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Ultra-Cold Neutrons and Spallation Neutron Sources

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Abstract

We present a brief introduction to the field of Ultra-Cold neutron (UCN) research including a review of the properties of UCN and some current and future applications.

We then discuss two types of UCN source suitable for use in connection with spallation neutron sources - "Doppler shifter" and "Superthermal" UCN sources

1) Properties of UCN

Ultra-cold neutrons (UCN) are neutrons with energies so low (a few times 10^{-7} ev) that they are totally reflected from many materials. While reflecting from a surface the UCN penetrate 100 or more Angstroms into the material. The loss probability per reflection depends on the material and the condition of the surface and ranges from 10^{-3} to 10^{-5} for selected materials. These properties mean that UCN can be stored in bottles made of selected materials for periods of time exceeding 100 seconds and perhaps approaching 1,000 seconds (the neutron decay lifetime) and open up a wide range of interesting applications.

2) Applications of UCN

a. The search for a neutron electric dipole moment (edm)

At the present time this is perhaps the UCN application which is being most energetically pursued. Groups at the ILL, Argonne National Laboratory, Leningrad and Dubna have all put many manyears of effort into this experiment. The search for the neutron electric dipole moment is interesting because the existence of an edm would be direct evidence for time-reversal violation outside the K°-meson system. The present best experimental limit corresponds to an edm $\leq 6 \times 10^{-25}$ e-cm is the result of a UCN experiment at Leningrad.
It is expected that the observation of a neutron edm will make a clear distinction between the superweak theory on the one hand, and the other theories (e.g. spontaneous T violation, unified theories of the weak and electromagnetic interactions) which have been proposed to account for the T violation.

The UCN densities expected from the sources discussed below are so large compared to currently available densities that the UCN density should no longer be a limiting factor on the experimental sensitivity which will undoubtedly be limited by magnetic field fluctuations. With such high UCN densities it will certainly be advantageous to push the UCN technique to its limit using superconducting magnetic shields and other aspects of low temperature technology. However the presence of the large iron radiation shield at SNQ may cause some perturbations to the magnetic environment.

b. Neutron β-decay

At present the neutron lifetime is only known to an accuracy of about 1 %. A more accurate determination of the neutron lifetime would improve our knowledge of the weak interaction constants appearing in the theory of β-decay, which are currently determined by a fit to a large number of measurements of β-decays of nuclei and elementary particles. There would also be an improvement in our knowledge of the radiative corrections to the β-decays. The knowledge of several of these theoretical parameters is currently limited by the 1 % accuracy of the neutron β- decay lifetime (1,2).

Classical methods of measuring the neutron lifetime involve separate detectors a) to measure the neutron density in the apparatus and b) either electron or proton detectors to measure the decay rate. Thus the measurement requires knowledge of the absolute efficiencies of a neutron and a charged particle detector. By using stored UCN the measurement can be carried out with a single detector whose absolute efficiency is not required.

This experiment has been actively pursued for several years by the group at Bonn (3) who are hoping to measure the lifetime of UCN stored in a magnetic bottle. The UCN will be produced by downscattering in liquid Helium similar to the UCN source discussed below.

UCN can also be used to study asymmetries in the β-decay of polarized neutrons and may prove useful for studying parity violation in (n, γ) reactions.

c. Material Studies with UCN

UCN have the unique property that they penetrate surfaces to depths of a few hundred Angstroms. The depth of penetration is a function of neutron energy as well as the density and composition of the material surface. The loss rate of UCN on a surface is also a function of these parameters. Thus the loss rate of a surface will be altered by the presence of a layer of oxide or film of other material on the surface and UCN will provide a unique way of studying such films.

The above properties suggest several interesting applications for UCN. For example one could study the depth of penetration of ions into a surface as a function of ion energy. After ion bombardment the surface will be exposed to the UCN which, penetrating to the depth of the implanted ions, will indicate the presence of the ions by the characteristic γ-rays resulting from (n, γ) reactions. With the high UCN densities expected from the "new generation" of sources it should be possible to obtain profiles for cases where the implantations are carried out with negligible surface damage and at low concentrations of the implanted ions.

