LA-UR -82-2648

Conf-8206118--7

LA-UR--82-2648

DE83 000665

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

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TITLE: MODERATED-NEUTRON PULSE SHAPES

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SUBMITTED TO: International Collaboration of Advanced Neutron Sources (ICANS-VI) Conference, Argonne, IL, June 28 - July 2, 1982.

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ICANS-VI

INTERNATIONAL COLLABORATION OF ADVANCED NEUTRON SOURCES

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MODERATED NEUTRON PULSE SHAPES

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I. INTRODUCTION

The time dependence of the neutron pulse from hydrogeneous moderators is well known in the showing down region. The full width at half maximum, Δt_{50}, behaves as $2/\sqrt{E}$ when time is measured in μs and energy in eV. The shape of the pulse throughout the slowing down region is a universal function of vt, $\phi(v,t) = (\Sigma_s vt)^2 \exp(-\Sigma_s vt)$. In this equation, v is the neutron velocity, Σ_s the macroscopic cross section of the moderating material and t is time. This infinite medium result is found to hold well even for small hydrogeneous moderators [1] and departures from this behaviour for reflected moderations are understood. Measurements of the time dependence have been made in the thermal region but no specific parameterization has been given. An empirical description is used in powder profile refinement [2] but this has no physical basis. The time behaviour depends strongly on the material and size of the moderator, the reflector and decoupler. Figure 1 shows the wavelength dependence of Δt_{50} in the thermal range for a series of possible moderator configurations, measured at the WNR [3]. Monte Carlo calculations have given some information on pulse shape [4], but are dependent on details of the scattering kernels used and are difficult to perform for other than simple moderators. As condensed matter experiments on pulsed neutron sources become more sophisticated, information will be needed on the shape of the thermal pulse in addition to Δt_{50}. In this paper, we attempt to find some guidelines to the time behaviour of moderated neutron spectra in the thermal region.

2. TIME DEPENDENT DIFFUSION THEORY [5]

The long time dependence of the moderated neutron pulse shape is, in time dependent diffusion theory, given by

$$\phi(t) = \exp(-t/\tau)$$

where

$$\tau^{-1} = \alpha_0 + DB^2 - CB^4 + \ldots$$

In these equations, α_0 is the absorption probability, D the diffusion coefficient, C the diffusion cooling constant and B^2 the geometric buckli. For a rectangular moderator of dimension, $L_1 \times L_2 \times L_3$

$$B^2 = \pi^2 \sum_{i}^{3} L_i^{-2} .$$

We must correct the physical dimension of the moderator by the extrapolation length, $d = 0.71\lambda_{tr}$, where λ_{tr} is the transport mean free path. Thus

$$B^2 = \pi^2 \sum_{L=1}^{3} \left(L_i + 2d\right)^{-2}$$

Table I gives the parameters α_0, D, C and λ_{tr} for four common moderating materials. With these parameters, we can anticipate the long time decay of neutron pulses from large moderators. Although not strictly applicable, we will proceed to use this theory as a guide to the behaviour of quite small moderator ($B^2 \sim 1$).

3. EXPERIMENTAL PROCEDURE

In this paper, we re-analyze two sets of data: time dependent measurements from a pyrolitic graphite crystal analyzer on a mock up spallation source at the CERN PS booster [6] and our own unpublished data taken with a similar analyzing system at the low current target area of the WNR [3]. An exponential is fitted to the long time decay portion of each reflection. At long wavelengths, this decay is found to be independent of reflection, although the intensity associated with the mode increases as energy decreases. In some cases, for example at small buckling, this mode totally dominates the peak shape. The fitted τ values and a description of the configuration are given in Table II.

4. COUPLED AND DECOUPLED SYSTEMS

All the data presented in Table II were taken on reflected systems. Only two of the runs had direct neutronic coupling between the moderator and the reflector. In Figure 2, we plot the τ vs B^2 prediction for beryllium, heavy water, light water and polyethylene using the diffusion parameters of Table I. The coupled run (CERN N) gives a τ value of 500 μs totally consistent with the mode expected from beryllium with a volume equal to that of the reflector used, and not with the decay expected from the polyethylene moderator. When the same reflector was decoupled (CERN B_4C and CERN Cd), the decay is well described by the moderator mode. An intermediate case is the partially coupled dataset, WNR 184. In this run two strongly separated modes were observed, a fast mode corresponding to the moderator decay and a slow mode of 300 μs (containing twice the intensity) resulting from the reflector decay. The system was decoupled, but no void liner was used. The WNR reflector, Figure 3, has a complex shape making the buckling difficult to calculate. However, reversing the analysis, for the 300 μs mode to result from beryllium would require $B^2 = 0.025\ cm^{-2}$, corresponding to a cube of side 36 cm. This is in good agreement with the physical size of the WNR reflector.

