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DETERMINATION OF h/m_n

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Résumé - La connaissance des constantes fondamentales peut être améliorée en déterminant de façon précise le rapport h/m_n (h constante de Planck, m_n masse du neutron). Une mesure préliminaire de h/m_n avec une incertitude relative d'environ 10^{-5} est décrite. Elle a été effectuée auprès du réacteur de l'Institut Laue-Langevin à Grenoble.

Abstract - Knowledge of the fundamental constants can be improved by precisely determining the ratio h/m_n (h Planck constant, m_n neutron mass). A preliminary measurement of h/m_n with a relative uncertainty of about 10^{-5} is described. It has been carried out at the reactor of the Institut Laue-Langevin in Grenoble.

1. Introduction

The recommended values of the fundamental constants are the results of least-squares adjustments which use measured values of these constants as well as combinations of them as input parameters. The last adjustment was carried out by Cohen and Taylor /1/ in 1973.

A measured value of h/m_n (h Planck constant, m_n neutron mass) would be a very helpful new input parameter for the adjustment, provided that its relative uncertainty is not larger than about 1×10^{-6} .

h/m_n can be determined by simultaneously measuring the wavelength λ and the velocity v of monochromatic neutrons. By means of the de Broglie equation, it follows from these two quantities that

$$h/m_n = \lambda v. \quad (1)$$

Several methods for such an experiment have been proposed /2-4/. The one which gives the best chance of achieving high accuracy /4/ has been used in a preliminary determination of h/m_n .

2. The measuring method

2.1. The principle

For measuring the velocity of the neutrons, a beam of polarized neutrons is modulated by periodically changing the direction of the polarization vector. After a path of several meters, the neutrons are back-reflected by a silicon single-crystal. They thus pass the modulator for a second time, where the beam is again modulated. The modulator defines the beginning as well as the end of a flight path. The total modulation is measured as a function of the length of the flight path. The velocity of the neutrons follows from this periodic function.

The wavelength of the neutrons is determined by back-reflection in the silicon crystal. Silicon is used because almost perfect crystals can be grown from this material and its lattice parameter is known with the required small uncertainty /5,6/.

2.2. The beam of polarized neutrons

A polarized neutron beam is produced by Bragg reflection in a Heusler crystal H1 (see Fig. 1). The polarization vector \vec{p} is antiparallel to the magnetic induction \vec{B}_H in the crystal and the magnetic guide field (magnetic induction \vec{B}_0).

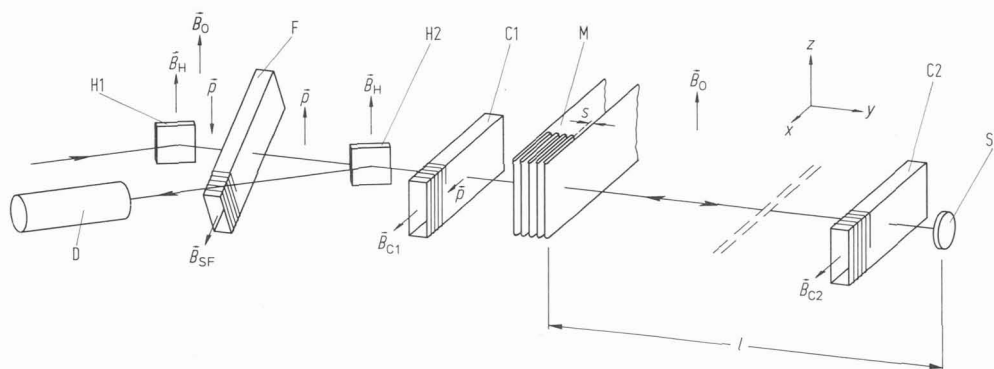


Fig. 1 - Arrangement for measuring h/m_n . (H1, H2) Heusler crystals, (F) flipping coil, (C1, C2) Mezei coils, (M) meander coil, (Si) silicon crystal, (D) detector. \vec{B}_0 magnetic induction of the guide field, \vec{B}_H magnetic induction magnetizing a Heusler crystal, \vec{p} polarization vector if the meander coil is not operating.

In the flipping coil F \vec{p} is reversed. The neutrons then hit a second Heusler crystal H2 which is magnetized in the same direction as H1. Due to the reversion of \vec{p} , the neutrons can traverse it without reflection. In the Mezei coil C1 \vec{p} is subsequently turned into the direction of the x axis.

The neutrons traverse the modulating assembly M, which should be disregarded at the moment, and a second Mezei coil C2. They are then reflected by the silicon crystal mentioned above and return to coil C1.

Along the entire path, from leaving coil C1 to reaching it again, \vec{p} precesses in the guide field. But the precession is cancelled by a technique which is similar to the spin-echo technique first used by Mezei /7/. For this purpose coil C2 is required. As the result \vec{p} is again parallel to the x axis when the neutrons enter coil C1 for the second time.

