thickness, and a non-oxidized layer.

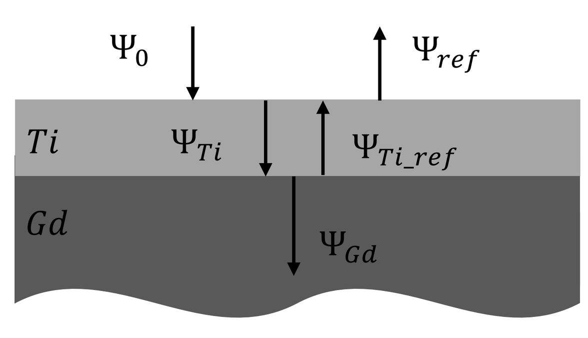


Fig. 3: Scheme of the Ti-Gd structure. The TiO_2-Gd structure appears the same.

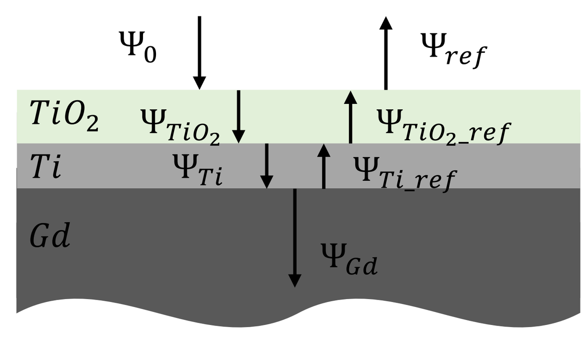
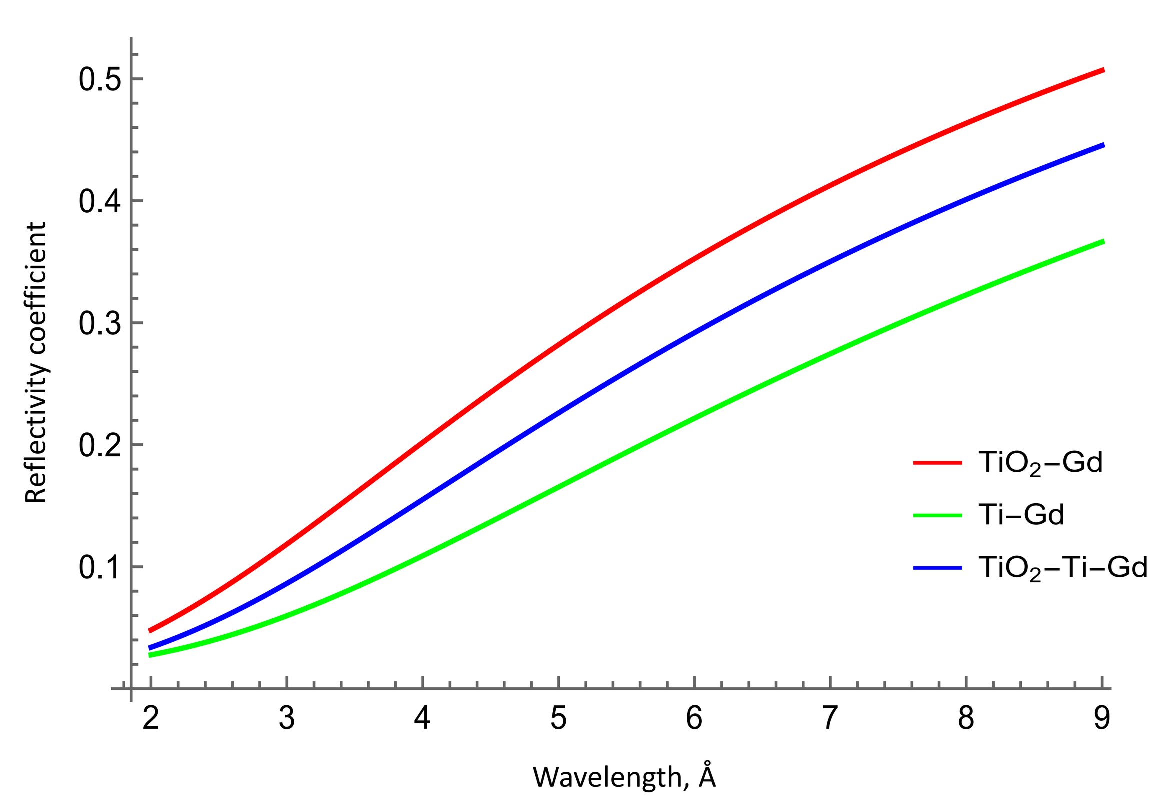


