Measurement of Deuterium Scattering Length

A recent high precision measurement of the scattering length, *b*, of deuterium gas has been performed using neutron interferometry at the NIST Neutron Interferometer and Optics Facility [1, 2]. Accurate measurement of the scattering length is important to the fundamental nature of how a neutron scatters from an atom. This scattering length depends on the nature of the nuclear potential, and, therefore, the prediction of this value is an important test for models of the nuclear potential. Currently only few nucleon systems can be accurately modeled, and measurements of scattering lengths of light nuclei are considered to be the most interesting. To date the most accurate methods to measure the scattering length have been neutron optical methods, and prior to this work the most accurate determination of the scattering length of deuterium has been that of gravity reflectometry. These neutron optical methods measure the bound coherent scattering length, *b*, by accurately determining the index of refraction, *n*, given by,

$$n = n_{\mathrm{r}} + i n_{\mathrm{i}} \approx 1 - \sum_{m} \left[\left(N_m \lambda^2/2\pi\right)\sqrt{b_m{}^2 - \left(\sigma_m/2\lambda\right)^2} + iN_m \sigma_m \left(\lambda/4\pi\right) \right]. \quad (1)$$

In Eq. (1), *m* is the elemental species (important when correcting for contaminants); *b* is the local mean forward coherent scattering length averaged over the two spin dependent free scattering channels

$$b = \left(\frac{m_{\mathrm{n}} + m_{\mathrm{d}}}{m_{\mathrm{d}}}\right)\left[(1/3)\,{}^{2}a_{\mathrm{nd}} + (2/3)\,{}^{4}a_{\mathrm{nd}}\right] \qquad (2)$$

where ${}^{2S+1}a_{\mathrm{nd}}$ (for S = total spin = [1/2 or 3/2]) are the free doublet and quartet scattering lengths; m_{n} is the neutron mass and m_{d} is the deuteron atomic mass; λ is the neutron deBroglie wavelength; σ is the total cross section made up of the scattering and absorption cross sections; n_{r} is the real part of the index of refraction; and N is the atom density of the material. For all elements the real part of n is nearly unity: the magnitude of (n_{r} - 1) for typical neutron-nucleus potentials is approximately 1×10^{-5}. The imaginary part of Eq. (1) accounts for the attenuation of the wave amplitude due to scattering and absorption. Although such inelastic processes do not contribute to the interference of the amplitudes that travel on the two different paths through the interferometer since they make the path distinguishable in principle, they appear in the expression for the forward scattering amplitude as a result of the optical theorem. The interferometer efficiently filters out such inelastic processes that occur in the sample and in the Si interferometer blades.

Neutron interferometry is mainly sensitive to the real part of the refractive index by measuring the phase shift of a sample placed on one of two indistinguishable paths in the silicon neutron interferometer [3]. This phase shift can be written as

$$\Delta\phi = \left(n_{\mathrm{r}} - 1\right)kD_{\mathrm{eff}} = -\sum_{m} \lambda N_m b_m D_{\mathrm{eff}} \qquad (3)$$

where D_{eff} stands for the effective thickness of the medium along the direction of wave propagation. This phase shift can be very large; thus the neutron interferometric method is very sensitive to the index of refraction. Here we present the results of a measurement of the phase shift of a 1 cm thick sample of D_2 gas. The experimental setup for this measurement is shown in Fig. 1. The phase shift data converted to scattering length by inverting Eq. (3) are shown plotted in Fig. 2. Finally, averaging all values in Fig. 2 and combining the statistical and systematic uncertainties, we obtain the value for the scattering length b_{nd} = (6.665 ± 0.004) fm, which is plotted relative to previous measurements of the scattering length in Fig. 3. The new world average is then b_{nd} = (6.669 ± 0.003) fm,

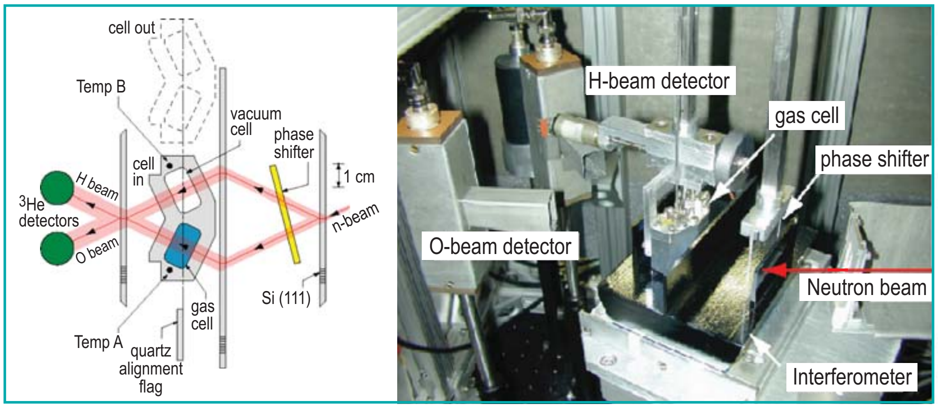

Fig. 1. A picture of the setup is shown on the right and a schematic plan view is shown on the left.

