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A CONCEPT FOR AN eV SPALLATION NEUTRON SOURCE

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I. The Accelerator and its Beam Parameters

ASTOR is a proposal for an isochronous cyclotron, using the SIN-ring cyclotron as an injector1). The 590-MeV proton beam would be injected for further acceleration and be stored by means of the phase expansion effect. A continuous mode of operation without storage could also be provided. In the storage mode the ASTOR acts as an adiabatic debuncher. About 75 % of the circumference of the extraction orbit would be filled with protons in order to leave some time to excite the kicker magnet for a clean extraction of the bunches. The number of protons which can be stored is restricted by Liouvilles Theorem.

Let be:

$\Delta\psi_i$	the phase width of the injected micro-bunches.
$\Delta\psi_f$	the phase width at extraction from ASTOR $\Delta\psi_f<360^o$.
a	the filling factor of the circumference ($a\simeq 0.75$).
ΔE_G	the energy gain per turn at injection. It should be as low as possible, that is just high enough in order to clear the injection septum.
ΔE_f	the total energy spread of the extracted beam

The number of particles which can be stored in one bunch is proportional to

$$N \simeq a \cdot \frac{\Delta\psi_f}{\Delta\psi_i} \cdot \frac{\Delta E_f}{\Delta E_G} \qquad (1)$$

Therefore, according to (1) the number of turns from the present SIN-cyclotron, which can be stacked into one bunch of ASTOR depends essentially on the energy spread, which can be tolerated in the extracted beam for a clean further transport and use of the beam. The peak intensity is thus determined by these conditions.

If we tolerate a momementum dispersion in the final proton beam of $\Delta p/p$ = 0.7 % we can stack 500 turns of the SIN-cyclotron into one bunch of ASTOR. The following beam parameters then follow:

Energy		2 GeV
Current (time averaged)		300 µA
Pulse length		240 nsec
Repetition rate		1.5 kHz
Peak intensity		$1.2 \cdot 10^{12}$ P/pls
Beam size:	radial	30 mm
	vertical	8 mm

The repetition rate can be decreased - however, only at the expense of time averaged current and hence not in favor of the peak intensity.

II. A "High" Energy Neutron Source and its Physics

If we insist to use the pulsed neutron source at ASTOR with the highest possible average beam current, we have to restrict the applications (and the optimization) of this facility to neutron energies $E \geqslant 1$ eV. According to the distance-time velocity plot (Fig. 1) for the neutrons, frame overlap problems for neutrons with lower energies are obvious. From the scientific point of view the following questions arise:

a) Are there any physics (or more generally - scientific experimental) investigations which should be treated preferentially with neutrons of energies $E \geqslant 1$ eV?

b) Are there - for such cases - simpler and/or more powerful alternatives?

An answer to the first question can be obtained by looking at the basic kinematics of a typical neutron scattering event[2)]. Let be

E_0 the energy of the incident neutron
θ the scattering angle in the lab.-system
$\hbar\omega$ the energy transfer to the scattered neutron
Q the momentum transfer.

Then, we have

$$\frac{\hbar^2 Q^2}{2m} = 2E_0 + \hbar\omega - 2(E_0^2 + E_0\hbar\omega)^{1/2} \cos\theta \qquad (2)$$

From (2) we recognize that the access to regions of

a) high energy transfer and low momentum transfer

and

b) high momentum transfer

are favored by a high energy of the incident neutron. The first region is relevant for investigation of e.g. Phonon Dispersion, Molecular Vibrations and Magnetic Excitations. Measurements in the second region determine e.g. Short Range Correlations of scattering centers in liquids. The basic principles of neutron scattering for these domains are summarized in the tables I - III.

Figure 2 shows the kinematical regions (energy-momentum transfer), which can be investigated by the various methods applied for research of condensed matter. We observe that the region a) mentioned above is just enclosed by the regions which are considered to be favorably treated by means of light and X-ray scattering. Hence the application of neutron scattering in this domain is possibly in competition with corresponding experiments at synchrotron light sources. The competitivity depends then clearly on the qualities of the sources and on the state of the art of the instrumentation.

The development of scattering instruments using these higher energy neutrons is still in its infant stage. A typical type of instrument is the resonance spectrometer, which has been discussed at ICANS'meetings[3)]. Therefore, instead of proceeding along that line we would rather like to make some guess, how a neutron source with high repetion rate could look like.

