Old and new stories about ultracold neutrons

Dubna, Prof. F. L. Shapiro memorial seminar, April 6, 2015

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My small contribution on this 100 year anniversary of Prof. Shapiro’s birthday:

- Some old ultracold neutron stories of ~50 years ago from “the other side of the Iron Curtain”
- (Time permitting) mention a new development in his suggestion of 1968 to search for the neutron electric dipole moment using stored UCNs.

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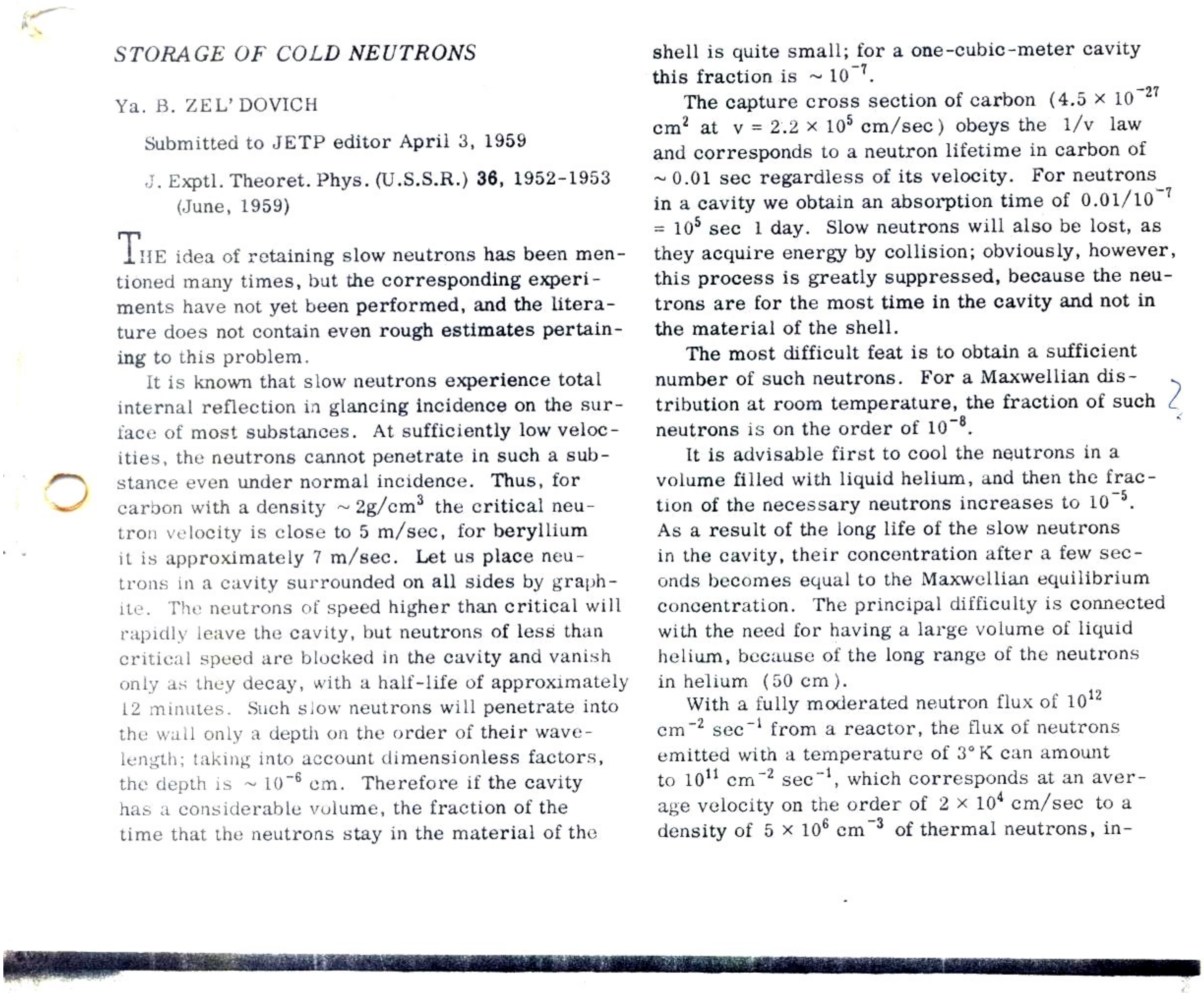

STORAGE OF COLD NEUTRONS

Ya. B. ZEL' DOVICH

Submitted to JETP editor April 3, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 1952-1953 (June, 1959)

THE idea of retaining slow neutrons has been mentioned many times, but the corresponding experiments have not yet been performed, and the literature does not contain even rough estimates pertaining to this problem.

It is known that slow neutrons experience total internal reflection in glancing incidence on the surface of most substances. At sufficiently low velocities, the neutrons cannot penetrate in such a substance even under normal incidence. Thus, for carbon with a density $\sim 2\text{g/cm}^3$ the critical neutron velocity is close to 5 m/sec, for beryllium it is approximately 7 m/sec. Let us place neutrons in a cavity surrounded on all sides by graphite. The neutrons of speed higher than critical will rapidly leave the cavity, but neutrons of less than critical speed are blocked in the cavity and vanish only as they decay, with a half-life of approximately 12 minutes. Such slow neutrons will penetrate into the wall only a depth on the order of their wavelength; taking into account dimensionless factors, the depth is $\sim 10^{-6}$ cm. Therefore if the cavity has a considerable volume, the fraction of the time that the neutrons stay in the material of the shell is quite small; for a one-cubic-meter cavity this fraction is $\sim 10^{-7}$.

The capture cross section of carbon (4.5×10^{-27} cm^2 at $v = 2.2 \times 10^5$ cm/sec) obeys the $1/v$ law and corresponds to a neutron lifetime in carbon of ~ 0.01 sec regardless of its velocity. For neutrons in a cavity we obtain an absorption time of $0.01/10^{-7} = 10^5$ sec 1 day. Slow neutrons will also be lost, as they acquire energy by collision; obviously, however, this process is greatly suppressed, because the neutrons are for the most time in the cavity and not in the material of the shell.

The most difficult feat is to obtain a sufficient number of such neutrons. For a Maxwellian distribution at room temperature, the fraction of such ? neutrons is on the order of 10^{-8}.

It is advisable first to cool the neutrons in a volume filled with liquid helium, and then the fraction of the necessary neutrons increases to 10^{-5}. As a result of the long life of the slow neutrons in the cavity, their concentration after a few seconds becomes equal to the Maxwellian equilibrium concentration. The principal difficulty is connected with the need for having a large volume of liquid helium, because of the long range of the neutrons in helium (50 cm).