UCN can be used for inelastic scattering studies of materials in several ways. For energy transfers large compared to the UCN energy, UCN can be upscattered from the surface region (or from the bulk of those samples which are penetrated by UCN) and the energy spectrum of the upscattered neutrons can be measured. Although this will have the disadvantage that only the region of the ω-Q plane that lies along the $\omega \propto Q^2$ curve of the free neutron is accessible, the technique may allow measurements which are impossible by other methods. For example UCN stored in liquid Helium will be upscattered as a result of interactions with the phonons and rotons at a rate which is temperature dependent. A measurement of the spectrum of the upscattered neutrons would provide information on $S(Q,\omega)$ in a region far from the phonon resonance at unprecedented levels of sensitivity - mean free paths of kilometers for 5 m/sec UCN. Such experiments seem to be impossible by any other technique and have become more interesting in the light of recent experimental and theoretical results. In addition one can study excitations in thin Helium films by a similar technique.

There is also the possibility of accelerating the UCN gas to $\lambda \sim 100 \div 200$ Å in order to do scattering experiments. One method to accomplish this is to gradually accelerate a container filled with UCN. When the container is suddenly stopped the neutrons will continue (through the walls of the container) with an average velocity given by the velocity of the container before deceleration. The advantage of such a scheme derives from the very high phase space density available in the UCN source.

Somewhat related to this is the possibility of accelerating the UCN stored in liquid Helium by means of a strong monochromatic phonon beam or perhaps a shock wave in the Helium. In addition to the possibility of producing an intense burst of approximately monoenergetic neutrons the latter approach may provide an interesting method for studying shock waves in the superfluid Helium.

Another method of using UCN to study condensed matter is by means of a UCN spectrometer such as the gravity spectrometer constructed by Steyerl (fig. 1). This offers the possibility of very high energy resolution (~ 10 neV) in the Q range of $10^{-3} \div 3 \times 10^{-2}$ Å^{-1} . Such a spectrometer could be used to study slow dynamics in biological systems, hyperfine splittings, magneto-crystalline anisotropies, lowlying rotational states and hindered rotations in very large molecules and the slow critical fluctuations close to a phase transition, in particular magnetic phase transitions.

Elastic scattering of UCN can be used to study inhomogeneities in materials and transmission of UCN to study thin films.

d. UCN optics

Steyerl and his co-workers have allready demonstrated the operation of an achromatic Fresnel lens for UCN. Such work can be expected to lead to the development of a UCN microscope with a resolution of perhaps 1μ. A prototype with a resolution of a few hundred microns is currently under construction (fig. 2). The advantage of such an instrument would be based on the different scattering properties of materials for neutrons as compared to other radiations, e.g. a UCN microscope is expected to be useful for studying the distribution of Hydrogen in a given sample.

Recent experiments at Garching have studied quasi-bound states in one-dimensional potentials produced by multi-layer structures. One could extend this work by constructing a UCN Fabry-Perot interferometer and studying transitions between different bound levels induced by an oscillating magnetic field as proposed by Steyerl. This would demonstrate the operation of the time dependent Schroedinger equation in an almost macroscopic system ($\sim 10^3$ Å).

3) New Generation UCN Sources

While existing UCN sources provide densities of at most 1 UCN/cm^3 , new neutron sources (e.g. spallation neutron sources) now being planned or constructed open up several possibilities for producing UCN densities on the order of 10^3 UCN/cm^3 or perhaps even significantly greater.

One type of "new generation" UCN source ("Doppler shifter" UCN source) is based on the slowing down of faster neutrons as a result of reflection from a reflector which is moving in the direction of the neutrons. Such a device would be placed at the end of a guide tube looking at a "cold" Hydrogen or Deuterium source and would produce a UCN density which is limited by Liouville's theorem to correspond to the phase space density in the peak of the pulse in the cold source since the UCN are admitted to a storage vessel by means of a shutter which opens in phase with the neutron pulse.

Two methods of realizing such a UCN source have been proposed. One makes use of the total reflection phenomena from a moving curved surface and produces UCN by slowing down 50 m/sec neutrons (Steyerl turbine). The second uses Bragg reflection from a moving crystal and requires 400 m/sec neutrons as an input; such a device has been constructed at Argonne. Both devices are expected to provide similar UCN densities which are estimated to be about 3×10^3 UCN/cm^3 at SNQ, produced outside the radiation shield at a position suitable for experiments.