In coil C1, \vec{p} is turned back into the direction of the z axis. The neutrons impinge on the Heusler crystal H2 for a second time. Because \vec{p} is parallel to \vec{B}_H , the neutrons are again not reflected. They cannot therefore reach detector D.

2.3. Modulating the neutron beam

Assembly M used for modulating the neutron beam consists of an aluminium foil, bent to form a meander. It is therefore referred to as a meander coil.

The meander coil forms a close sequence of single coils, each with one turn. If an electric current is passed through them, the magnetic inductions in neighbouring coils are antiparallel. If alternating current is used, there is a phase difference of π between the magnetic inductions in the neighbouring coils. An arrangement of this type, operated with direct current, was used by Drabkin et al. /8/ for the construction of a velocity filter for polarized neutrons.

To modulate the direction of \vec{p} , the meander coil is operated with high-frequency alternating current. The coil field is parallel to the guide field. The thickness s of the single coils is such that the neutrons pass each of them in half a period of

the alternating current. As a consequence, the neutrons find the same variation of the magnetic induction in all the single coils. Hence, \vec{p} precesses in the same way in all of them. In the whole meander coil the precession angle adds up to

$$\phi(t) = \hat{\phi} \cos 2\pi\nu t, \quad (2)$$

$$\hat{\phi} = N(4\mu_n \hat{B}_m / h\nu) \quad (3)$$

(ν frequency of the electric current, t time, N number of single coils of which the meander coil consists, μ_n magnetic moment of the neutron, \hat{B}_m amplitude of the alternating magnetic induction within the coil).

2.4. Measuring the velocity of the neutrons

When the neutrons leave the meander coil for the first time, the direction of \vec{p} is modulated as given by Eq. (2). \vec{p} is at any time in the xy plane (see Fig. 1). Returning from the silicon crystal, the neutrons traverse the meander coil for a second time. The direction of \vec{p} is again modulated, this time by the angle

$$\phi(t+2l/v) = \hat{\phi} \cos[2\pi\nu(t+2l/v)], \quad (4)$$

where l is the distance between the meander coil and the silicon crystal.

The two modulations add up to the total modulation

$$\phi_{\text{tot}}(t, l) = \phi(t) + \phi(t+2l/v) = 2\hat{\phi} \cos(2\pi\nu l/v) \cos[2\pi\nu(t+l/v)]. \quad (5)$$

After the second modulation, the neutrons traverse coil C1 in which \vec{p} is turned from the xy plane into the yz plane. $\phi_{\text{tot}}(t, l)$ is then the angle between \vec{p} and the z axis.

The neutrons again hit the Heusler crystal H2. Because the direction of \vec{p} varies, the probability of reflection varies, too. Hence, a time-dependent neutron current reaches the detector. The detector measures the mean neutron current \bar{I} which is given by

$$\bar{I}(l) = (I_0/2) \{1 - J_0[2\hat{\phi} \cos(2\pi\nu l/v)]\}. \quad (6)$$

J_0 is the zero-order Bessel function, and I_0 the neutron current if \vec{p} is anti-parallel to the z axis. Fig. 2 shows $\bar{I}(l)/I_0^0$ as calculated for $\hat{\phi} = 0.61 \pi$ and $\hat{\phi} = 1.22 \pi$.

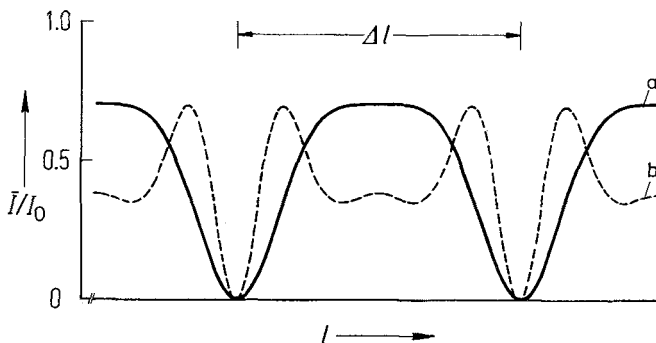


Fig. 2 - Calculated ratio \bar{I}/I_0^0 as a function of the distance l . Parameter: (a) $\hat{\phi} = 0.61 \pi$, (b) $\hat{\phi} = 1.22 \pi$.

The velocity of the neutrons is given by

$$v = 2\Delta l\nu, \quad (7)$$

as follows from Eq. (6). Δl is the difference between values of l belonging to neighbouring minima of $\bar{I}(l)/I_0$.

In order to determine v with high accuracy, a large multiple of Δl must be measured. For this purpose, two minima of $\bar{I}(l)/I_0$ are determined, the l values of which differ by several meters. To change l , the meander coil is moved.