Fig. 4: Scheme of the TiO_2-Ti-Gd structure.

Fig. 5: Dependence of the reflection coefficient on the wavelength of neutrons



Presence of the oxide in the surface layer significantly affects the value of the reflection coefficient!

Possible new experiment

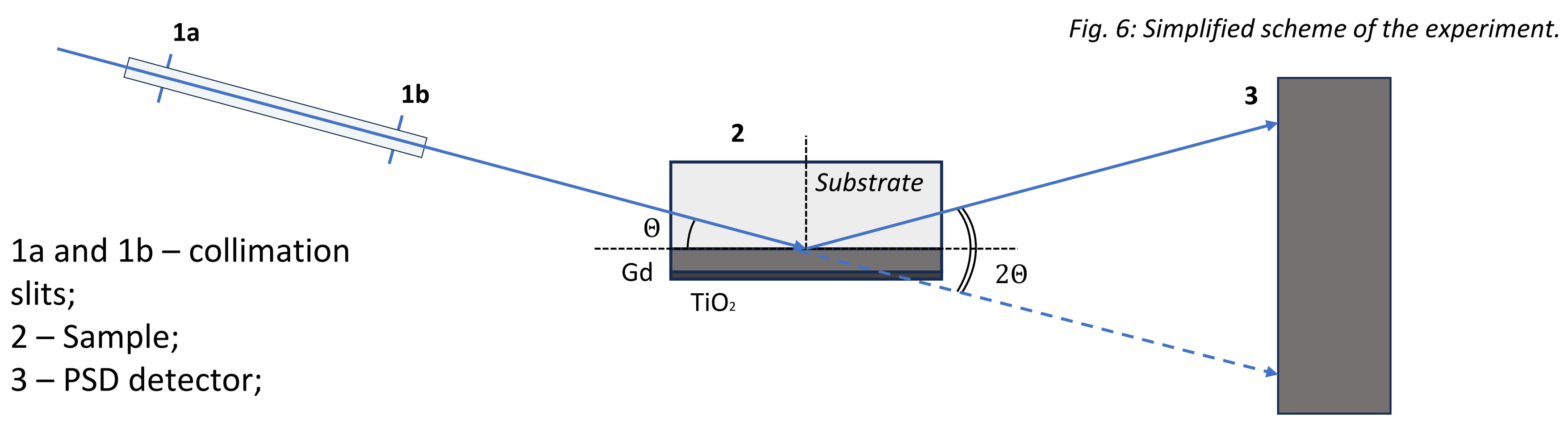


Fig. 6: Simplified scheme of the experiment.

The main difference between the planned experiment and the previous one is the use of the so-called **"inverse" geometry:** neutrons will fall on gadolinium through a glass substrate.

This approach has several advantages:

- neutron beam is directed to the Gd through a glass substrate, which is weakly interacts with thermal neutrons, and therefore can be considered transparent;
- such a structure has only one glass-gadolinium interface, which greatly simplifies the calculations.

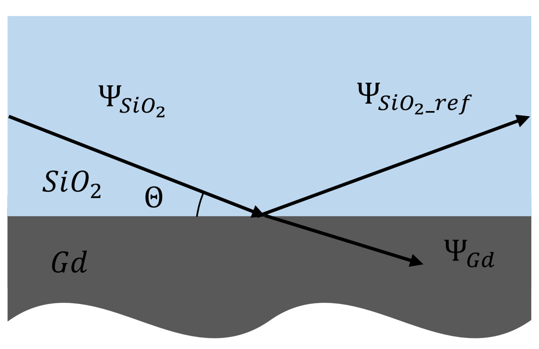


Fig. 7: Scheme of the SiO_2-Gd structure.