III. The Neutron Source

A 'low' frequency pulsed neutron source consists of a spallation target and a small moderator usually containing hydrogen. In order to increase the neutronic coupling between the target and the moderator, a reflector surrounds the latter. Normally the moderator is decoupled from the reflector suppressing the backflow of thermal neutrons into the moderator and hence dumping off the tail in the neutron pulses. Cooling of the moderator has two favored consequences:

a) The slowing down nature (1/E) of the neutron spectrum is extended to lower energies.
b) Neutron pulses become shorter for neutrons in the ambiant temperature region.

For a 'high' frequency pulsed source with emphasis of neutrons with higher energies (E>1 eV) the criterias are somewhat different. No thermal neutrons (not even lower epithermals) should be emitted by the moderator into the beam tubes. This can be achieved by the following means:

a) Encloser of the moderator (including the emitting surface) by proper absorbing materials. A sandwich of Au, Rh and Cd layers might be sufficient (Fig. 3).
b) The size of the moderator has to be carefully optimized for high leakage rate of neutrons with the wanted energy. That is the maxwellian has to be minimized - an absorbed neutron is a lost neutron and increases the energy deposition in the absorbing layer. The moderator will therefore be rather small.
c) Heterogeneous instead of surface absorption might be considered in order to deposit the resulting heat more evenly over the moderator volume.

1. Moderator Size

In order to estimate the size of a moderator let us make a guess of the migration area for a neutron which is slowed down to (say) 5 eV. The Fermi age can be written as[4)]

$$\tau(E) = \frac{2}{\xi(1-2/3A)} \int_{E}^{E_Q} \lambda_S^2(E') \frac{dE'}{E'} \qquad (3)$$

ξ is the average log.-energy loss per collision, A the atomic mass of the moderator and λ_S the mean free path of the neutron. The average energy of the source neutrons is $E_Q \approx 2$ MeV. The migration area is

$$r^2(E) = 6\ \tau(E) \qquad (4)$$

In the following table τ [cm^2] is given for an energy of E = 1.46 eV (Indium-resonance) and an estimate scaled up to E = 5 eV for various moderating materials

	E = 1.46 eV	E = 5 eV
H_2O	27 cm^2	22 cm^2
D_2O	109 cm^2	90 cm^2
Be	80 cm^2	66 cm^2
C	313 cm^2	258 cm^2

An estimate for the thickness of a slab formed moderator is

$$D \simeq (1/3\ r^2)^{1/2} \qquad (5)$$

That is 6.6 cm for H_2O - and 11.5 cm for Be. The surface of the moderator is given by the size of the beam tubes - 100 - 200 cm^2.

2. Moderation Time and Pulse Shape

An analytic solution of the slowing down integral equation can be given for the space independent case, that is far an infinite moderator medium. The corresponding pulse shape of the neutrons for an incident δ-shaped source pulse can serve as a guide line for our discussion.

The energy and time dependence of the pulse is given by[4]

$$N(E,t) \simeq \frac{1}{2E} \frac{y^{2/\gamma}\, e^{-\gamma}}{\Gamma(2/\gamma)} \qquad (6)$$

where

$$\gamma = \begin{cases} 1 & \text{for atomic mass } A = 1 \\ \frac{4A}{3} & \text{for large atomic mass } A \end{cases}$$

and

$$y = \frac{\xi}{\gamma} N \cdot \sigma_{tot} \cdot (vt)$$

v = v(E) is the neutron velocity for energy E. The other parameters have the usual meaning. Figure 4 shows the pulses and their energy dispersion in a Be- and an H_2O-moderator. In view of the importance of the pulse width for the figure of merit in time of flight experiments it is likely that the moderator with a high hydrogen content will be favored.

For the H_2O-moderator the pulse width due to moderation is 1 μsec or longer. The contribution to the pulse length of the neutrons, due to the pulse width of the proton pulse (240 nsec), is therefore not significant.

3. Coupling of the moderator to the target

In order to keep the background of high energy neutrons as low as possible, a wing geometry for the target-moderator arrangement (Fig. 5a) is usually chosen. Due to the small thickness of our moderators their coupling to the target would be particularly weak, just for this geometry. A reflector surrounding the moderator could of course improve the coupling. However, the resulting pulse lengthening has, also carefully to be considered. Furthermore, if we want to avoid an increase of the moderating power of the system a heavy material has to be chosen as a reflector.