The second general type of UCN source ("superthermal source") is based on the slowing down of 400 m/sec neutrons as a result of the emission of phonons by the neutrons (inelastic down-scattering) in superfluid liquid He^4. The Helium is contained in a vessel suitable for storing UCN so that the UCN, once produced, remain in the source until they are removed as the result of interactions with the Helium or the walls. The steady state UCN density in the source then depends on the production rate and the loss rate. After a time on the order of the UCN storage time the UCN density approaches its steady state value and this high density UCN "gas" can be extracted by means of a valve which would be opened to release the UCN. This device is not limited by Liouville's theorem which applies to the complete system - neutrons and phonons - and not to the neutrons alone.

Such a source, installed 70 cm from the bottom of the SNQ D_2O tank is expected to produce densities $\sim 4 \times 10^5$ UCN/cm^3 in the source. In order to be useful, for most experiments the UCN will have to be transported from the source to an apparatus outside the spallation source radiation shield, a process which will introduce some losses.

Steady state currents can be extracted from the UCN storage bottles in both of the sources under consideration (the Helium source and the Doppler shifter source) by fitting the bottle with an outlet port. In both cases the currents available would be proportional to the saturation densities in the sources so the comparisons we give here are also applicable to the case of scattering experiments.

The gain in available density expected from these "new generation" sources in comparison with existing sources is so great that one can expect that an entirely new range of research applications with UCN will be opened.

4) Doppler Shifter UCN Source (4)

A sketch of the apparatus as realized at the Argonne Spallation neutron source is shown in fig. 3. Neutrons (400 m/sec) are transported from a liquid Hydrogen moderator through a 5 m long vertical guide tube. After leaving the guide the neutrons are reflected from a moving crystal which leaves them with a very small velocity after the reflection. The result is a cloud of UCN some of which move into the UCN guide tube which is kept closed by a slotted rotating disc except during the time when the neutron pulse is approaching the UCN guide.

This synchronous opening and closing of the guide allows the UCN density in the guide to build up (in principle) to that corresponding to the phase space density in the peak of the pulse.

Since the phase space density for a Maxwellian spectrum corresponding to total flux $\emptyset_o$ is given by:

$$n(v_o) = \emptyset_o e^{-(v_o/v_T)^2} (2\pi \cdot 100\, v_T^4)^{-1} \; n \cdot cm^{-3} (m/s)^{-3} \tag{1}$$

v_T = thermal velocity - m/sec

v_o = velocity of incident neutrons

the maximum UCN density available with this technique is:

$$\rho_{UCN} = \hat{n}(v_o) \left[\frac{4\pi}{3} v_c^3 \right] \tag{2}$$

where v_c is the maximum UCN velocity that can be stored and $\hat{n}(v_o)$ is the phase space density corresponding to the peak of the neutron pulse, because the reflection from the moving crystal ideally shifts the velocity without changing the phase space density.

However because of inefficiencies due to crystal reflectivity, pulse broadening, etc, the UCN density produced is expected to be only 10 % of (2).

In addition the Bragg scattering process distorts the sphere in velocity space so that only a disc around the equator of the sphere is populated. This reduces the expected UCN density by a further factor of 6 as confirmed by experiment and Monte-Carlo calculations, but perhaps some of this can be recovered by a suitable angular collimator at the input of the UCN guide.

5) The "superthermal" UCN source using superfluid He^4

a. Production of UCN by down scattering in liquid Helium

If a volume of Helium is exposed to a flux of neutrons there will be a production of UCN given by

$$P_{UCN} = \frac{d\emptyset(E^*)}{dE} E_{lim} \frac{4}{3} \left[\sqrt{\frac{E_{lim}}{E^*}} \right] S(k^*)\, N \sigma_o \quad UCN/sec/cm^3 \tag{3}$$

where E_{lim} is the limiting energy for UCN storage

$E_{lim} = 2{,}5 \times 10^{-7}$ eV

$= 2{,}9 \times 10^{-3}$ K for Beryllium

N is the density of Helim atoms in the liquid = 2,18 x $10^{22}/\text{cm}^3$

σ_0 is the free atom coherent scattering length = 1.1 barns

E* is the critical energy for UCN production by phonon emission

$$E^* = \hbar\,\omega_0\,(k^*) = \hbar^2\ k^{*2}\,/2\,m \tag{4}$$

$$E^* = 12\ \text{K}$$

where ω_0 (k) is the phonon dispersion curve for liquid Helium

S(k*) = 0.1 is the one phonon structure factor and

$d\phi/_{dE}$ (E*) is the energy spectrum of the incident neutrons evaluated at E*