The experiment is planned to be carried out at one of the **reflectometers of the IBR-2 reactor of the FLNP JINR**.

Parameters in Breit-Wigner formula, with the exception of b_0, were taken from the ENDF nuclear data library [6]. The constant part of the scattering length b_0 **is a variable parameter**.

The **number of resonances** in the radiation capture cross-section of gadolinium is **~200 for ^{155}Gd and ~90 for ^{157}Gd**. However, not all of these resonances significantly affect. After sorting, the number of resonances taking into account was significantly **reduced to ~80 for ^{155}Gd and ~20 for ^{157}Gd.** The contribution from other resonances will simply be an addition to the constant part of the scattering length b_0.

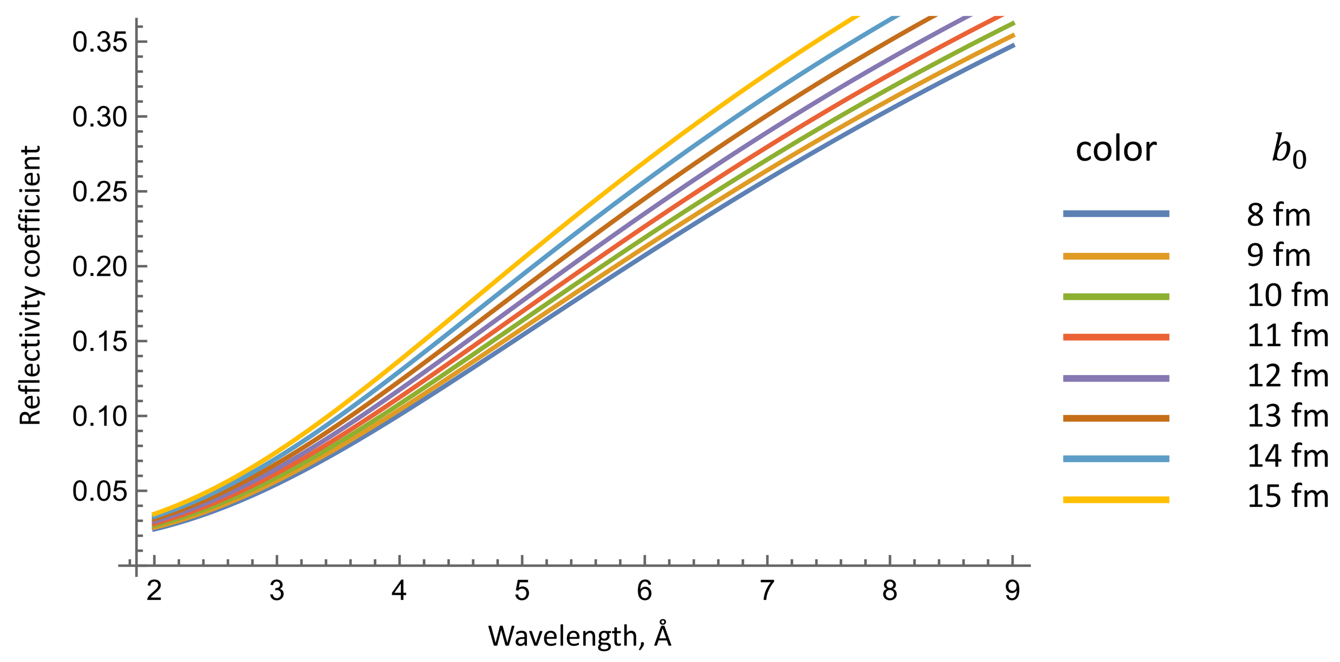


Fig. 8: Dependence of the reflection coefficient on the wavelength.

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