For the case of polyethylene moderators we now extend the comparison of diffusion theory to our data to very large values of buckling. In Figure 4 the solid line is the result obtained using the diffusion parameters of Table I. The open triangles and circle are results for decoupled, homogeneous moderators. The closed symbols are decoupled heterogeneously poisoned moderators. In these cases, the moderator dimension is taken to be that in front of the 0.025 mm gadolinium poison which neutronically isolates the moderator from the premoderator for energies less than 150 meV. Both these sets of data are seen to be in excellent agreement with the diffusion result even at values of B^2 as large as $3.36\ cm^{-2}$.

The open square of Figure 3 (WNR 265) is, however, anomalously high. This configuration had a void liner but no decoupler between the moderator and the beryllium reflector. The 100 μs decay time is dramatically lower than the 300 μs expected from the reflector. This

obvious effect of omitting the decoupler must be contrasted with our study of the effect of decoupler and void liner on the full width at half maximum of the pulse, Figure 5. These data show only a 3 μs degradation in Δt_{50} compared with the 30 μs increase in decay time. The slow mode does not appear to dominate the peak in these coupled and weakly decoupled systems but does significantly change the shape at levels lower than the half height. Often considerable intensity is to be found in these tails. Simple spectral measurements which indicate a gain in intensity at a particular energy may, therefore, be an erroneous guide to the most effective moderator.

6. CRYOGENIC MODERATORS

An extension of this approach to cryogenic moderators may be of some value, particularly since one application of these moderators is the production of pulses of long wavelength neutrons, where the exponential decay may be expected to dominate. Cryogenic materials of interest are liquid and solid methane and liquid hydrogen. The behaviour of methane should be similar to that of polyethylene with good agreement expected, with the appropriate diffusion parameters, even for small systems.

The equilibrium form of hydrogen at 20°K is para-hydrogen. A substantial decrease in its cross-section occurs for neutrons unable to excite the lowest level rotational transition (14 meV). Below 14 meV para-hydrogen is virtually transparent to neutrons. It is for this reason that para-hydrogen moderators should not show the gain reported for reentrant grooved methane and polyethylene moderators [7,8].

The diffusion parameters for various ortho-para mixtures have been measured at Los Alamos by G. Hansen [9], Figure 6. Unlike previous measurements [10], these data give consistent values of the absorbtion probability between the two spin states of hydrogen. The 99.8% para-hydrogen curve in Figure 5 confirms that for the size of moderators used on a pulse source, no fundamental mode will exist.

7. CONCLUSION

Simple diffusion theory may be used to describe some aspects of the behaviour of small hydrogeneous moderators in the thermal region. The

measurement of diffusion parameters for methane, both liquid and solid, would be valuable. Unfortunately, such a general description does not seem applicable to parahydrogen.

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Table I

Diffusion Parameters [5]

Moderator	α_0	D	D	λ_{tr}
	(s^{-1})	($cm^2 s^{-1}$	($cm^4 s^{-1}$)	(cm)
CH_2	5,900	26,600	2,600	0.35
H_2O	4,800	36,900	5,100	0.43
D_2O	19	$2.0\ 10^5$	$5.3\ 10^5$	2.43
Be	285	$1.2\ 10^5$	$2.8\ 10^5$	1.48