Let us make some estimates with a lead reflector. From the investigation for SNQ at mock-up experiments[5)], we know that a lead reflector should have side length of 30-40 cm. We assume that the tail of the neutron pulse shows an exponential behaviour with a time constant essentially given by the reflector

$$\tau_R^{-1} = \alpha = v\Sigma a + DvB^2 \qquad (7)$$

B^2 is the buckling of the reflector

$$B^2 = \pi^2 \left[3\left(\frac{1}{l}\right)^2\right] \qquad (8)$$

For the neutron velocity we chose $v \simeq 3.13$ cm/μs which corresponds to an energy of 5 eV. The diffusion constant is approximated by $D \simeq 1/3\Sigma_s$ with $\Sigma_s \simeq 0.3\ \text{cm}^{-1}$. We then obtain a relaxation time for the reflector

$$t_R \simeq 15\ \mu s$$

Hence, an efficient reflector dominates the decay time of the neutron pulse and therewith spoils the resolution at the instrumentation. If we have to renounce a reflector, the only means to increase the target-moderator coupling is the choice of a slab geometry. With this arrangement the instruments view through the thin moderator directly onto the target. This leads to a rather untolerable background of high energy neutrons. A possible way out is the Flux Trap Geometry (Fig. 5b). This geometry has been proposed for LANSCE at Los Alamos[6)]. This split target geometry increases the accepted solid angle for the moderators and therefore their coupling to the target, without suffering too much from penalties of background.

Of course, for a reasonable optimization of such a target-moderator system careful bench-marking - experimental as well as computational - is needed.

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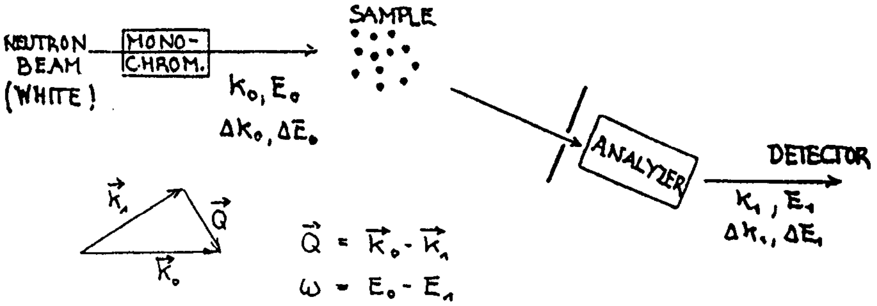
X-RAYS	$\lambda \sim$ Å	$E \sim 100$ keV $\Delta E \sim$ meV-μeV	$\frac{\Delta E}{E} \sim 10^{-8}-10^{-11}$!
LIGHT	$\lambda \sim 10^{3}$ Å !	$\Delta E \sim$ meV-μeV	POSSIBLE
NMR RAMAN-SCATT.	LOCAL PROBING NO LONG RANGE CORRELATION		
NEUTRONS	$\lambda \sim$ Å	$E \sim 10$ meV $\Delta E \sim$ meV-μeV	$\frac{\Delta E}{E} \sim 10^{-1}-10^{-4}$ (OK)



$$\vec{Q} = \vec{k}_0 - \vec{k}_1$$

$$\omega = E_0 - E_1$$

$$\boxed{\frac{d^2\sigma}{d\Omega\, dE_1} = \frac{k_1}{k_0} S(\vec{Q}, \omega)}$$

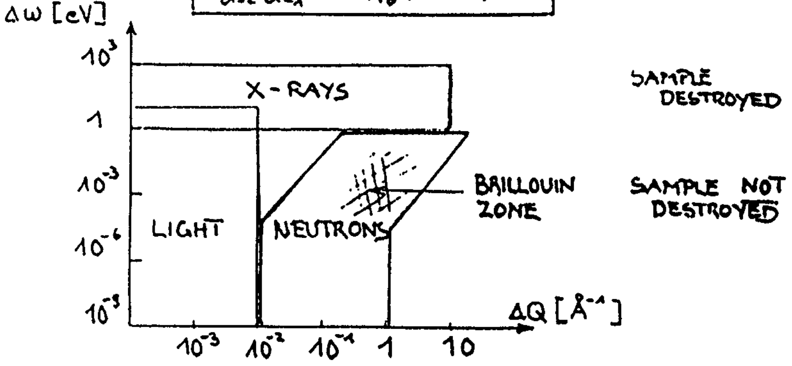


Table I

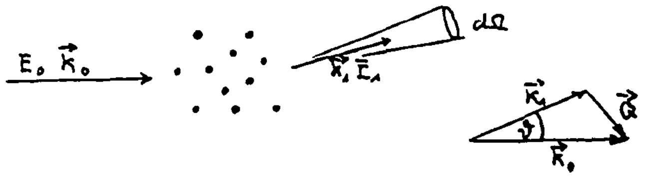
1) The wave length of X-rays is properly matched to the distance of atomic objects in condensed matter. Due to their high energies an incredilary high energy-resolution has, however, to be demanded for dynamical investigation of matter. For light scattering the energy resolution can be achieved but the wave length is matched to much bigger objects only. With thermal neutrons, both the wave length and the energy have the right order of magnitude in order to map the Brioullin-zone of solids.