With a fully moderated neutron flux of 10^{12} cm^{-2} sec^{-1} from a reactor, the flux of neutrons emitted with a temperature of 3° K can amount to 10^{11} cm^{-2} sec^{-1}, which corresponds at an average velocity on the order of 2×10^4 cm/sec to a density of 5×10^6 cm^{-3} of thermal neutrons, in-

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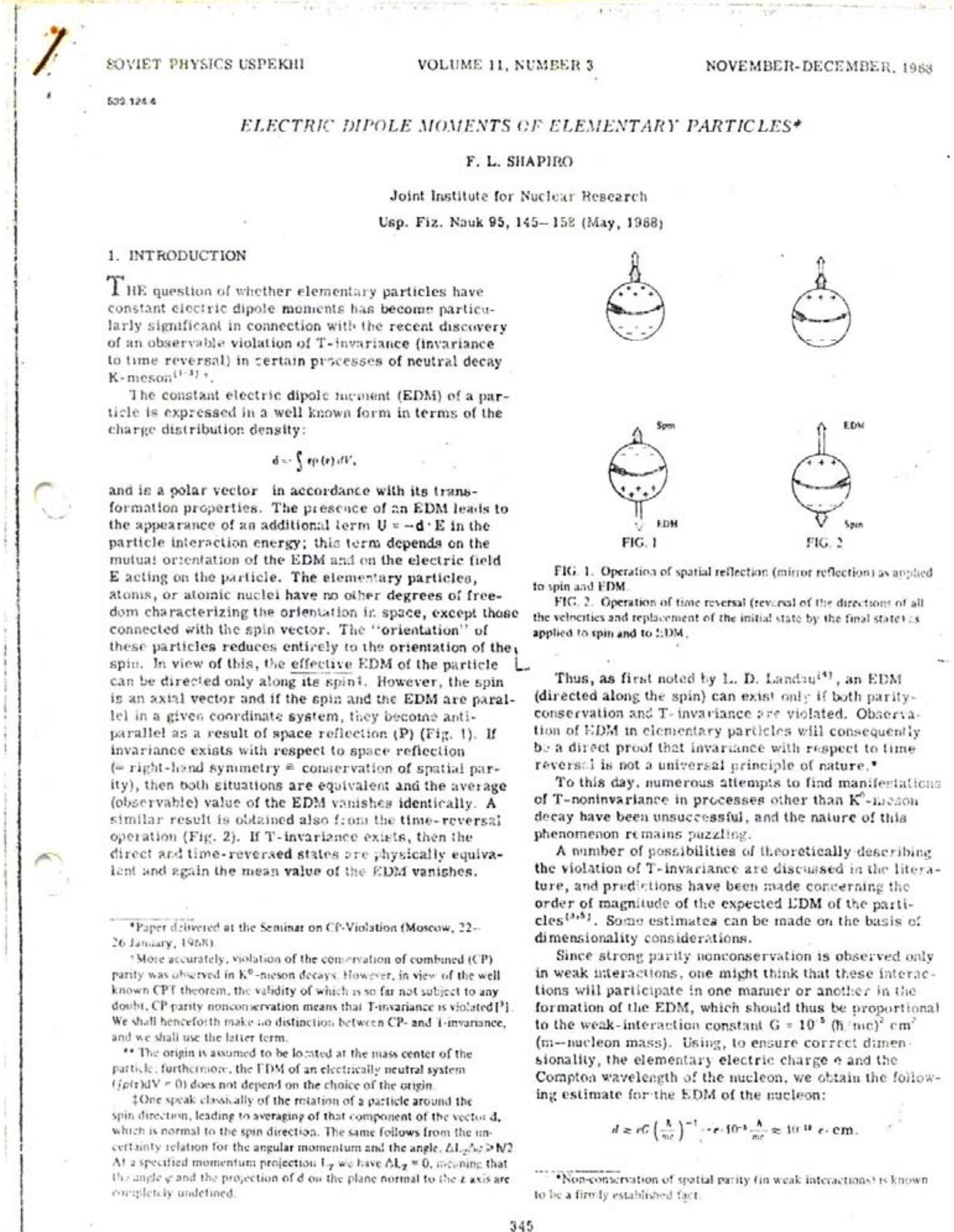
- Shapiro 1968: Suggestion to use stored UCN for an EDM experiment.

F. L. Shapiro 1968



SOVIET PHYSICS USPEKHI VOLUME 11, NUMBER 3 NOVEMBER-DECEMBER, 1968

539.124.4

*ELECTRIC DIPOLE MOMENTS OF ELEMENTARY PARTICLES**

F. L. SHAPIRO

Joint Institute for Nuclear Research

Usp. Fiz. Nauk 95, 145–158 (May, 1968)

1. INTRODUCTION

THE question of whether elementary particles have constant electric dipole moments has become particularly significant in connection with the recent discovery of an observable violation of T-invariance (invariance to time reversal) in certain processes of neutral decay K-meson[1-3] †.

The constant electric dipole moment (EDM) of a particle is expressed in a well known form in terms of the charge distribution density:

$$\mathbf{d} = \int \mathbf{r}\rho(\mathbf{r})\,dV,$$

and is a polar vector** in accordance with its transformation properties. The presence of an EDM leads to the appearance of an additional term $U = -\mathbf{d}\cdot\mathbf{E}$ in the particle interaction energy; this term depends on the mutual orientation of the EDM and on the electric field E acting on the particle. The elementary particles, atoms, or atomic nuclei have no other degrees of freedom characterizing the orientation in space, except those connected with the spin vector. The "orientation" of these particles reduces entirely to the orientation of the spin. In view of this, the effective EDM of the particle can be directed only along its spin‡. However, the spin is an axial vector and if the spin and the EDM are parallel in a given coordinate system, they become antiparallel as a result of space reflection (P) (Fig. 1). If invariance exists with respect to space reflection (= right-hand symmetry ≡ conservation of spatial parity), then both situations are equivalent and the average (observable) value of the EDM vanishes identically. A similar result is obtained also from the time-reversal operation (Fig. 2). If T-invariance exists, then the direct and time-reversed states are physically equivalent and again the mean value of the EDM vanishes.

FIG. 1 FIG. 2

FIG. 1. Operation of spatial reflection (mirror reflection) as applied to spin and EDM.

FIG. 2. Operation of time reversal (reversal of the directions of all the velocities and replacement of the initial state by the final state) as applied to spin and to EDM.

