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研究課題名（和文）Development of high transmission guides for polarized ultracold neutrons

研究課題名（英文）Development of high transmission guides for polarized ultracold neutrons

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研究成果の概要（和文）：偏極超冷中性子(UCN)をUCN源から中性子電気双極子モーメント測定装置まで輸送するためのUCNガイドを開発した。まず、UCNガイドのコーティング方法を決めるため、コーティングのサンプル板を数種作成し、液体窒素中で耐久性試験を行った。そして、J-PARC・MLFの冷中性子反射計を用いてサンプル板に冷中性子を照射し、冷中性子の反射率を測定した。結果、ニッケル・リン合金めっきが最適なコーティングとわかった。
次に、異なる材質と表面荒さをもつUCNガイドを作成し、スイス・PSIのUCNビームラインでUCN輸送率を測定した。結果、UCN輸送率97%を達成し、当初の目的通りのUCN ガイド開発に成功した。

研究成果の概要（英文）：This research program aimed to create new guides for the transport of polarized ultracold neutrons (UCN) from a new superthermal UCN source to an experimental setup built to measure the electric dipole moment of the neutron. The first part of the research was focused on the characterization of new materials for these guides (understanding how resistant they are using thermal stress test, how they can reflect neutrons). Tests were performed at MLF, J-PARC using cold neutron reflectometry and confirmed the possible use of Nickel-Phosphorus alloys as UCN guides coatings. The second part of the research was focused on the building of the new guides and test of different substrates and roughnesses. The produced guides were tested with ultracold neutrons at the Paul Scherer Institut (Switzerland). We were able to achieve a transmission of 97% for one of the guides, which is suitable for our purpose.

研究分野：Nuclear and particles Physics

キーワード：Ultracold neutron　Fermi potential　Reflectivity　Nickel Phosphorus alloy

１．研究開始当初の背景

The Standard Model (SM) describes the world of elementary particles and fundamental interactions. It is a coherent model in particles physics and is commonly used for 40 years.

Nevertheless, it fails to explain the charge-parity (CP) symmetry violation required to explain the baryon asymmetry of the universe (BAU) [1]. The non-zero value of the electric dipole moment (EDM) of a particle violates CP. EDM measurements are currently on going for several particles. The current upper limit on the neutron EDM is: $|d_n| < 3.0 \cdot 10^{-26}$ e cm (90 % C.L) [2]. The predicted neutron EDM value in the SM is at the level of 10^{-31} to 10^{-32} e cm and is currently unreachable. Several extensions of the SM have been built in order to find new CP violation sources. A non-zero value of the neutron EDM is a powerful test of these extensions [3]. The neutron EDM value predicted in the Super-SYmmetric model (SUSY) is around 10^{-27} to 10^{-28} e cm. Our international (Japan-Canada) TUCAN collaboration plans to reach the limit of 10^{-27} e cm and thus testing the validity of the SUSY model. The measurement of the neutron EDM is done using the so-called Ramsey technique: neutrons are set in the presence of both homogeneous electric and magnetic fields, parallel or anti-parallel. The difference of accumulated phase during spin free precession is proportional to the EDM of the neutrons. UltraCold Neutrons (UCN) are very low energy (around some hundreds of neV) neutrons and can be stored inside material bottles. The UCN, thanks to their long storage time (some hundreds of seconds) can accumulate more phase during the Ramsey sequence and thus are a very efficient tool for this study. A new high density UCN source is been developing for this purpose. This source needs new guides in order to reach expected UCN density for the neutron EDM experiment.