Table II

Long Time Decay Modes

Data Set	Moderator	Poison Decoupler			τ	B^2
	cm^3	Premoderator	Moderator		μs	cm-2
WNR 63	10 X 10 X 1.27	Cd	--	Cd	14 ± 3	3.36
WNR 62	10 X 10 X 1.27	Gd	--	Cd	19 ± 3	3.36
WNR 326	8.7 X 8.7 X 1.27	Gd	B	B*	16 ± 3	3.38
WNR 325	10 X 10 X 1.27	Gd	Cd	Cd*	15 ± 3	3.36
WNR 323	10 X 10 X 1.27	Gd	Cd	Cd	17 ± 3	3.36
WNR 324	10 X 10 X 1.27	Gd	--	Cd	19 ± 3	3.36
WNR 322	10 X 10 X 1.59	--	Cd	--	17 ± 3	2.46
WNR 145	10 X 10 X 1.91	Gd	--	Cd	25 ± 3	1.90
CERN B_4C(Gd)	18 X 8 X 2.00	Gd	B	B	30 ± 5	1.74
CERN Cd(Gd)	20 X 10 X 2.00	Gd	Cd	Cd	30 ± 5	1.69
WNR 64	10 X 10 X 2.54	Gd	--	Cd	33 ± 3	1.25
CERN B_4C	18 X 8 X 7.00	--	B	--	72 ± 5	0.34
WNR 265	10 X 10 X 7.62	--	--	--	100 ± 5	0.33
CERN Cd	20 X 10 X 7.00	--	Cd	--	80 ± 5	0.29

*Boral Void Liner. All others have a Cd void liner.

Figure Captions

Figure 1. The energy dependence of the full width at half maximum (FWHM) of the time structure from moderators poisoned at a depth of 1.27 cm, 1.91 cm and 2.54 cm by 0.025 mm of gadolinium. The no poison case, where the premoderator is viewed directly, is also shown.

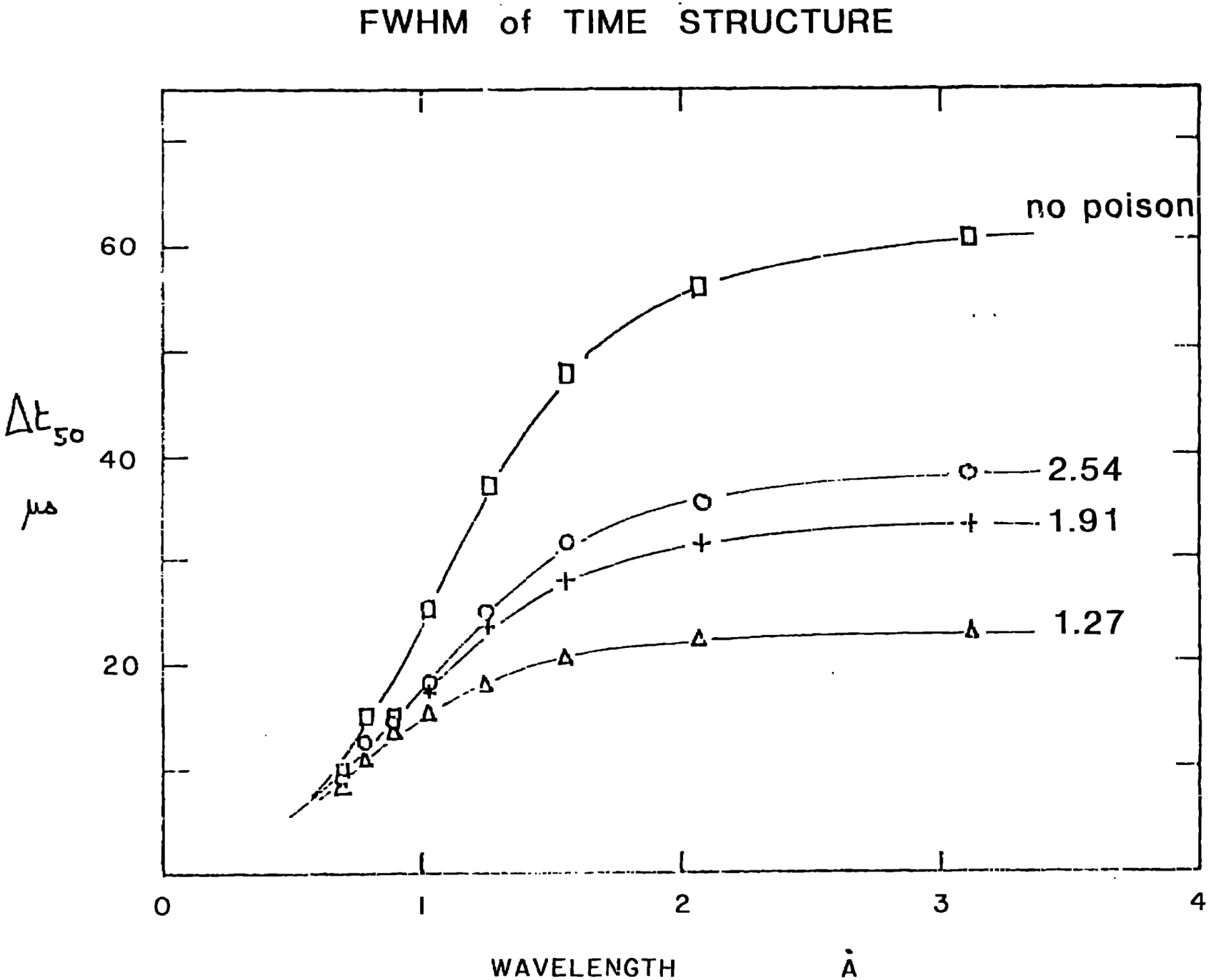
Figure 2. The long time decay mode constant as a function of B^2 for Be, D_2O, H_2O and CH_2 moderators. The open triangle is the mode from CERN N and the open circle the mode from WNR 184.

