Search For Anomalous n-p Scattering At 60 eV - 140 keV

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Abstract. A search for an anomalous n-p scattering from a polyethylene sample (CH_2) at 8 final energies between 64 eV and 2.5 keV was carried out. The scattering intensities were compared to that from a graphite (C) sample. The results were found to confirm our previous n-p results on H_2O at a final energy of 24.3 keV where no n-p scattering anomaly was observed. The present results refute all proposed models attempting to explain the occurrence of any n-p scattering anomaly at keV neutron energies.

Keywords: n-p scattering cross section, CH_2 sample, ^{238}U-neutron filter
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INTRODUCTION

During the last ten years, several experiments were reported concerning the observation of a strong anomalous drop of ~ 40%, in the n-p differential scattering cross section compared to the accepted values [1,2]. This anomaly was reported for 10 eV - 200 eV neutrons, scattered from H-containing samples at room temperature. More than 10 different samples (such as water (H_2O), benzene (C_6H_6), and hydrides of Nb and Pd) were studied, revealing more or less the same effect. An attempt to explain the anomaly, in terms of a breakdown of the Born-Oppenheimer approximation during the very short times ~ 10^{-15} s of the scattering process was made. It was suggested that because of the high energy and momentum transfers involved in the scattering, electronic excitations may occur in the neutron-nucleus collision. This process diminishes the energy of the scattered neutrons hence also the number of neutrons entering the peak. However, a calculation by Colognesi [3] has shown that such a process has a negligible effect on the scattering intensity. An alternative explanation involving short lived (10^{-15} to 10^{-16}s) quantum entanglement of protons was proposed. It was suggested that during the very short times of the scattering process, no quantum de-coherence is expected to take place and quantum entanglement of protons can be observed. To test the above suggestions, we scattered keV neutrons [4], from pure liquid H_2O and compared the scattering intensity to that of pure D_2O and also relative to H_2O-D_2O mixtures at room temperature. At such higher energies and the shorter scattering times (10^{-17} to 10^{-18}s), de-coherence is less likely to occur, and the effect of quantum entanglement of the protons was expected to show up more clearly. However in the actual measurement, no anomaly was observed and the scattering intensity ratios

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were found to agree with conventional values [4]. In Ref. [4] the neutrons were generated by the RPI Electron Linac and a final neutron energy of 24.3 keV was selected using a pure iron filter. Following this work, several objections were raised [2,5] claiming that the calculation of the differential neutron scattering intensity ratios from the H_2O/D_2O samples of Ref. [4] was wrong, and that a "proper" evaluation reveals a large anomaly of ~ 20%.

CREATING FALSE ANOMALIES IN N-P SCATTERING

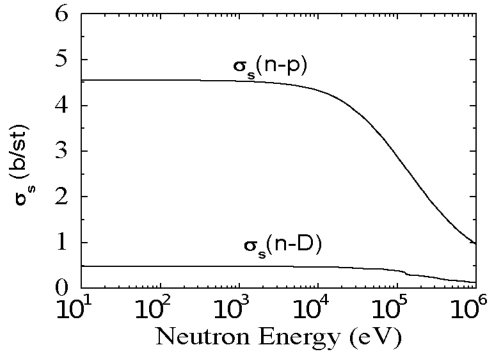

FIGURE 1. n-p and n-D scattering cross sections at 45° in the lab system.

Before going into the details of those objections, we must point out that there are some basic differences between the ISIS (Rutherford) and the RPI experiments which if ignored can create erroneous and artificial anomalies. At ISIS, the n-energies involved are low, $E_n < 200$ eV and the samples were very thin, while at RPI the n-energies were in the 100 keV range and the samples were relatively thick. At $E_n < 1$ keV, the n-p scattering cross section σ_s(n-p) is essentially constant with no angular dependence, while at $E_n > 30$ keV, σ_s(n-p) drops with increasing E_n and the angular dependence cannot be ignored. Fig. 1 compares the E-dependence of σ_s(n-p) with σ_s(n-D) at 45°. In an attempt to check our results in [4], the authors of Ref. [2] repeated our calculations but *ignored the E-dependence* of σ_s(n-p), creating an artificial and erroneous n-p scattering anomaly [2] of ~ 20%. This was interpreted as a proof that our calculations are incorrect, that the σ_s(n-p) anomalies exist at energies $E_n > 30$ keV and that the results of [4] were in fact "in surprisingly good agreement with the results of ISIS".