Thus, as first noted by L. D. Landau[4], an EDM (directed along the spin) can exist only if both parity-conservation and T-invariance are violated. Observation of EDM in elementary particles will consequently be a direct proof that invariance with respect to time reversal is not a universal principle of nature.*

To this day, numerous attempts to find manifestations of T-noninvariance in processes other than K^0-meson decay have been unsuccessful, and the nature of this phenomenon remains puzzling.

A number of possibilities of theoretically describing the violation of T-invariance are discussed in the literature, and predictions have been made concerning the order of magnitude of the expected EDM of the particles[3,5]. Some estimates can be made on the basis of dimensionality considerations.

Since strong parity nonconservation is observed only in weak interactions, one might think that these interactions will participate in one manner or another in the formation of the EDM, which should thus be proportional to the weak-interaction constant $G = 10^{-5}\,(\hbar/mc)^2\ \mathrm{cm}^2$ (m—nucleon mass). Using, to ensure correct dimensionality, the elementary electric charge e and the Compton wavelength of the nucleon, we obtain the following estimate for the EDM of the nucleon:

$$d \approx eG\left(\frac{\hbar}{mc}\right)^{-1} \approx e\cdot 10^{-5}\frac{\hbar}{mc} \approx 10^{-19}\ e\cdot\mathrm{cm}.$$

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*Paper delivered at the Seminar on CP-Violation (Moscow, 22–26 January, 1968).

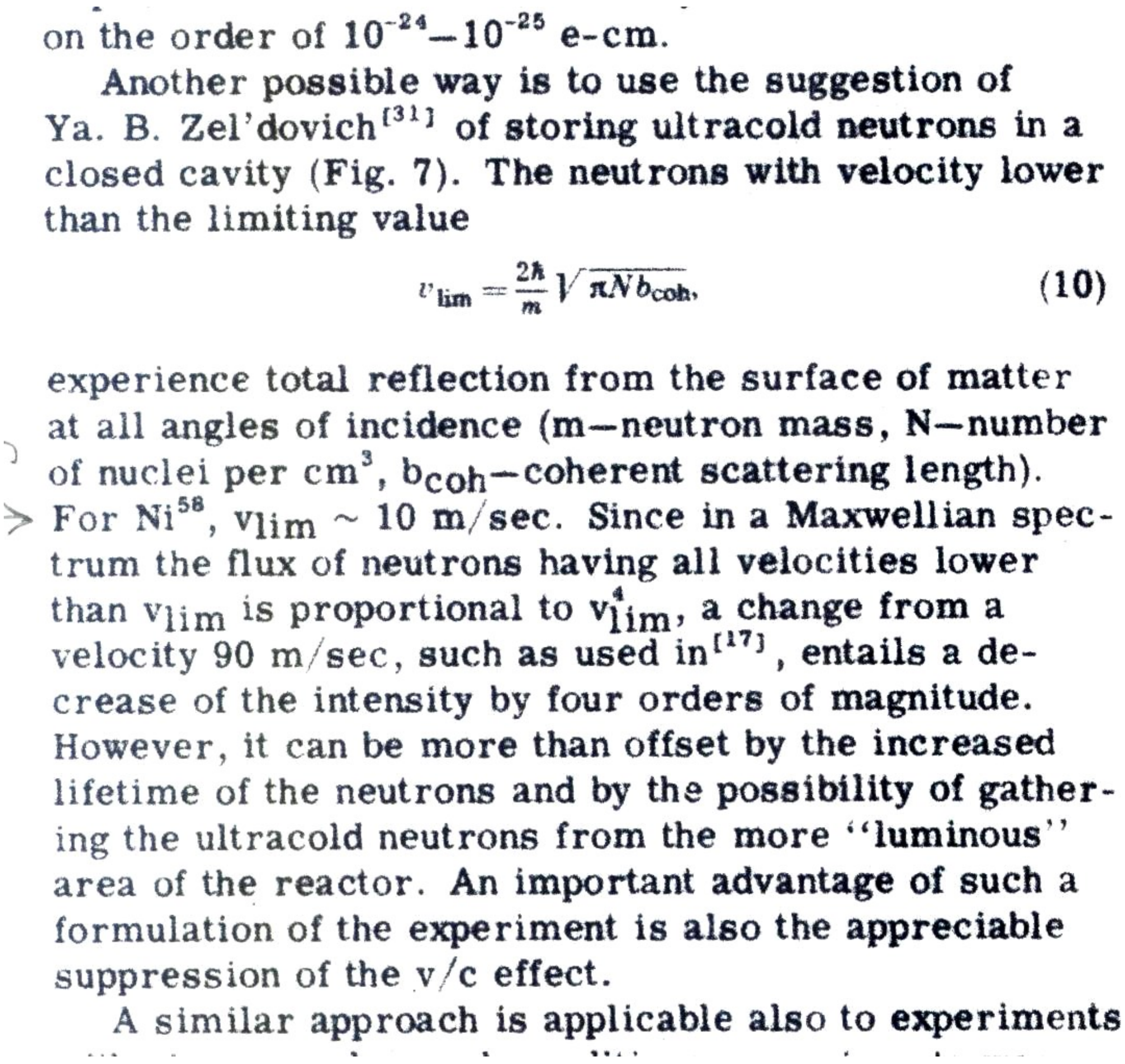
†More accurately, violation of the conservation of combined (CP) parity was observed in K^0-meson decays. However, in view of the well known CPT theorem, the validity of which is so far not subject to any doubt, CP parity nonconservation means that T-invariance is violated[3]. We shall henceforth make no distinction between CP- and T-invariance, and we shall use the latter term.

** The origin is assumed to be located at the mass center of the particle; furthermore, the EDM of an electrically neutral system ($\int\rho(\mathbf{r})dV = 0$) does not depend on the choice of the origin.

‡One speak classically of the rotation of a particle around the spin direction, leading to averaging of that component of the vector d, which is normal to the spin direction. The same follows from the uncertainty relation for the angular momentum and the angle, $\Delta L_z\Delta\varphi \geq \hbar/2$. At a specified momentum projection L_z we have $\Delta L_z = 0$, meaning that the angle φ and the projection of d on the plane normal to the z axis are completely undefined.

*Non-conservation of spatial parity (in weak interactions) is known to be a firmly established fact.

Shapiro's proposal: Use UCN for EDM



on the order of 10^{-24}—10^{-25} e-cm.