2) The observable in a neutron scattering experiment is the differential cross section with respect to the scattering angle and the neutron energy. This cross section is proportional to a structure function of momentum- and energy-transfer, which contains all the information.

NEUTRON SCATTERING

A TOOL FOR CONDENSED MATTER RESEARCH

ESSENTIALS : L. van Hove Phys. Rev 95 (1954) 249



1) COHERENT

$$\frac{d^2\sigma_c}{d\Omega\, d\omega} = N \frac{k_1}{k_0} (\bar{b})^2 S(Q,\omega)$$

2) INCOHERENT [ISOTOPES, SPIN-FLIP]

$$\frac{d^2\sigma_i}{d\Omega\, d\omega} = N \frac{k_1}{k_0} \left\{ \overline{b^2} - (\bar{b})^2 \right\} S_i(Q,\omega)$$

$$\frac{\hbar^2 Q^2}{2m} = 2E_0 + \hbar\omega - 2\left(E_0^2 + E_0\hbar\omega\right)^{1/2} \cos\vartheta$$

$$S(Q,\omega) = \frac{1}{2\pi}\int dt \int dx^3\, G(\vec{x},t)\, \exp[i(\vec{Q}\vec{x} - \omega t)]$$

$$S_i(Q,\omega) = \frac{1}{2\pi}\int dt \int dx^3\, G_s(\vec{x},t)\, \exp[i(\vec{Q}\vec{x} - \omega t)]$$

INFORMATION : $G_s(\vec{x},t)$ ATOMIC MOTION (DIFFUSION)

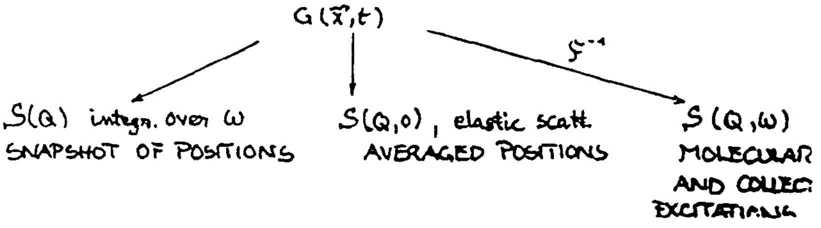
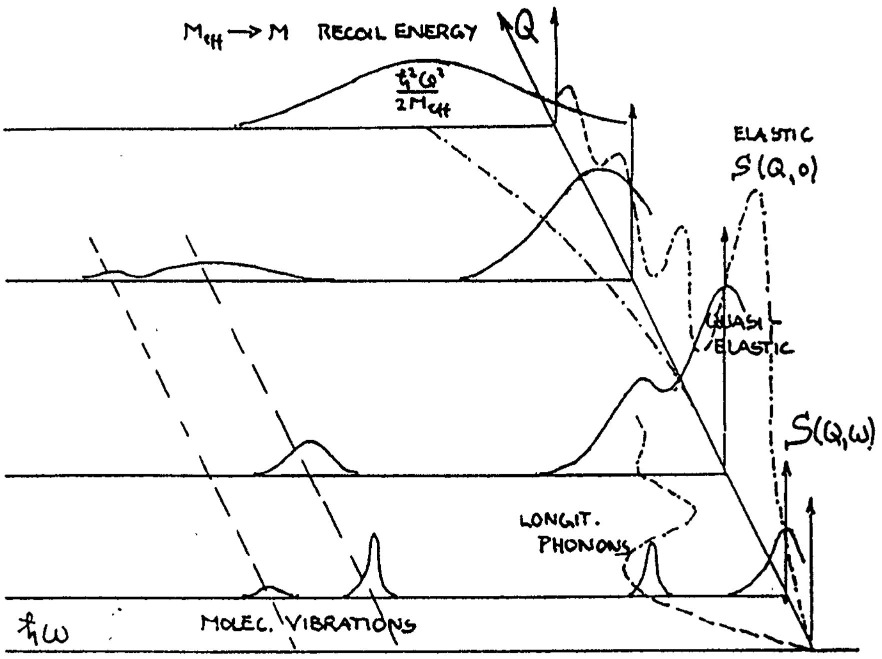


Table II

Since the elementary scattering length of neutron at different isotopes is usually different and also generally spin dependent, the scatter coherently as well as incoherently at condensed matter. Hence a coherent and an incoherent structure function can be defined. They contain different information. Both structure functions are the space-time Fourier transforms of correlation functions between the scattering centers.



