PH D proposal: Low Energy Cross Sections of Liquid and Solid Deuterium

General project outline

Solid deuterium [1] is since more than 15 years the favorite converter material for the next generation of UCN sources. It exists in two states, ortho and para, which are connected to the even or odd rotational states of the D_2 molecule. A UCN sD_2 converter should be in the ideal case only in the ortho state. UCN are produced by super-thermal conversion [2] of cold or thermal neutrons. UCN are low energy (typical neV region) neutrons. They are very suitable neutral particles for fundamental experiments with the neutron itself, the exact measurement of the neutron lifetime [3] or determining a possible finite electric dipole moment of the neutron [4]. UCN can be also used to study the decay products in the β-decay of the free neutron. One major project is to measure the β asymmetry A_0 [5] with UCN [6]. Low energy neutrons like UCN are strongly influenced by week gravitational field of the earth. It was discovered a few years ago [7], that UCN occupy discrete quantum states if they are bound in the gravitational field of the earth (trapped in a material bottle). Recent experiments [8] with UCN could prove that external mechanical vibrations could induce transitions between different quantum states of gravitational trapped UCN. With this kind of experiments it should be possible to test Newton's gravity law and the equivalence principle in the micrometer region. All these shortly introduced experiments have the potential to test the standard models of particle physics or gravity, or even discover physics beyond these models. For the experiments, mentioned above, powerful UCN sources are needed. Typically UCN densities of ρ_{UCN} >= 1000 cm^{-3} [9,10a] should be achieved of the new UCN sources.
So far in most of the cases only prototype sources were constructed and tested at different facilities [10a-15]. The experimental results are promising and developing of powerful UCN sources are ongoing. It is expected to have these facilities soon available. The UCN source at Los Alamos [16] is already working and delivers at the moment a UCN density of ρ_{UCN}~ 80 cm^{-3} outside the biological shield of the source. The UCN source at the PSI in Switzerland has been completed and produces at the moment ρ_{UCN} ~ 25 cm^{-3} in a stainless steel test bottle [10b]. A further sD_2 UCN source at the TRIGA reactor in Mainz was constructed, and is now in the testing phase. In first test measurements UCN densities of ρ_{UCN} ~ 18 cm^{-3} in a small storage chamber were detected [17].

State of the art

The high expectations on the performance of these sources make it necessary to understand the production and losses of UCN in soD_2 precisely. The physics behind the UCN production in sD_2 is in the meantime well understood [18-23]. Cold or thermal neutrons are down-scattered to the UCN region by

exciting phonons and/or rotational transitions (J=0 -> 1). The sD_2 converter should be operated at a temperature T< 10 K [21] and the content of solid-para-deuterium (spD_2) should be minimized, because it exhibits a large up-scattering cross-section [22,23] for UCN. The origin of UCN losses in sD_2 is still unclear. Measurements of total cross sections [24] for UCN energies show quite large cross sections. These cross sections are at least one order of magnitude larger as expected from theoretical calculations [22]. These calculations are based on the incoherent approximation [25], disregarding the real hcp crystal structure [26] of sD_2. The measured cross section is strongly dependent on crystal growing technique and on temperature cycling. Atchison et al. [24] explain these experimental findings with possible crystal defects caused by improper growing technique or too extreme temperature cycling. In other series of experiments of producing UCN in sD_2 [11] it was discovered, that smooth temperature cycling (T -> 5K -> 11K -> 5K) can improve the yield of UCN in the converter. This behavior is on the first view in contradiction to the results of [24]. It seems that the experimental results are solid, but the possible explanations are more speculative and unsatisfying. The basic question is whether the nature of this large cross section is inelastic or elastic. To clarify these open questions we performed recently neutron transmission experiments on sD_2 with UCN.
The precise determination of UCN cross sections for (ortho- and para-) deuterium is a longstanding problem in the physics of UCN. Precise values are highly desirable and necessary for design and flux calculation of cold and ultra cold neutron sources, working mostly with deuterium.
There is a lot of previous work in this field, beginning with the reports of Seiffert [27], Egelstaff [28] and Schott [29] on liquid and solid H_2 and D_2 for thermal and sub-thermal neutrons. The route down to VCN- and UCN-energies was followed later by Kasprzak [30], Brys [31] and Atchinson et al. on liquid [32] and solid [24] o-deuterium, presenting a carefully performed experiment, but a less convincing data analysis. No corrections for quantum-mechanically induced reflectivity [33] and multiple scattering [34] due to the condition $\Sigma d>1$ valid in these experiments (Σ: macroscopic cross section, d: sample thickness) have been applied to the data. Hence these experiments show results, which differ up to 33 barn [31] from theoretical calculations [35,36,22].
Gutsmiedl and Frei continued the experimental work on solid deuterium with regard to a solid state UCN converter [37,28].

Project description and preliminary work

1) The Solid Case

Recently we performed an UCN experiment at ILL (exp.no. 3-14-311) to re-measure scattering cross sections on liquid and solid $o\text{-}D_2$ in the neV-range to clear up the existing discrepancies in the cross sections of about 25%. Again a constant, i.e. elastic off-set of about 30 barn was found in solid deuterium, which is attributed to surface scattering in the solid case/15/. To confirm this finding, it is highly desirable to continue with an UCN experiment, in which the influence of surface scattering is scrutinized by variation of the surface-to-volume ratio of the sample. This requires a series of otherwise identical experiments with different sample thicknesses (at least three). This strategy was not followed up to now, and may provide valuable general information on the correction of surface scattering in UCN transmission experiments.

2) SANS at Solid Deuterium (FRMII)

Complementary to these UCN experiments at ILL we plan a small angle scattering experiment at the instrument SANS1 (FRMII). In this SANS experiment we will study density inhomogeneities on the length scale of about 1000 Angstroem in solid deuterium. The aim of this study is to differentiate eventually between the contributions from surface- and bulk-scattering in solid deuterium.

3) The Liquid Case

The third line of progress concerns the liquid case. The data of Atchinson et al./6,7/ are fitted with a merely empirical 1/v-law. Applying simple diffusive dynamics in the liquid case, the cross section is calculated on theoretical grounds and is again lower than the experimentally found result/16/.As disorder scattering from sample surfaces cannot contribute significantly to the cross section in the liquid case, other physical processes must be involved in UCN-scattering in liquid D_2. The processes in question are very probably thermal luctuations, as liquid D_2 is by far no “harmonic liquid”, but shows significant contributions from heat fluctuations to the scattering law at low q . It is the aim of this proposal to follow this conjecture in a series of UCN transmission experiments on liquid o-D_2 at various temperatures to study these fluctuations and to include them into the theoretical calculation of UCN cross sections on a quantitative level.

This is a program for 2.5 to 3 years with about 3 to 4 time consuming 3-weeks experiments, where the experimental set-up (cryostat, gas handling system, para-ortho converter and slow control) for the work is already available at Physics-Department E18/E21 at TU Munich. In a first step the cryostat shall be optimized for lower temperature (T~ 6K) experiments. Furthermore the cryostat will be modified in way that measurements on thin layers (~ 1mm) of sD_2 frozen on single crystal silicon wavers with no entrance and exit windows for UCN are possible. With this modification a careful study of surface effects should be feasible.

Financing

A 50 % co-financing by FRM II Munich is assured for three years.

III. References

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