Another possible way is to use the suggestion of Ya. B. Zel'dovich[31] of storing ultracold neutrons in a closed cavity (Fig. 7). The neutrons with velocity lower than the limiting value

$$v_{\lim} = \frac{2\hbar}{m}\sqrt{\pi N b_{\mathrm{coh}}}, \tag{10}$$

experience total reflection from the surface of matter at all angles of incidence (m—neutron mass, N—number of nuclei per cm^3, b_{coh}—coherent scattering length). For Ni^{58}, $v_{lim} \sim 10$ m/sec. Since in a Maxwellian spectrum the flux of neutrons having all velocities lower than v_{lim} is proportional to v_{lim}^4, a change from a velocity 90 m/sec, such as used in[17], entails a decrease of the intensity by four orders of magnitude. However, it can be more than offset by the increased lifetime of the neutrons and by the possibility of gathering the ultracold neutrons from the more "luminous" area of the reactor. An important advantage of such a formulation of the experiment is also the appreciable suppression of the v/c effect.

A similar approach is applicable also to experiments

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First an introduction to the scenery, the FRM reactor (Forschungsreaktor München):

- Swimming pool type
- light-water moderated
- thermal flux ~10^{13} $\mathrm{cm}^{-2}\mathrm{s}^{-2}$; no Cold Source

(~1% of ILL; ~10^3 times mean flux of IBR30)

The “atomic egg” alias reactor FRM

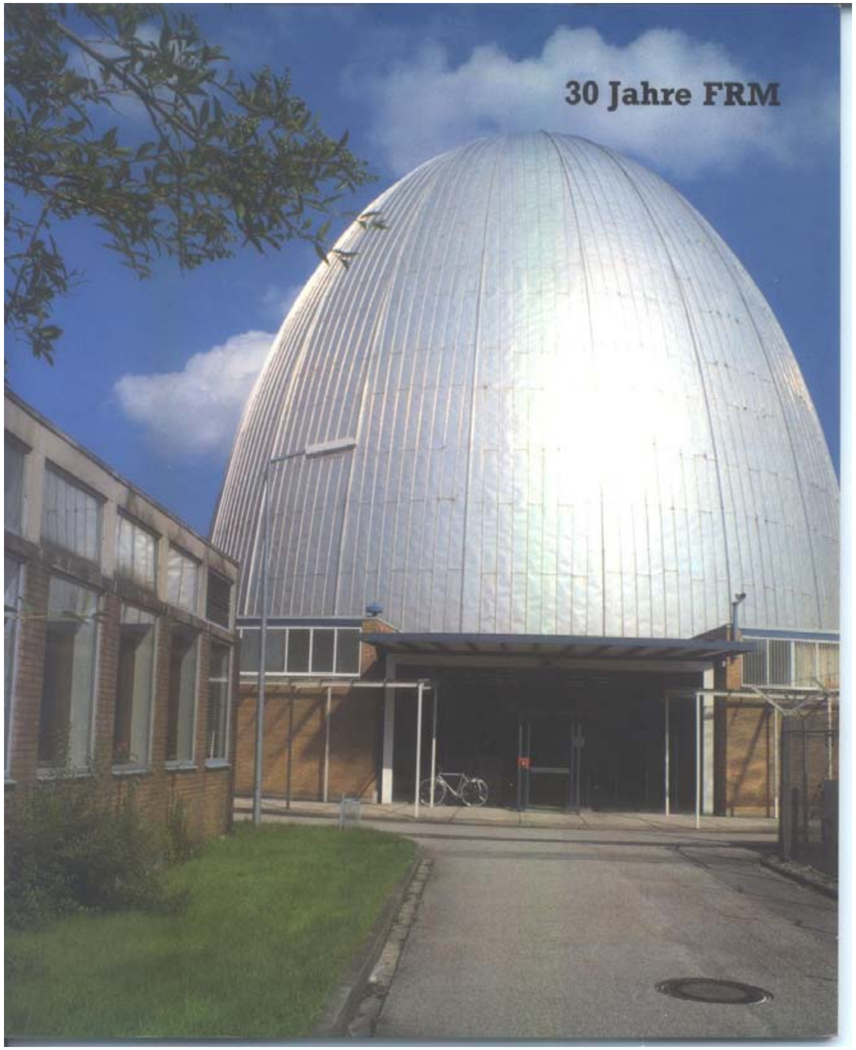

Abb. 3: Heinz Maier-Leibnitz, der wissenschaftliche Leiter des FRM während der ersten 10 Jahre.

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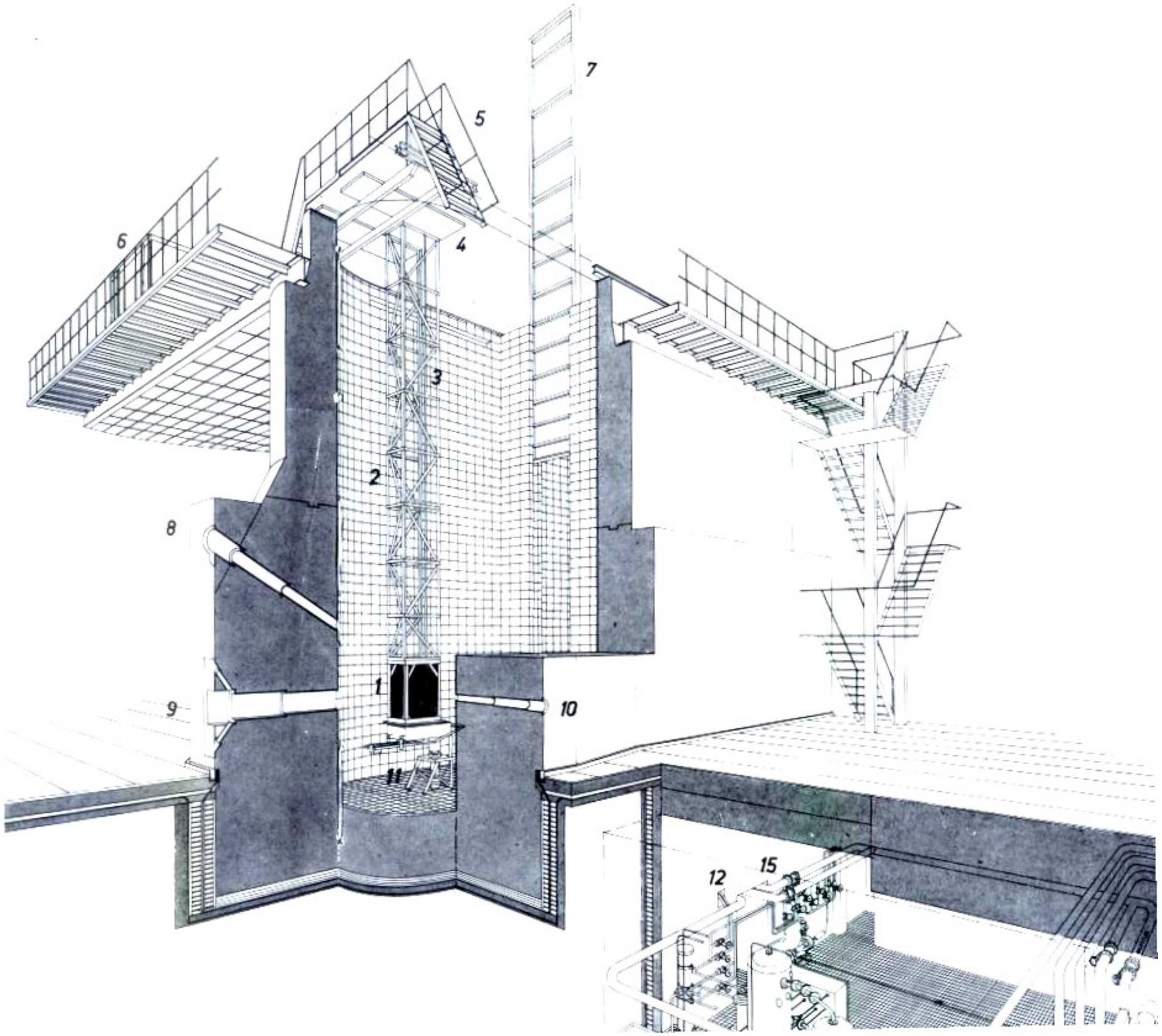
- Typically, every student built their apparatus themselves.