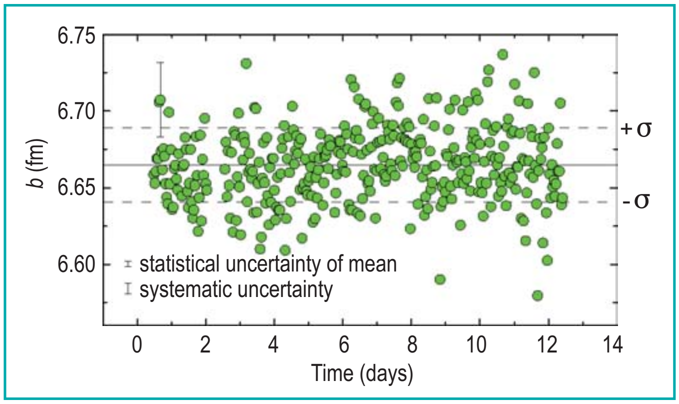

Fig. 2. All of the phase shift measurements made are shown here. The estimated statistical uncertainty per point agrees well with the statistical scatter of the data. The sizes of the final statistical and systematic uncertainties are also shown here for comparison purposes.

which is slightly lower than the previous world average of $b_{\mathrm{nd}} = (6.673 \pm 0.0045)$ fm.

This measurement has improved on the uncertainty reported by previous interferometric measurements by more than a factor of 10, and by nearly a factor of two over the previous results from gravity reflectometry. Such precision measurements of the scattering length are important for various theories dealing with 3 nucleon forces (3NF). Looking back at Eq. (2), the quartet scattering length, which is a long-range nuclear interaction, can be calculated accurately from nucleon-nucleon potentials and is insensitive to 3NF effects that are currently used to calculate the shorter range doublet scattering length. Because the effective range function in the quartet spin channel is a smooth function of energy, the quartet scattering can be accurately extracted from an energy dependent phase shift analysis, so that experimental measurement of the bound coherent scattering length and theoretical calculation of the quartet scattering length allow the doublet scattering length to be extracted and compared to calculation using 3NF models. Only one of the scattering length calculations reported previous to this result falls within the (± 1)σ confidence band of this measurement shown in Fig. 4.

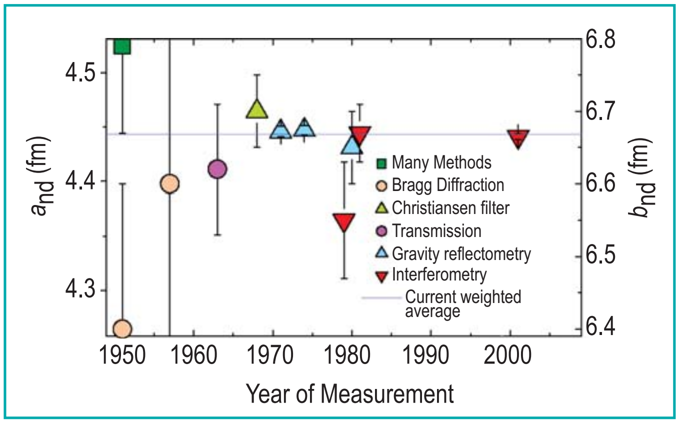

Fig. 3. Shown here are all the values and names of methods used to measure *b* for deuterium over the years. The average is a weighted average including all of these measurements.

Future experiments will be able to lower the combined systematic and statistical uncertainty by as much as a factor of 5. This would allow one to measure higher order effects due to molecular binding in H_2 and D_2. Other elements such as ^{3}He and $^3H_2$ could also be measured with lower uncertainties than those currently in the open literature.

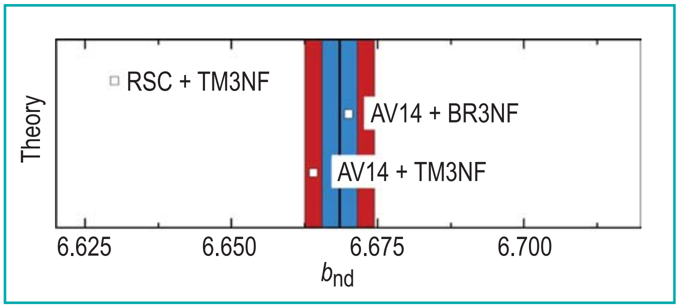

Fig. 4. The 1σ (blue) and 2σ (red) confidence intervals are shown here. Only two theories fall within 2σ of this result.

References

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