$$S(Q) = \int_{-\infty}^{+\infty} d\omega\, S(Q,\omega) \quad \text{———} \quad S(Q) = 1 + \frac{4\pi\rho}{Q}\int_0^\infty \{g(r)-1\}\, r \sin(Qr)\, dr$$

$$g(r) = 1 + \frac{1}{2\pi^2 N r}\int_0^\infty Q\{S(Q)-1\} \sin(Qr)\, dQ$$

SHORT RANGE CORRELATION } ——— DATA AT HIGH Q [RECOIL EFFECTS]

PHONON· DISPERSION
MOLECULAR VIBRATION } ——— HIGH ENERGY TRANSFER ($\hbar\omega$) AT LOW Q

ALSO IN SOLIDS
MAGNETIC EXCITATION { MAGN. FORM FACTOR HIGH ENERGY TRANSFER

Table III

Those regions in the kinematical plane and the corresponding dynamical phenomena, which could favor higher energy (then thermal) neutrons for their investigation are emphasized.

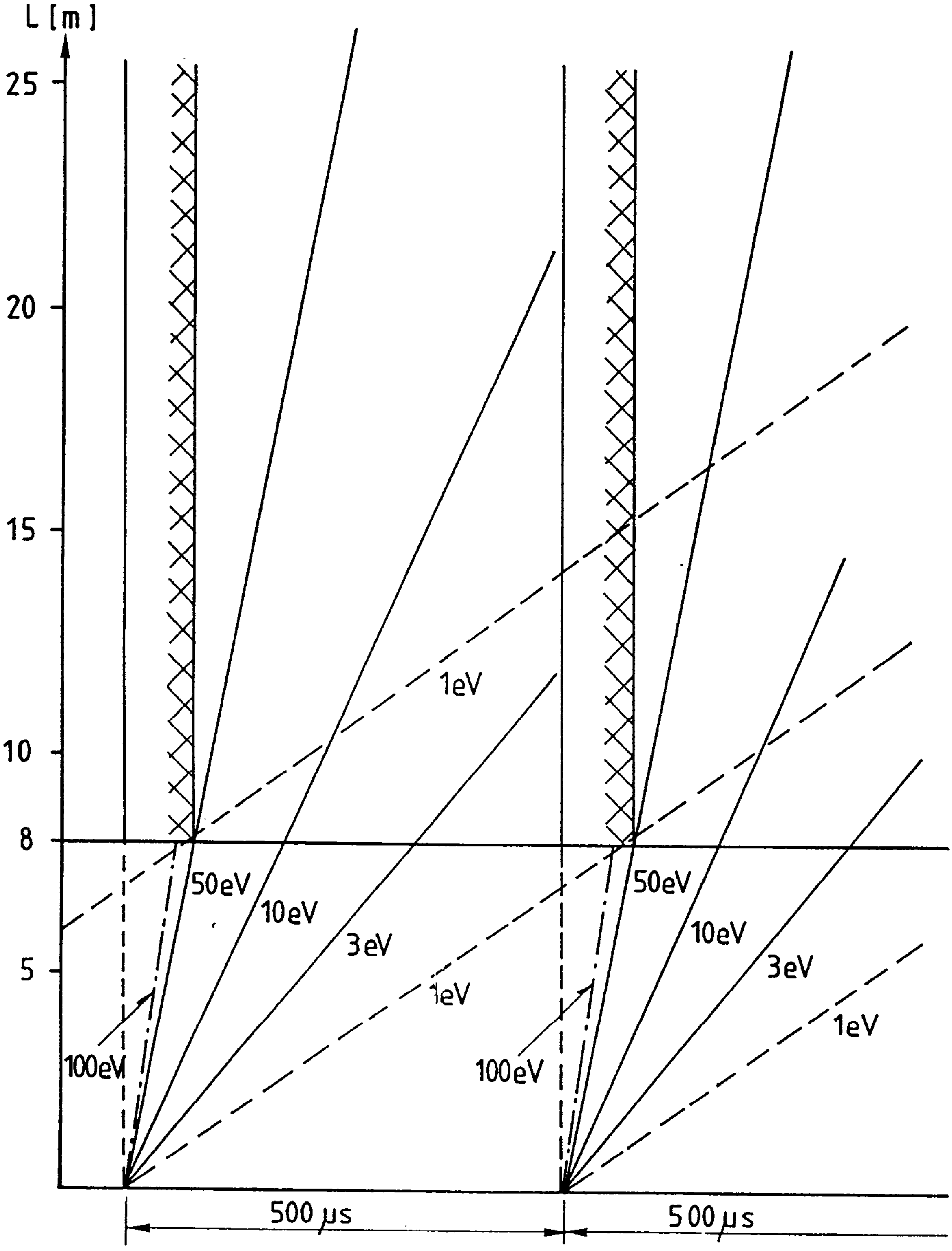


Fig. 1 Distance-time velocity plot for neutrons with a pulse repetition frequency of 2 kHz.