Vertical cut through the reactor pool

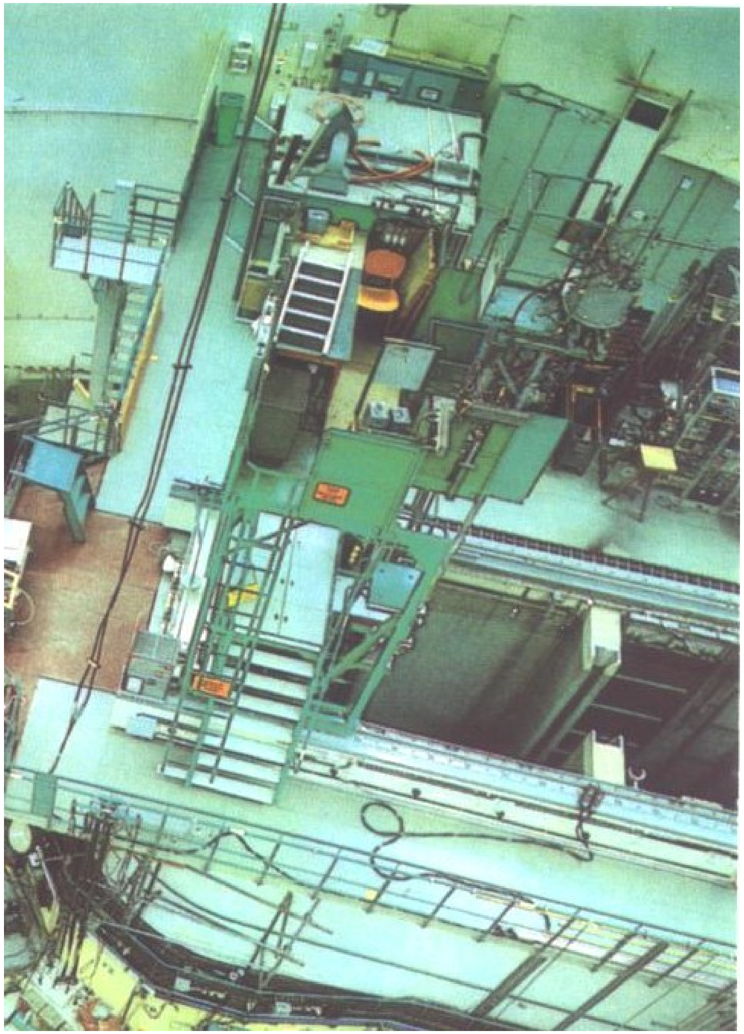


Bird’s eye view of FRM instruments

Upper platform with “chicken ladder”

Overview 1987 with LWS, turbine and NESSIE

Abb. 1: Innenansicht der Reaktorhalle. Im Bild



A glance a the history of the vertical guide for very slow neutrons (or LWS for long wavelength beam tube):

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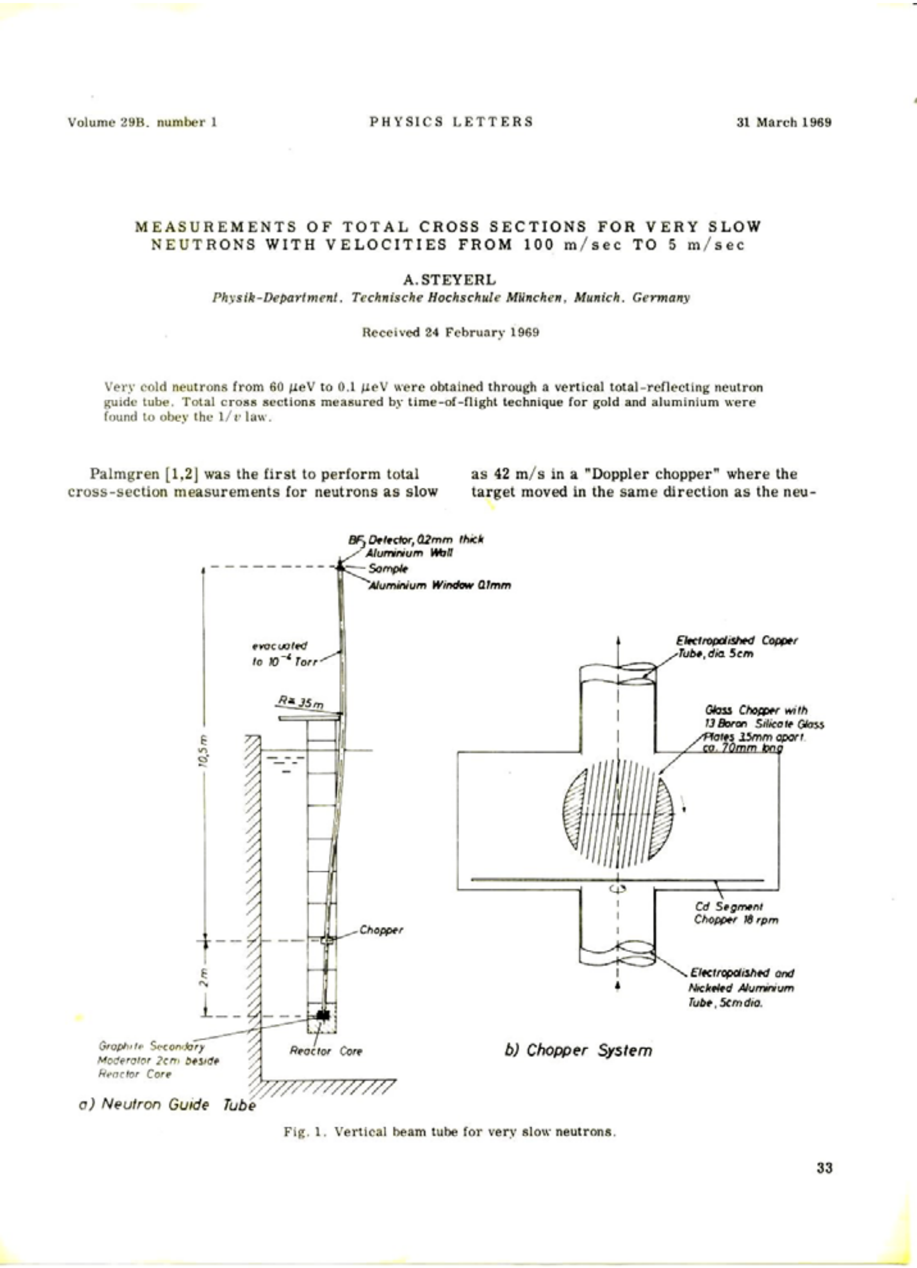
- Vertical solution had tricky features of its own.