２．研究の目的

Efficient transport of polarized UCN is one of the major requirement for the measurement of the neutron EDM. Indeed, the statistical error on the neutron EDM is a proportional to the square root of the number of counted UCN, and a function of the initial polarization of the UCN beam. The transportation efficiency depends mainly on three parameters. The first one is the capacity of the guide’s walls to contain the UCN. UCN have a large wavelength compared to the atomic radius (50 to 130 nm compared to 0.1 nm). Therefore, during a scattering process, a UCN interacts with hundreds of nuclei. The mean potential experienced during the scattering, called the Fermi potential, depends on the material. In order to store the UCN, the Fermi potential must be as high as possible. Typical materials used for UCN storage have a Fermi potential from 200 to 300 neV. The second parameter is the roughness of the surface. Indeed, transportation is more efficient if the roughness is low: the probability of having a specular reflection is increased. Empirically, a roughness can be considered acceptable if it is lower than the UCN wavelength. The last parameter is related to the polarization. UCN can be depolarized during a collision because of different processes, such as incoherent nuclear scattering, paramagnetic scattering or high magnetic field gradients. Each material has an average probability of depolarization per bounce. This probability must be as small as possible. Our next generation high density UCN source is a super-fluid Helium (He-II) vessel with a critical energy (Fermi potential of the walls) of about 210 neV. In order to extract the UCN from the He-II volume, we will use a 3.5 T superconducting (SC) magnet. Indeed, the magnetic interaction intensity is 60 neV/T, and the critical energy is 210 neV, so a 3.5 T extraction field allow 100% extraction efficiency for a dedicated spin state. Since the magnetic interaction is spin dependent, only one spin state can pass through the super conducting polarizer magnet. Thus, our source is a source of polarized UCN, and is expected to be the most powerful in the world. We have tested the extraction of UCN with a SC magnet successfully in 2014. In order to keep a large UCN density after the extraction from the source, we need to use a material with a Fermi potential at least as large as the one of the source itself (210 neV). Most materials suitable for this purpose have very low Fermi potential. We need to apply a thin coating of a high Fermi potential material at the surface. Nickel is attractive, but magnetic. Nevertheless, with a part (around 10 to 15% in weight) of Phosphorus, the alloy loses its magnetic properties and can be used for non-magnetic coatings. The first part of the research was focusing on characterizing different possible Nickel-Phosphorus alloys (with different Phosphorus concentrations) and other alloys using Cold Neutron reflectometry. Borosilicate glass could be candidates for room temperature guides. The temperature at the level of the SC magnet is 100 K. Glass cannot be used at this place, we decided to investigate Titanium and stainless steel (SUS) guides, which looks promising in term of thermal conductivity and coating adhesion. Having new high transmission guides for polarized UCN will increase the UCN density for the neutron EDM experiment and all other futures experiments. The second part of the research was to produce different UCN guides (Stainless steel, Titanium) with different roughness qualities and coatings (bare or NiP). These guides were tested at the Paul Scherrer Institute in order to determine their UCN transmission.

３．研究の方法

1) Characterization of materials using Cold Neutron Reflectometry. The neutron

reflectometer SOFIA at MLF (J-PARC) [4] has been used for this study (Fig.1 shows a scheme of the reflectometer). Several samples were prepared. The ones directly related to this research are Silicon wafer of 3 mm thickness where a 200 nm thick layer of Copper was sputtered. This conductive layer is required in order to perform the NiP platting. There different weight ratio were produced: 5% P, 10% P and 15% P. The samples were placed on the reflectometer. The determination of the critical momentum (the momentum transfer when the reflectivity decreases) is directly correlated to the Fermi potential of the material. In Addition, temperature stress tests (using SUS and Ti samples coated with NiP) were perform by dipping the samples in liquid Nitrogen and performing adherence tests.

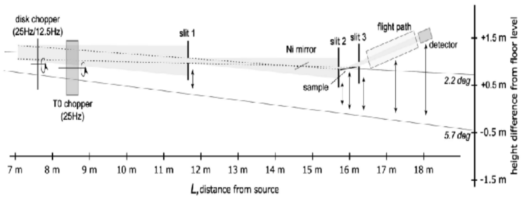

Fig.1. Schematic view of the SOFIA reflectometer. Taken from [5]

2) Characterization of guides with Ultracold neutrons. Our initial plans was to measure the depolarization per bounce of NiP coated guides using the setup developed at PSI [6]. Nevertheless, an issue with the main magnet of this experiment canceled the measurement. Instead, we determined another important parameter for the guide: their UCN transmission. In order to do this experiment, we used the “prestorage method” developed by the PSI group [7]. A prestorage vessel is filled with a defined number of UCN prior to their release into the test guide or directly into the detector. These stored UCN can then be directly measured with a detector mounted onto the vessel and hence be used as calibration. Then, an additional guide to be tested is mounted between the prestorage vessel and the detector and the measurement is repeated. The comparison of the integrated UCN counts in the two measurements is defined as the UCN transmission through the test guide. Four guides were tested during this experiment: SUS guide (no coating) with careful polishing (mechanical and electro polishing), the same but with a NiP (15% P) coating, a SUS guide only mechanically polished with NiP (15% P) coating and a Ti guide mechanically polished with NiP (15% P) coating.