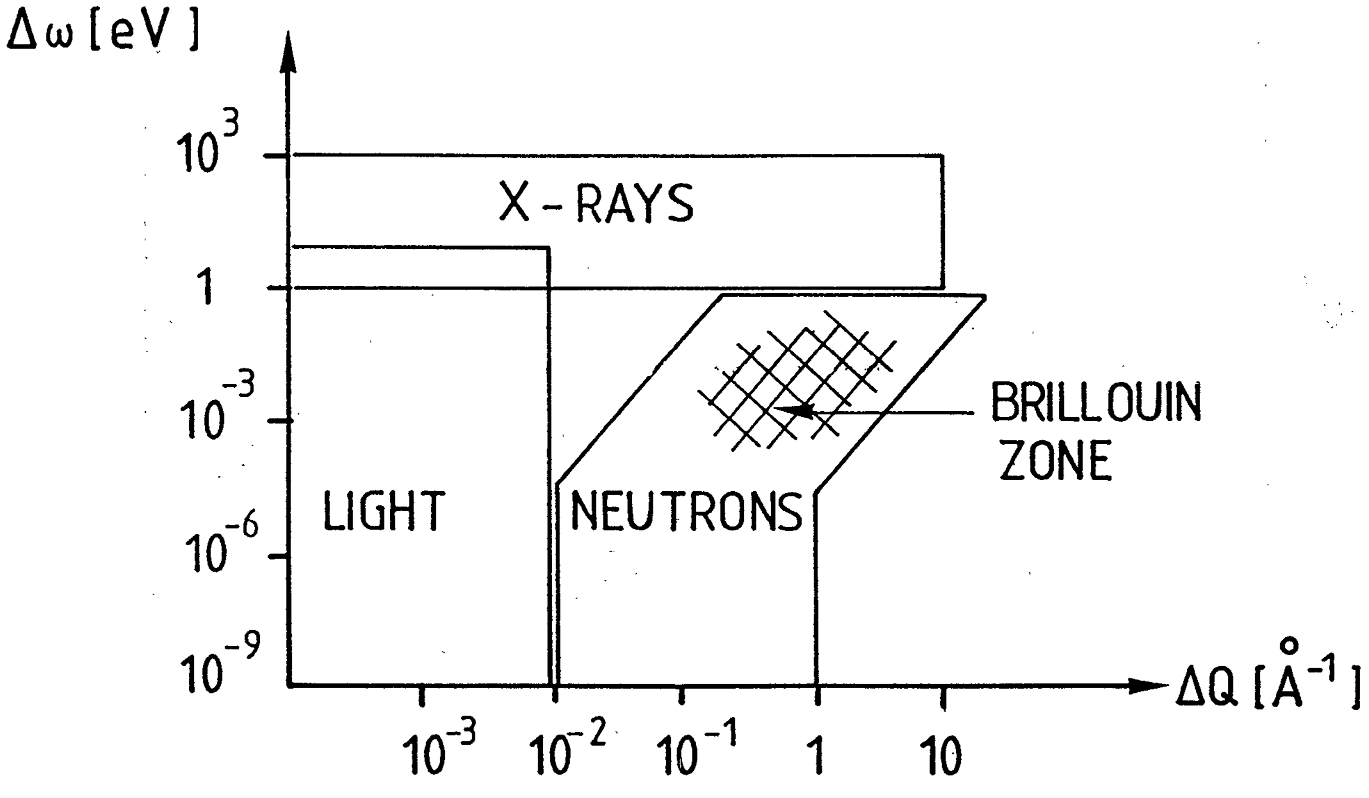


Fig. 2 Region of energy-momentum transfer favored by various experimental methods.