Vertical guide tube LWS



Volume 29B, number 1 PHYSICS LETTERS 31 March 1969

MEASUREMENTS OF TOTAL CROSS SECTIONS FOR VERY SLOW NEUTRONS WITH VELOCITIES FROM 100 m/sec TO 5 m/sec

A. STEYERL
Physik-Department, Technische Hochschule München, Munich, Germany

Received 24 February 1969

Very cold neutrons from 60 μeV to 0.1 μeV were obtained through a vertical total-reflecting neutron guide tube. Total cross sections measured by time-of-flight technique for gold and aluminium were found to obey the 1/v law.

Palmgren [1,2] was the first to perform total cross-section measurements for neutrons as slow as 42 m/s in a "Doppler chopper" where the target moved in the same direction as the neu-

Fig. 1. Vertical beam tube for very slow neutrons.

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- Pool water enters the guide

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Very cold neutron transmission through a copper foil

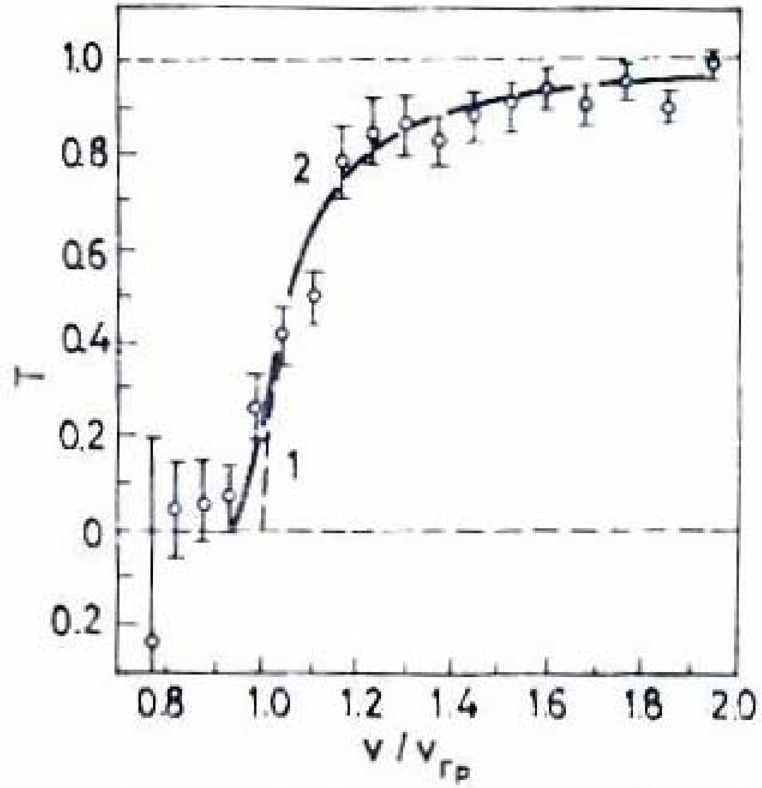

Fig. 7. Transmission of Cu foil for UCN

Some disasters (not in chronological order):