Note that a similar shortfall of the n-p scattering intensity may be created by ignoring the attenuation effect of the neutrons in our relatively thick H_2O/D_2O samples. This is illustrated in Fig. 2 where an ingoing neutron making a path x_1 inside the sample scatters at point O at an angle $\theta_1+\theta_2$ and passes a distance x_2 before leaving the sample. Thus the n-intensity is attenuated in the sample by a factor $exp(-\Sigma_1 x_1-\Sigma_2 x_2)$ where Σ_1 and Σ_2 are the total neutron cross sections at incident energy E_1 and scattered energy E_2. In H_2O the n-attenuation is much larger than in D_2O. Thus, ignoring the n-attenuation will increase the calculated ratio of n-scattering intensities from H_2O/D_2O causing a faulty anomaly.

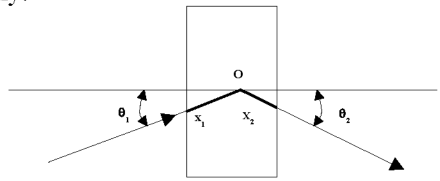

FIGURE 2. Illustrating the path of a neutron entering and scattering from a sample

In fact the authors of Ref. [5] have misleadingly compared our experimental results with calculations in which the n-attenuation in the H_2O/D_2O samples was **ignored.** We illustrate this point in Fig. 3 below where the measured points and the solid curve were taken from our data given in Fig. 3 of Ref. [4]. The solid curve represent the scattered intensity ratios calculated by including the n-attenuation in the samples where a good agreement was obtained with experiment and no anomaly was observed. However, if the n-attenuation is **ignored** (as shown in the dashed curve of Fig. 3 below), an artificial and false anomaly of 23% in the scattered intensity ratio from pure H_2O relative to D_2O is created. This calculated dashed curve is identical to the solid line given in Fig. 2 of Ref. 5 which was presented as an "evidence" for the existence of an anomaly in the n-p scattering intensities at keV neutron energies.

The result in [4] has in fact shown that all models involving atomic excitation [5] brought forward by the above authors to explain the n-p scattering anomaly were wrong and in any case could not explain the absence of any anomaly at higher neutron energies around and below the keV range.

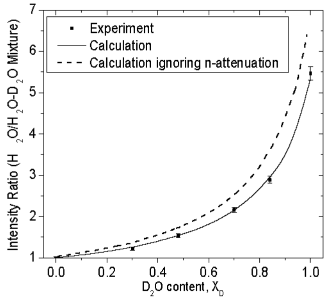

FIGURE 3. Measured (squares) with error bars of scattered intensity ratios versus X_D, the D_2O concentration in the H_2O-D_2O mixture sample, taken from Fig. 3 of [4] at $\theta = 45°$. The solid line represents calculated ratios obtained by including the n-attenuation in the H_2O-D_2O samples. The dashed line is the result of **ignoring** the n-attenuation in the H_2O-D_2O samples, creating a false and artificial anomaly of 23%. This calculated line is presented in Fig. 2 of [5] as an "evidence" for the existence of a 23% anomaly in the n-p scattering intensities at keV neutron energies.

The authors of [5] raised yet another point claiming that our calculations of multiple scattering (MS) corrections made in [4] were wrong. In these calculations, we employed the Monte Carlo code, MCNP5 developed over the years at Los Alamos. In [5], 'hand-waving' arguments were brought up to "show" that our MS calculations are incorrect. These were not supported by any real MS calculation to validate their claim.

In order to refute the above allegation [5] about the MS corrections, we carried out more detailed calculations using MCNP5 simulating the exact experimental situation occurring in [4]; all the results were within 6% of our published H_2O/D_2O ratio. Some of those calculations appeared in [6].

EXPERIMENTAL METHOD

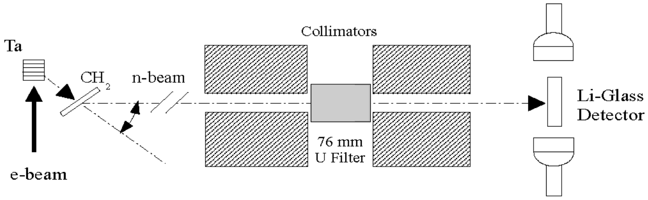

FIGURE 4. Layout of the experiment (not to scale). Ta n-source to detector distance is 25.3 m.