Figure 3. A cross-section through the reflected 'T'-shaped moderator used at the WNR.

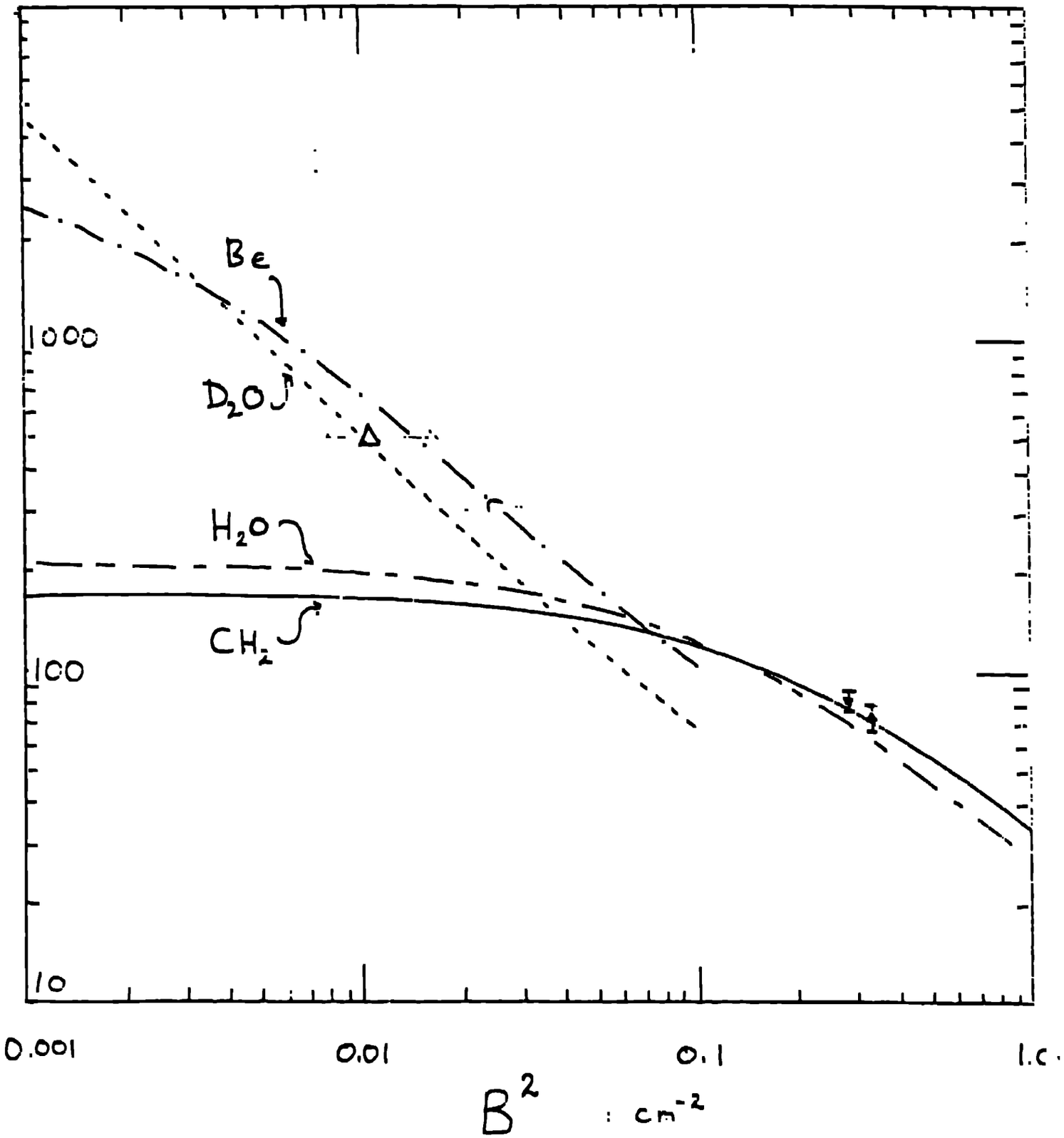
Figure 4. The long time decay mode constant as a function of B^2 for a CH_2 moderator. The open symbols are homogeneous moderators and the closed symbols are heterogeneously poisoned moderators.