Putting in the numbers we find from (3)

$$P_{UCN} = \frac{d\phi(E^*)}{dE}\quad 1{,}44 \times 10^{-7}\quad \text{UCN/sec/cm}^3 \tag{5}$$

For a Maxwell Spectrum at temperature T

$$\frac{d\phi}{dE} = \phi_{th}\ \frac{E}{T^2}\ e^{-E/T} \tag{6}$$

where ϕ_{th} is the total thermal flux. Thus

$$P_{UCN} = 1{,}92 \times 10^{-11}\ \phi_{th} \quad \text{for } T = 300°\text{K} \tag{7}$$

b. Saturation steady state UCN density in the Source

Given the production rate P_{UCN}, the saturation density of UCN is given by

$$\rho_{UCN} = P_{UCN}\,\tau \tag{8}$$

where τ is the storage time of UCN in the Helium containing vessel

$$\frac{1}{\tau} = \frac{1}{\tau_{He}} + \frac{1}{\tau_{abs}} + \frac{1}{\tau_{wall}} + \frac{1}{\tau_{\beta}} \tag{9}$$

τ_{He}, the relaxation time for upscattering of UCN in the Helium,

τ_{abs} is the absorption time $(\rightarrow\infty)$ in He^4

τ_{wall} is the relaxation time for wall losses

and $\tau_\beta = 10^3$ sec is the ß-decay lifetime.

According to calculations τ_{He} = 4000 sec at 0.6 K
and = 500 sec at 0.8 K

6) Comparison of UCN Sources

From equations (1) and (2) we can write the UCN density from the Doppler shifter source as

$$\rho_{\text{Dop}} = \frac{\bar{\phi}_o \, (E_o)}{\eta} \; \frac{(\Delta E)}{v_o} \left(\frac{\Delta \Omega_{Dop}}{4\pi} \right) \qquad (10)$$

where η is the duty cycle of the neutron pulses ($\bar{\phi}/\eta$ is the peak flux $\hat{\phi}$)

$$\Delta E = (2/3)\, m\, v_o\, v_c \qquad (11)$$

and $$(\Delta\Omega_{Dop}/4\pi) = (1/4) \quad (v_c/v_o)^2 = 7.6 \times 10^{-5} \qquad (12)$$

for $v_c = 7$ m/sec, $v_o = 400$ m/sec.

From equations (3) and (8) we can write

$$\rho_{\text{He}} = \Sigma_o\, (\Delta E) \; \bar{\phi}_o\, (E_o)\; \tau\; (\Delta\Omega_{\text{He}})/4\pi \qquad (13)$$

with Δ E defined by (11) and

$$\Sigma_o = N\, \sigma_o \;\; S\, (k^*) \;\; (k_c/k^*)^2 = 4 \times 10^{-7} \text{cm}^{-1} \qquad (14)$$

Thus if both sources were placed at the end of the same guide tube the ratio of UCN densities produced would be

$$\rho_{\text{He}} / \rho_{\text{Dop}} = \Sigma_o\, v_o\, \tau\, \eta \left(\Delta\Omega_{He} / \Delta\Omega_{Dop}\right) \qquad (15)$$

In the case when the solid angle for the Helium source is limited by the guide $\Delta\Omega_{\text{He}} = \Delta\Omega_{\text{Dop}}$

and $$\rho_{\text{He}} / \rho_{\text{Dop}} = \Sigma_o\, v_o\, \tau\, \eta \qquad (16)$$

$$= 0.8 \times 10^{-2}\, \tau\eta \quad = 3.2\, \eta$$

(if we take τ = 400 sec)

for the case when the Doppler shifter source gives the maximum output allowable by Liouville's theorem.

However we have seen above that the density produced by the Doppler shifter source must be reduced by an unavoidable factor of 10 so that (16) becomes

$$\rho_{\text{He}} / \rho_{\text{Dop}} = 32\eta \qquad (17)$$

Now at Argonne $\eta \simeq 1/165$ so the Doppler shifter source would appear to be slightly better while at SNQ $\eta \sim 1/12$

However the real advantage of the Helium source (at a spallation neutron source) becomes apparent when we consider that while $(\Delta\Omega)_{Dop}$ is limited by the mechanism of total reflection to be given by (12), $(\Delta\Omega)_{He}$ is only determined by the geometric arrangement of the UCN source relative to the primary neutron source.