- Pool water enters the guide;
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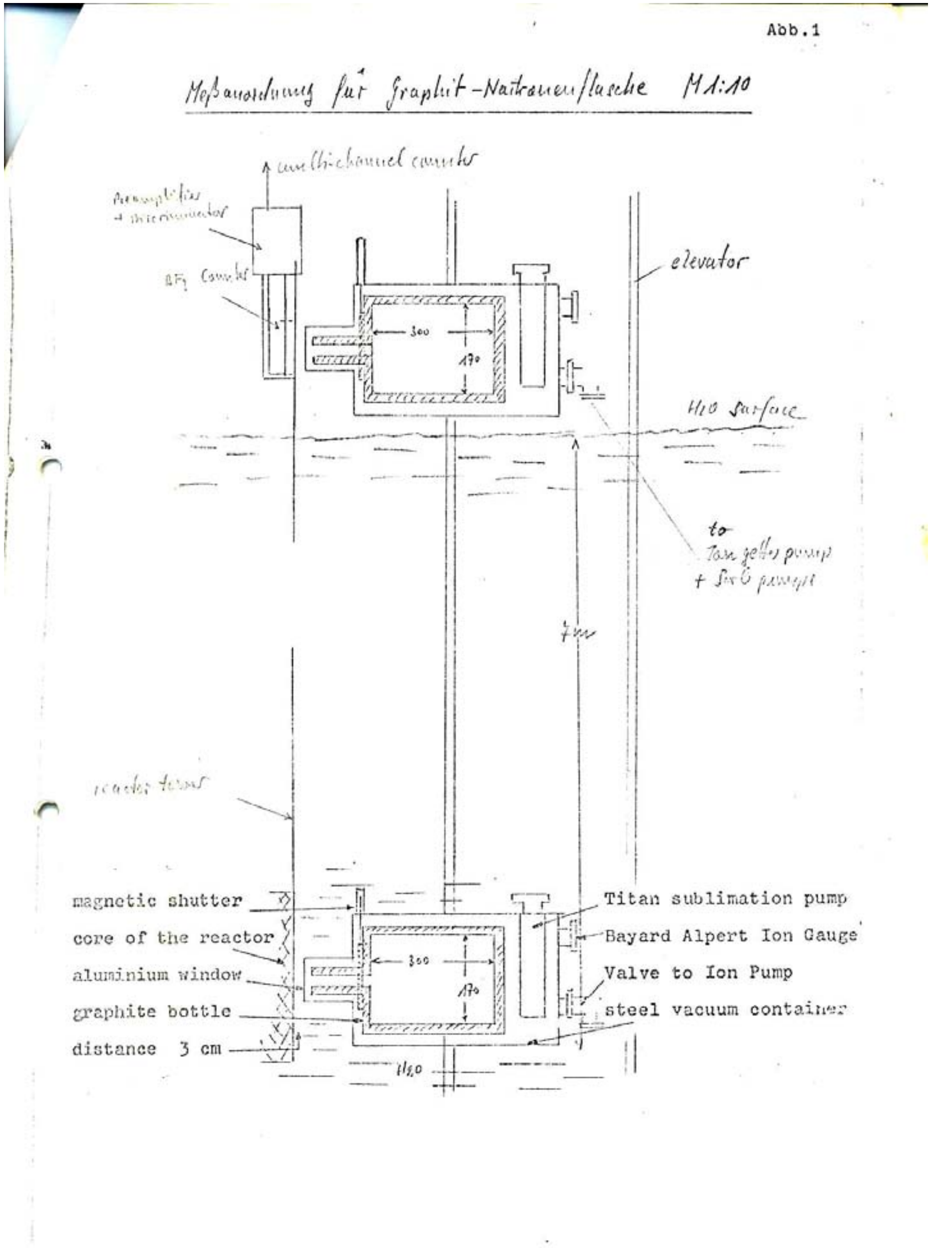
- The ill-fated submerged graphite bottle.

Schematic of the movable bottle (Trűstedt, Koester, Steyerl)



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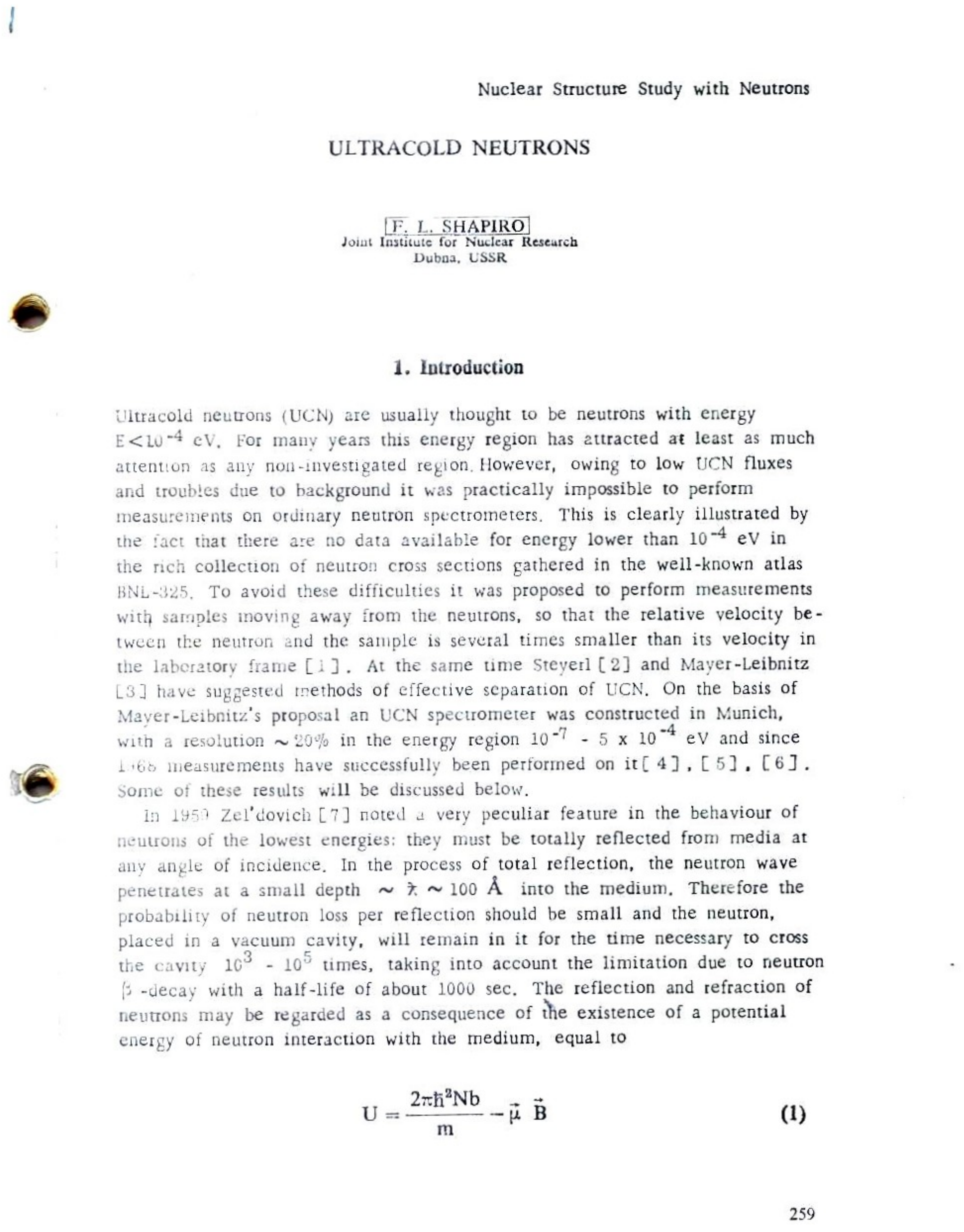
F. L. Shapiro, paper for Budapest, 1972