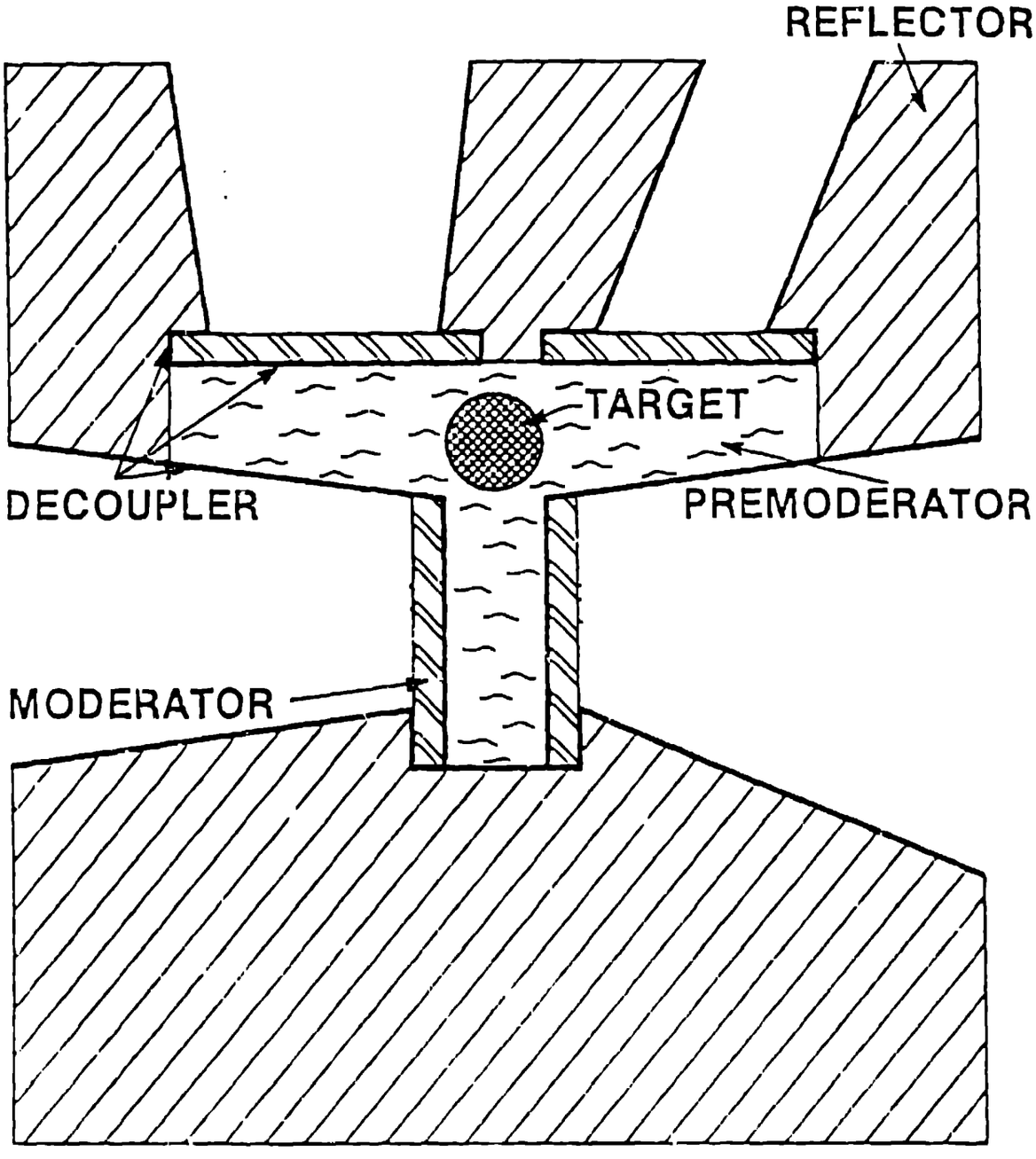
Figure 5. The energy dependence of the FWHM of the time structure of a 1.27 cm moderator for various combinations of recoupler and void liner. The solid line is from a high statistics run on the 1.27 cm case.