For a practical case on the SNQ (fig. 4) we have $(\Delta\Omega)_{He}/4\pi = 0.27$
or $(\Delta\Omega)_{He}/(\Delta\Omega)_{Dop} = 350$

in a position where there is an acceptable heat input to the Helium container.

Because the cold source supplying the guide tube for the Doppler shifter source can be in a higher flux, and can be larger and hence more efficient than the cold source supplying the "Superthermal" Helium source we have
$\eta_{eff} = 10^{-2}$ for SNQ

and (17) becomes

$$\rho_{He}/\rho_{Dop} = 32 \times 10^{-2} \times 350 = 110$$

This figure applies only to the UCN produced inside the Helium, so it must be reduced by the losses associated with extraction of the UCN from the Helium to a position where they can be used for experiments. It seems reasonable to suppose that these losses can be kept below a factor of ten so that the "Superthermal" Helium source can offer significantly increased UCN densities if the engineering problems associated with its construction can be overcome.

References

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North Holland, 1973

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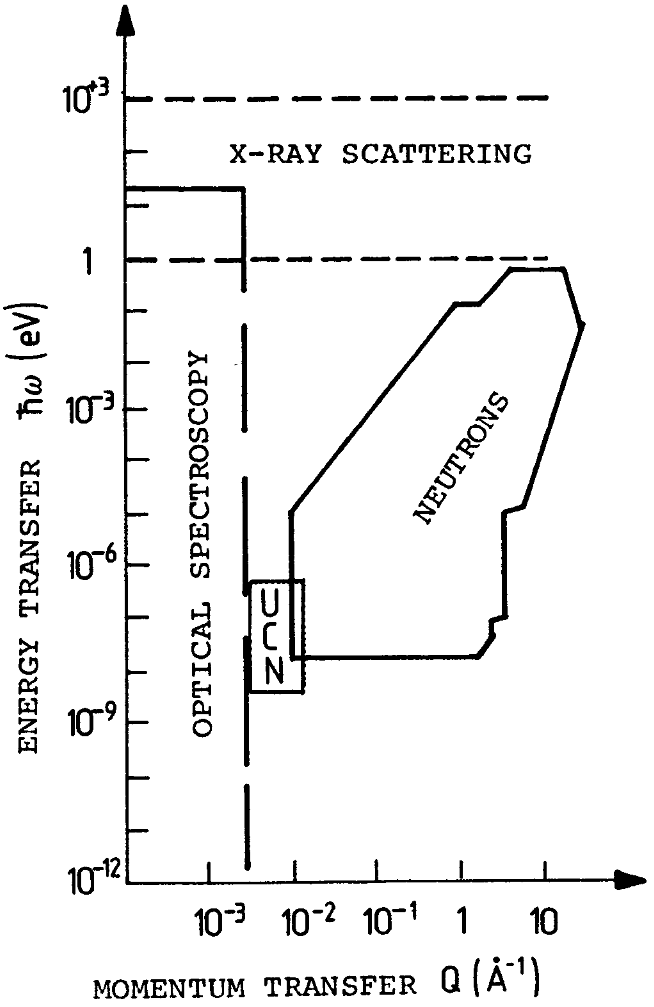
6) Steyerl and Hermann, (1981) Private Communication

Fig. 1 a) ω, Q space showing region accessible to UCN scattering
b) UCN inelastic scattering spectrometer (5)

a)



b)