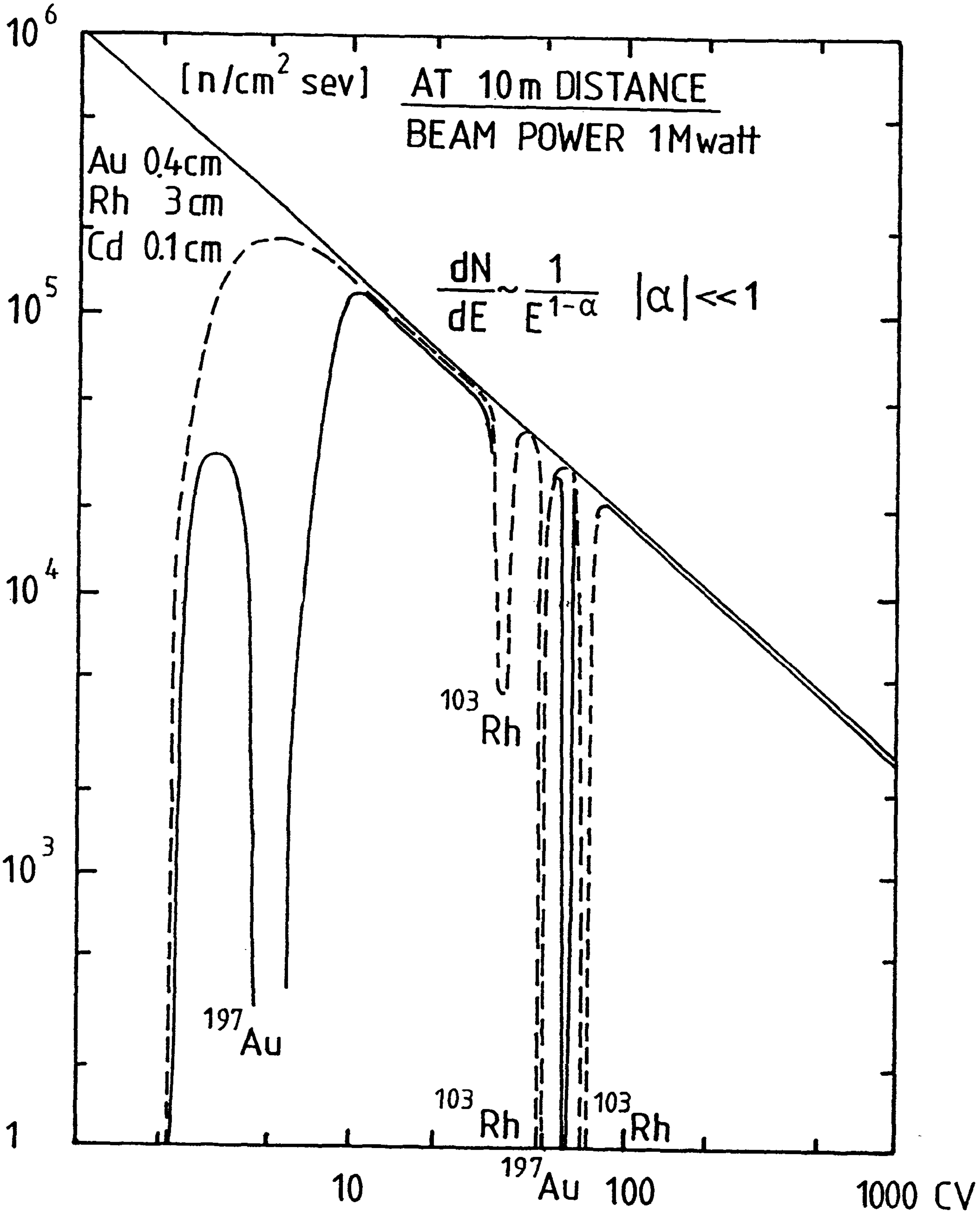


Fig. 3 Upper slowing down spectrum taylored by various absorbers.