We also carried out another experiment [7] where several improvements were introduced compared to Ref. [4]. First, solid samples, CH_2 (polyethylene) and C (graphite) were used, where the n-p scattering from CH_2 was compared to that from C. These are preferable over liquid H_2O/D_2O samples having thin-walled containers which tend to change their shape. A solid sample is also self-supporting hence has lower background. Second, the thicknesses of CH_2 (1.2 mm) and C (3.94 mm) were selected in such a way as to make the calculated MS correction of the neutrons in the two samples nearly the same. Third, CH_2 contains C-H bonds where the n-p anomaly in the 10 eV range was reported to be large of around 60%. Fourth, the measurement was carried out at 16 discrete *final* n-energies between 64 eV and 2600 eV obtained using a ^{238}U filter. These neutron lines correspond to the minima in the total neutron cross sections of ^{238}U, and were produced in conjunction with the pulsed RPI Linac [7]. The scattering arrangement for the experiment (Fig. 4) is similar to that of the previous work [4]. The neutrons were generated via the (γ,n) reaction using ~ 50 MeV electron beam striking a water-cooled Ta target. The white n-spectrum produced was scattered by either CH_2 or C then passed through a 7.6 cm depleted ^{238}U filter (0.02% ^{235}U) converting it into a multi-line spectrum [8]. The energies and widths of the lines were measured by detecting the time of flight of the neutrons to reach a Li-glass scintillator set a distance of 25.3 m from the neutron source. The widths of the neutron lines varied from 1.3 to 7.0 eV. More details concerning this experiment appeared in the original paper [7].

RESULTS AND DISCUSSION

The measured ratios between n-p and n-C scattering intensities (Fig. 5) revealed no shortfall in n-p scattering and were in good agreement with calculations using the known neutron total cross sections. The effect of multiple scattering in the samples was calculated (solid line in Fig. 5) and no anomaly was observed [7]. The calculated CH_2/ C intensity ratio corresponding to a 40% drop in σ_s(n-p) is ~ 2.6, being far below the scale of Fig. 5. This result shows beyond any doubt that no σ_s(n-p) anomaly occurs for final neutron energies E_n = 64 eV – 2600 eV corresponding to incident energies in the range 100 eV to 15 keV. Combining this result with the H_2O/D_2O experiment, we conclude that no σ_s(n-p) anomaly was observed at *incident* energies of 100 eV to ~140 keV.

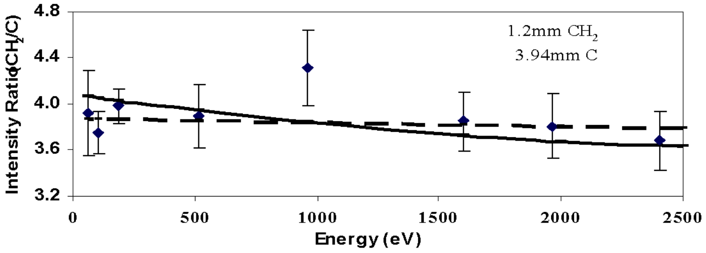

FIGURE 5. Measured scattering intensity ratios from CH_2 and C. Dashed and solid lines are the calculated ratios assuming single and total (including multiple scattering) respectively.

It is important to note that in our CH_2/C paper [7], we emphasized the role of the coherence length in scattering processes. It turned out however that coherence effects and quantum entanglement play no role in explaining the suggested anomaly. This also means that the explanation of the anomaly of Ref. [9] by assuming interference effects cannot be correct. Hence it is impossible to refute the claim of Ref. [10] who suggested that the occurrence of a σ_s(n-p) anomaly cannot be reconciled with the known values of the total neutron cross section of H_2O and D_2O at 1 eV to 100 eV.

Due to the fact that the proposed anomaly reported in Ref. [1,2,5] could not be explained using any of the theoretical models, it was proposed [11] that the anomaly could be due to a breakdown of the impulse approximation or a breakdown of the conventional neutron scattering theory for n-p scattering. It was also suggested in [11] that the anomaly could be due to some unexpected energy dependence of the efficiency of the monitor detectors used in the experiment at ISIS and that this should be precisely measured before any final conclusion could be drawn.

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