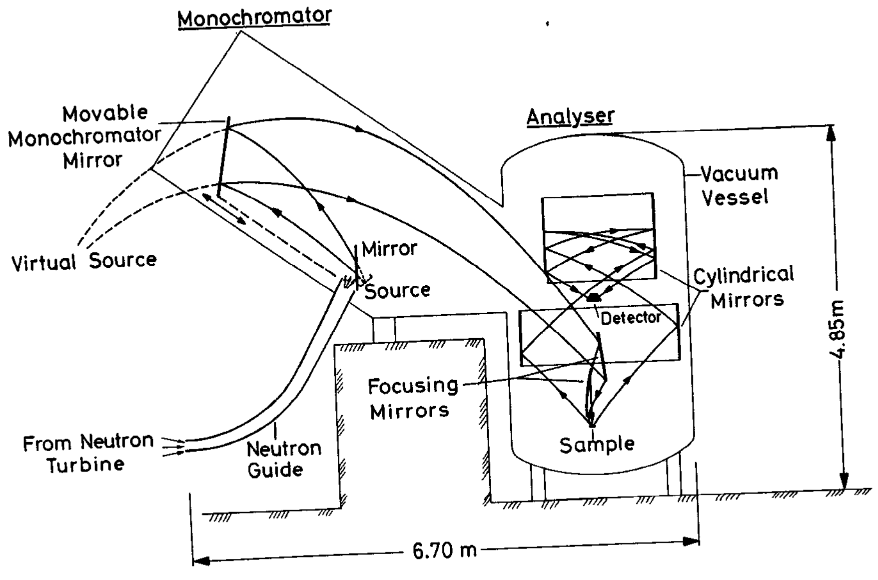
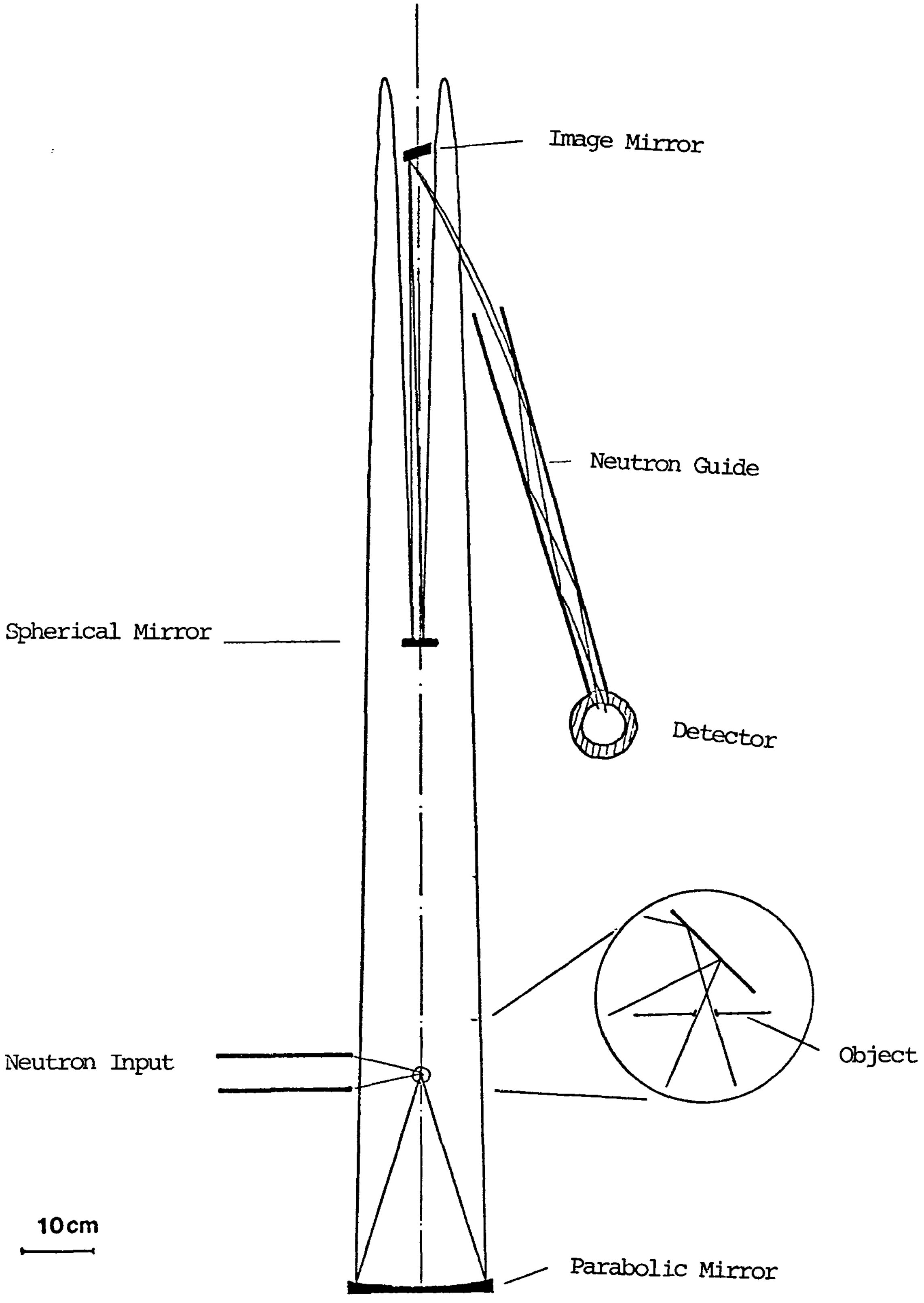