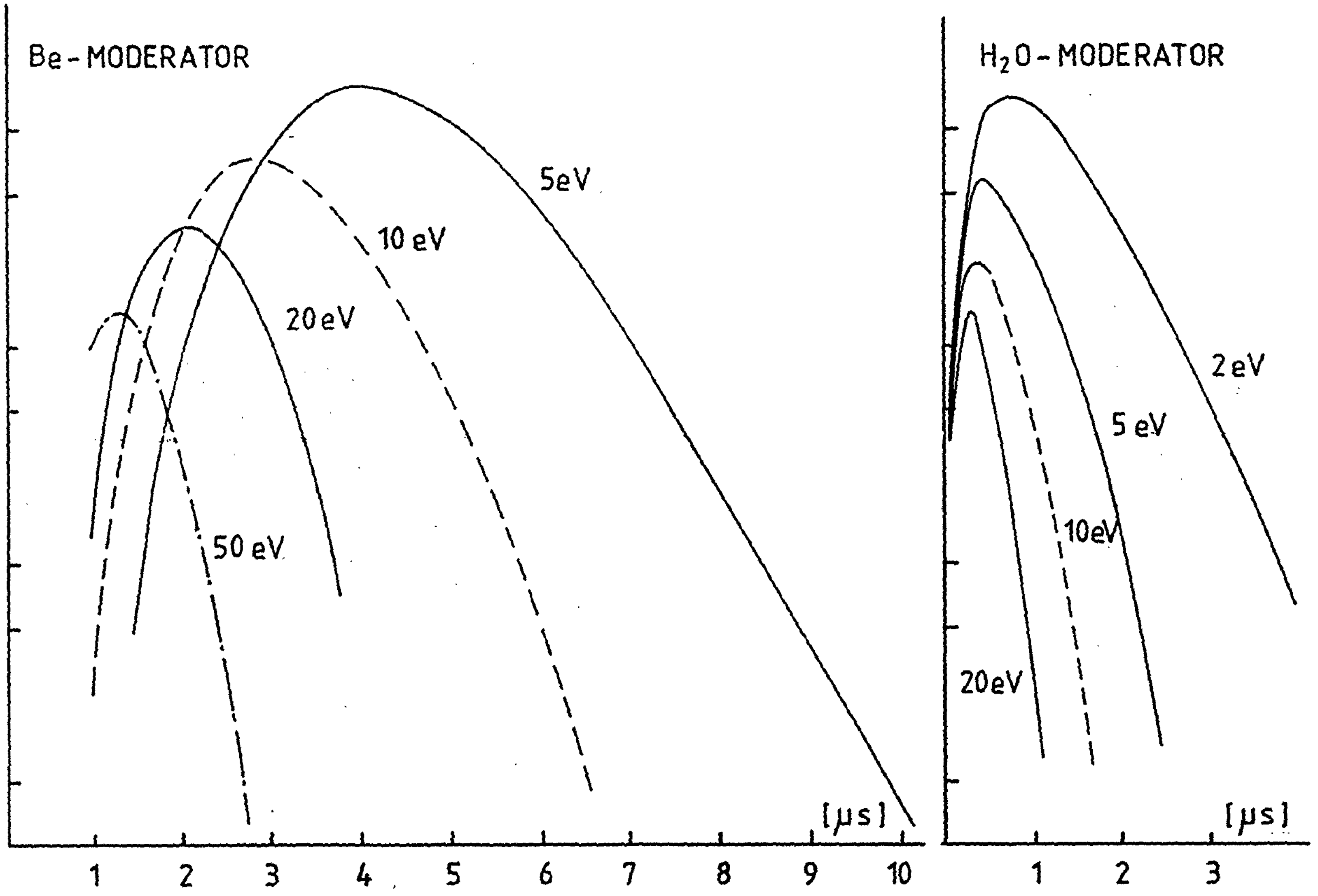


Fig. 4 Neutron pulses and their energy dispersion from a Be- and an H_2O-moderator.

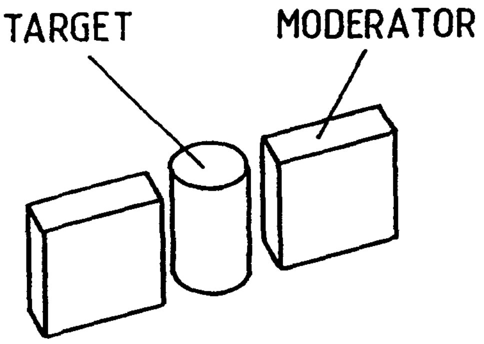

TARGET
MODERATOR

Fig. 5a

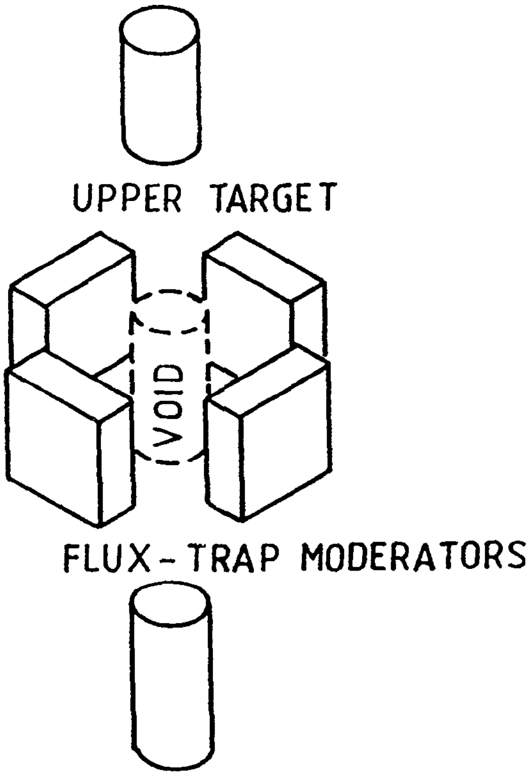

UPPER TARGET
VOID
FLUX-TRAP MODERATORS
LOWER TARGET

Fig. 5b