ULTRACOLD NEUTRONS

F. L. SHAPIRO
Joint Institute for Nuclear Research
Dubna, USSR

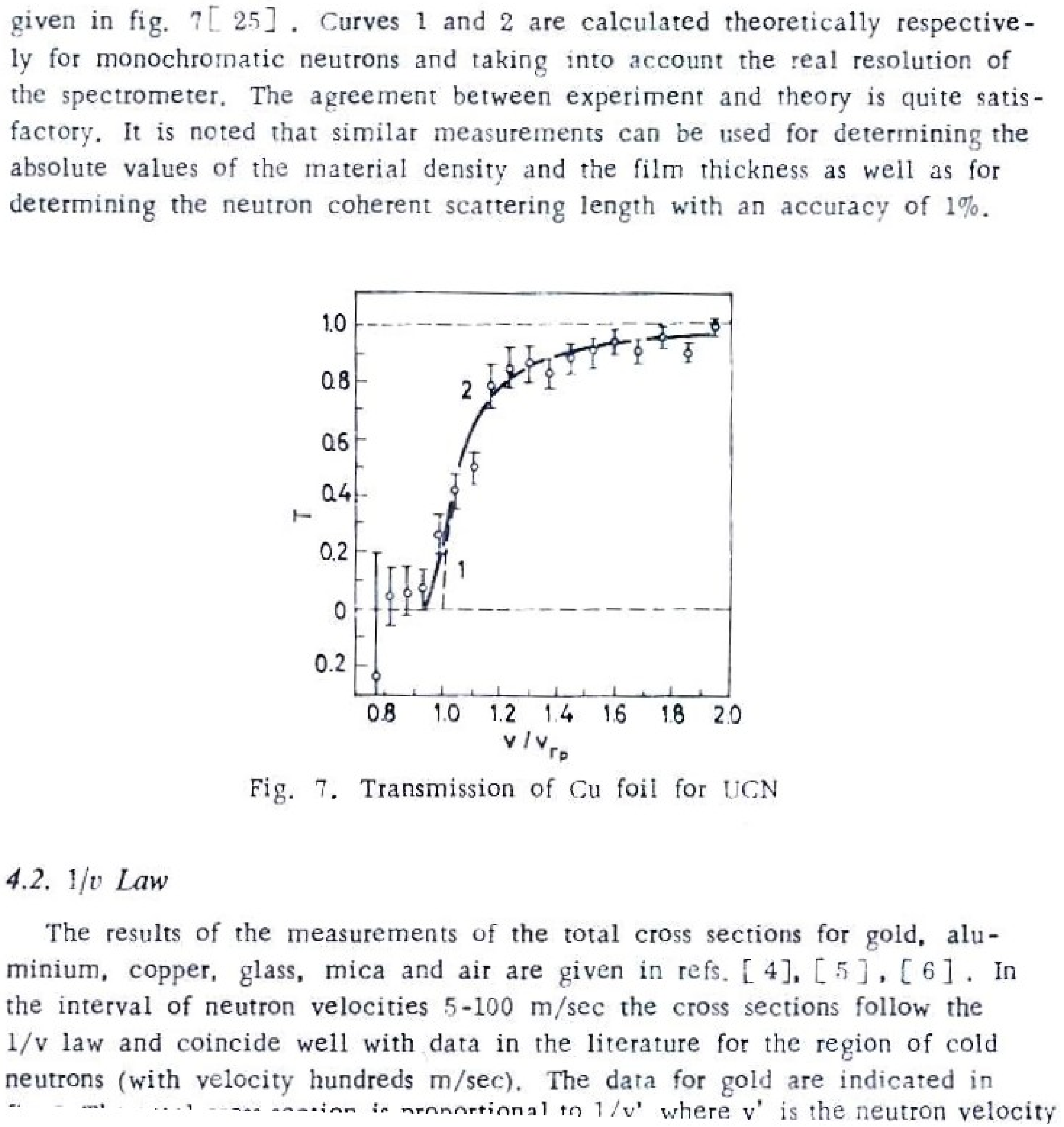
1. Introduction

Ultracold neutrons (UCN) are usually thought to be neutrons with energy $E < 10^{-4}$ eV. For many years this energy region has attracted at least as much attention as any non-investigated region. However, owing to low UCN fluxes and troubles due to background it was practically impossible to perform measurements on ordinary neutron spectrometers. This is clearly illustrated by the fact that there are no data available for energy lower than 10^{-4} eV in the rich collection of neutron cross sections gathered in the well-known atlas BNL-325. To avoid these difficulties it was proposed to perform measurements with samples moving away from the neutrons, so that the relative velocity between the neutron and the sample is several times smaller than its velocity in the laboratory frame [1]. At the same time Steyerl [2] and Mayer-Leibnitz [3] have suggested methods of effective separation of UCN. On the basis of Mayer-Leibnitz's proposal an UCN spectrometer was constructed in Munich, with a resolution ~ 20% in the energy region 10^{-7} - 5×10^{-4} eV and since 1968 measurements have successfully been performed on it [4], [5], [6]. Some of these results will be discussed below.

In 1959 Zel'dovich [7] noted a very peculiar feature in the behaviour of neutrons of the lowest energies: they must be totally reflected from media at any angle of incidence. In the process of total reflection, the neutron wave penetrates at a small depth $\sim ƛ \sim 100$ Å into the medium. Therefore the probability of neutron loss per reflection should be small and the neutron, placed in a vacuum cavity, will remain in it for the time necessary to cross the cavity 10^3 - 10^5 times, taking into account the limitation due to neutron β-decay with a half-life of about 1000 sec. The reflection and refraction of neutrons may be regarded as a consequence of the existence of a potential energy of neutron interaction with the medium, equal to

$$U = \frac{2\pi\hbar^2 N b}{m} - \vec{\mu}\,\vec{B} \qquad (1)$$

F. L. Shapiro, 1972: One of 4 figures giving credit to our work at Garching



given in fig. 7[25]. Curves 1 and 2 are calculated theoretically respectively for monochromatic neutrons and taking into account the real resolution of the spectrometer. The agreement between experiment and theory is quite satisfactory. It is noted that similar measurements can be used for determining the absolute values of the material density and the film thickness as well as for determining the neutron coherent scattering length with an accuracy of 1%.

Fig. 7. Transmission of Cu foil for UCN

4.2. 1/*v* Law

The results of the measurements of the total cross sections for gold, aluminium, copper, glass, mica and air are given in refs. [4], [5], [6]. In the interval of neutron velocities 5-100 m/sec the cross sections follow the 1/v law and coincide well with data in the literature for the region of cold neutrons (with velocity hundreds m/sec). The data for gold are indicated in

cross section is proportional to 1/v' where v' is the neutron velocity

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- Our work (2014) starting directly from the Schrödinger eq. rather than from density matrix: UCN signal may also be affected directly (not only indirectly);
- → Even higher precision in alignment of **E** and **B** may be required.

Thank you