４．研究成果

1) Characterization of materials using Cold Neutron Reflectometry. The three concentrations of Phosphorus in the different samples (5, 10 and 15% weight) decreases the Fermi potential of the alloy, as expected. The results are also compatible with theoretical values. Fig.2. is showing an example of a reflectivity plot. The Fermi potentials were extracted by fitting the reflectivity plot with a Parrat slab model (considering the Si wafer, the Cu layer and the NiP coating). It is hard to

fit the high Q fringes because of systematic effects. We obtained the following Fermi potentials:

- V_F (NiP 5%) : 220+/-10 neV (theo: 233)
- V_F (NiP 10%): 205+/-8 neV (theo: 214)
- V_F (NiP 15%): 194+/-7 neV (theo 202)

A paper is currently being written in order to publish these results (in addition with other tested materials suitable for UCN equipments). Submission is planned for the summer.

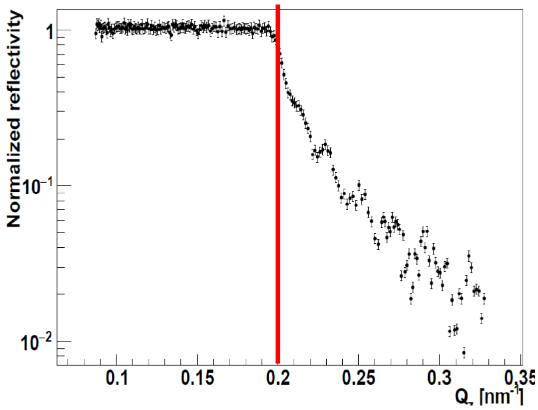

Fig. 2. The reflectivity plot for the NiP (10%) sample.

2) Characterization of guides with Ultracold neutrons. The transmission of the four guides was measured using the PSI apparatus. The main issue with the data analysis was the constant UCN yield decrease of the PSI source, because of the structure of its UCN converter: the solid deuterium crystal is heated during irradiation, which modifies its structure and thus decreases its performances. Daily calibration measurements allows us to re normalize the data. Data were taken as a function of time and the transmission was extracted from time of flight (tof) spectra. An example of tof data is shown on Fig. 3. Systematics effects were taken into account, and transmission was extracted with a 1% accuracy level. The main parameter for a large transmission is the quality of the roughness. Guides with electropolishing have the largest transmissions. The SUS guide without coating has a transmission of 93+/-1%/m. With the addition of a NiP coating, this transmission is reaching 97+/-1%/m. The SUS guide which was not electropolished has a transmission of 70+/-1%/m, even with a NiP coating. The Ti guide is even worst and has a transmission of 50+/-1%/m. This difference is maybe because of a possible degradation of the coating (Titanium is a UCN absorber. Transmission will decrease if a part of the coating is missing). The performances of the best guide make it a good candidate for an extraction guide of the next generation UCN source.

A second paper summarizing these results is currently being written. Submission is planned for the summer.

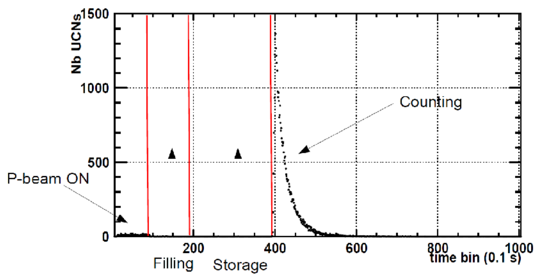

Fig.3. Time of flight spectrum.

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５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計 ０件）
2 are currently being written.
〔学会発表〕（計 ４件）

E.PIERRE: UCN guides development for the TRIUMF UCN source. *JPS 73 annual meeting*, Tokyo (Japan). 03/25/2018

E.PIERRE: Status of the UCN guide development for the TRIUMF UCN source and TRIUMF neutron EDM experiment. *nEDM2017 Workshop*, Harrison Hot Springs (Canada). 10/17/2017

E.PIERRE: Characterization of non magnetic materials for the transport of Ultracold neutrons. *Fall meeting of the APS Division of Nuclear Physic*, Vancouver (Canada). 10/14/2016

E.PIERRE: Characterization of new materials for Ultracold Neutrons transport and storage. *JPS Autumn meeting*, Miyazaki (Japan). 09/23/2016

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