Fig. 2 Neutron microscope using UCN (6)



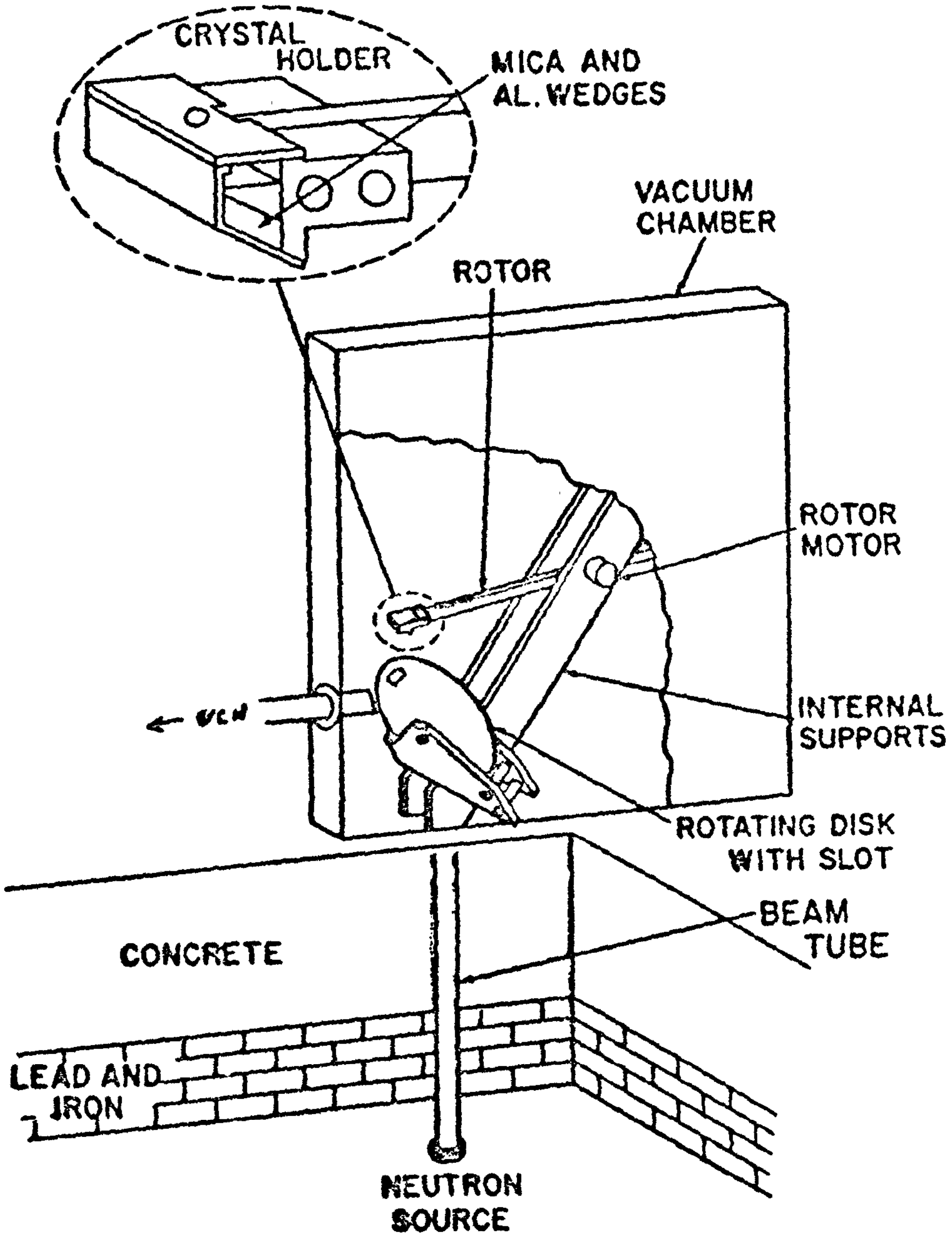


Fig. 3 Doppler shifter UCN source using rotating crystal as realized at Argonne (4)

Fig. 4 Superthermal UCN source proposed for SNQ