3. Preliminary measurement

The measuring method was first tested at the reactor of the Physikalisch-Technische Bundesanstalt /9-11/. The experiments turned out very successfully, and h/m_n could be determined with a relative uncertainty of 1×10^{-3} . However, detailed tests could not be carried out because of the small neutron current. The measurements were therefore continued at the high-flux reactor of the Institut Laue-Langevin in Grenoble.

A preliminary version of the apparatus is installed at the thermal neutron guide H21. The neutrons are reflected out of the guide by oriented graphite. They then hit the Heusler crystal H1 (see Fig. 1).

The arrangement is as schematically shown in Fig. 1, except for a small difference: the neutrons reflected by the crystal H2 do not reach detector D directly. They are first reflected by an additional crystal (oriented graphite). Thus those neutrons which crystal H2 scatters inelastically out of the incoming beam cannot reach the detector. In this way the background could considerably be reduced.

The (331) reflection of silicon is used, corresponding to the wavelength $\lambda=0.2492$ nm.

The meander coil is made of aluminium foil, 60 μm thick and 90 mm wide. It consists of $N = 99$ single coils, each of which is $s = 1.058$ mm thick. The modulation frequency is $\nu = 750.3$ kHz. The meander coil can be moved by 50 cm. Its displacement is measured by means of a laser interferometer.

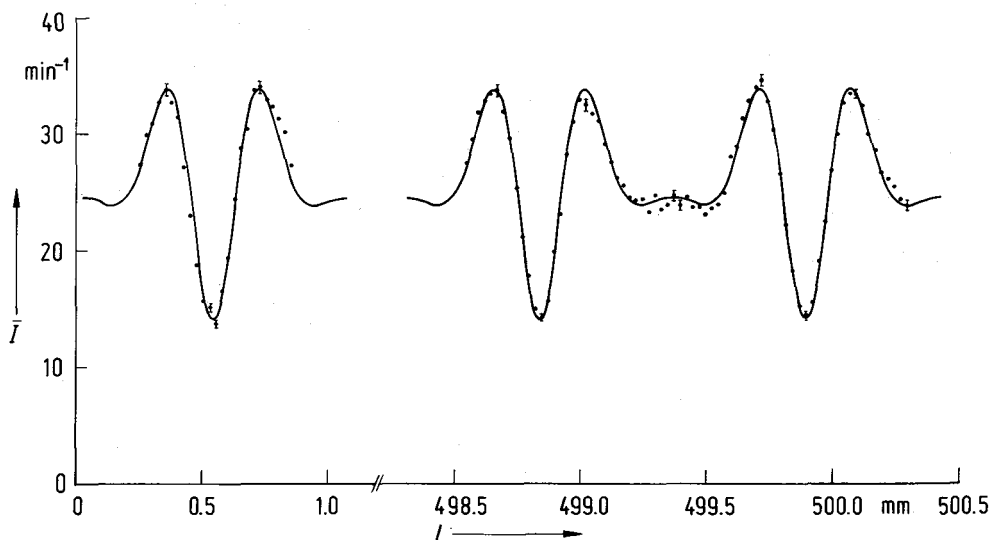


Fig. 3 - Mean neutron current \bar{I} measured as a function of the displacement L of the meander coil.

Fig. 3 shows the mean neutron current \bar{I} measured as a function of the displacement L of the meander coil. Each point has been measured for a period of 2 hours. 470 minima have been omitted between the two stages of the measurement, following from the previously known value of h/m_n .

A curve of the theoretically expected shape is fitted to the measured values. From the positions of their minima it follows that:

$$h/m_n = (3.956093 \pm 0.000063) \times 10^{-7} \text{ m}^2 \text{ s}^{-1}. \quad (8)$$

In accordance with the preliminary character of the measurement, no systematic uncertainties have been considered.

The measured value of h/m_n is in good agreement with the more accurate one calculated from the recommended values of h and $m_n/1$, which is

$$h/m_n = (3.956034 \pm 0.000007) \times 10^{-7} \text{ m}^2 \text{ s}^{-1}. \quad (9)$$

4. The final experiment in preparation

In order to reduce the uncertainty of the measurement by an order of magnitude, a new apparatus is under construction. It differs from the preliminary version in the following points:

- a) The distance l can be varied by 10 m.
- b) The neutron beam and the measuring light beam of the laser interferometer are inside a vacuum chamber, thus increasing the neutron current and avoiding corrections of the light wavelength.
- c) The mechanical set-up is very precise, and deviations from the correct adjustment are automatically corrected.

5. Conclusion

A preliminary measurement of h/m_n with a relative uncertainty of about 10^{-5} has been carried out at the reactor of the Institut Laue-Langevin in Grenoble. The experiment showed that it should be possible to reduce the uncertainty by a further order of magnitude. An apparatus suited for such a measurement is under construction.

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