Figure 6. The reciprocal of the long time decay mode plotted against B^2 for several values of the ortho-para ratio in liquid hydrogen [9].

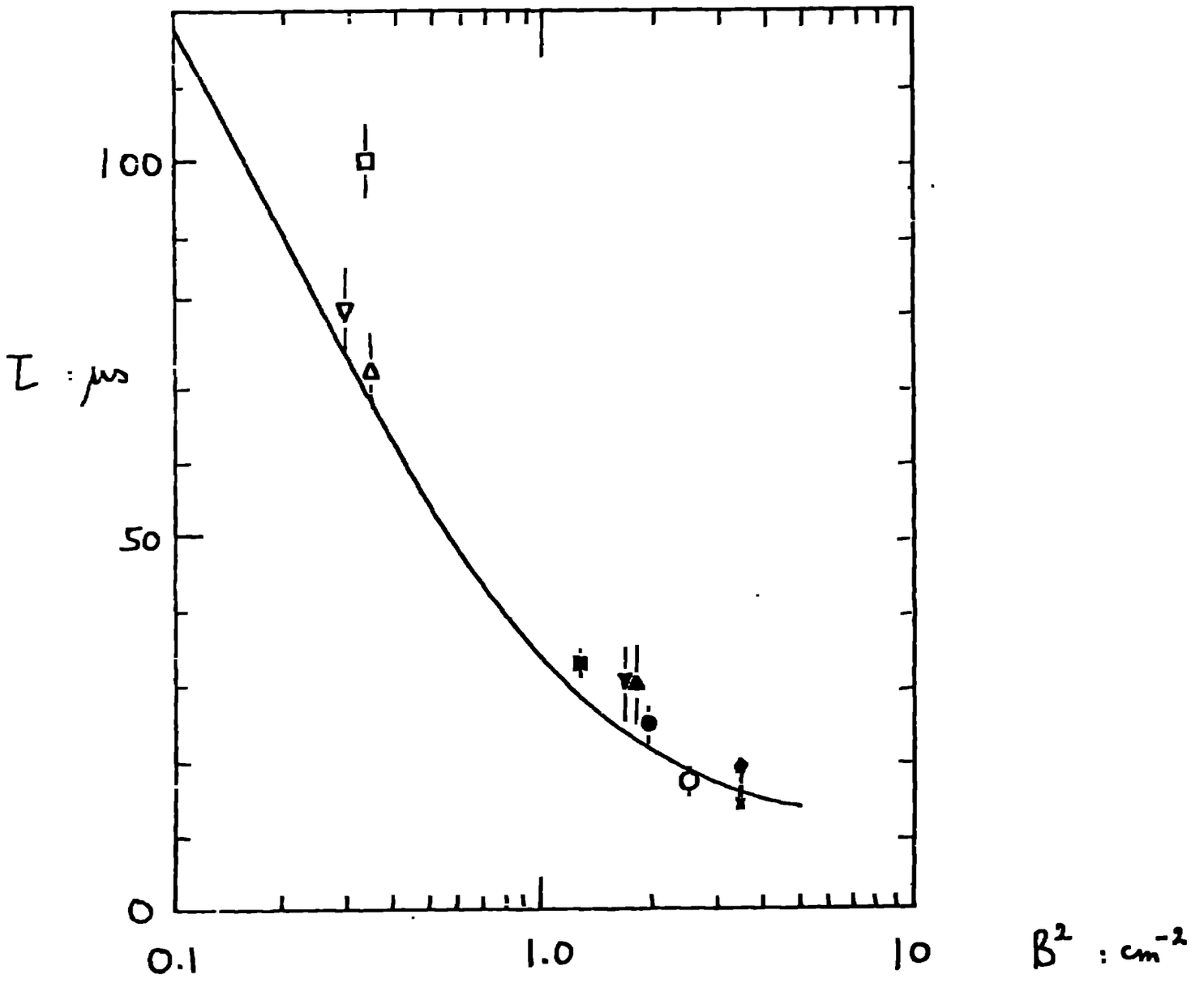

FWHM of TIME STRUCTURE
no poison
2.54
1.91
1.27
60
40
20
0
1
2
3
4
Δt_{50}
μs
WAVELENGTH
Å

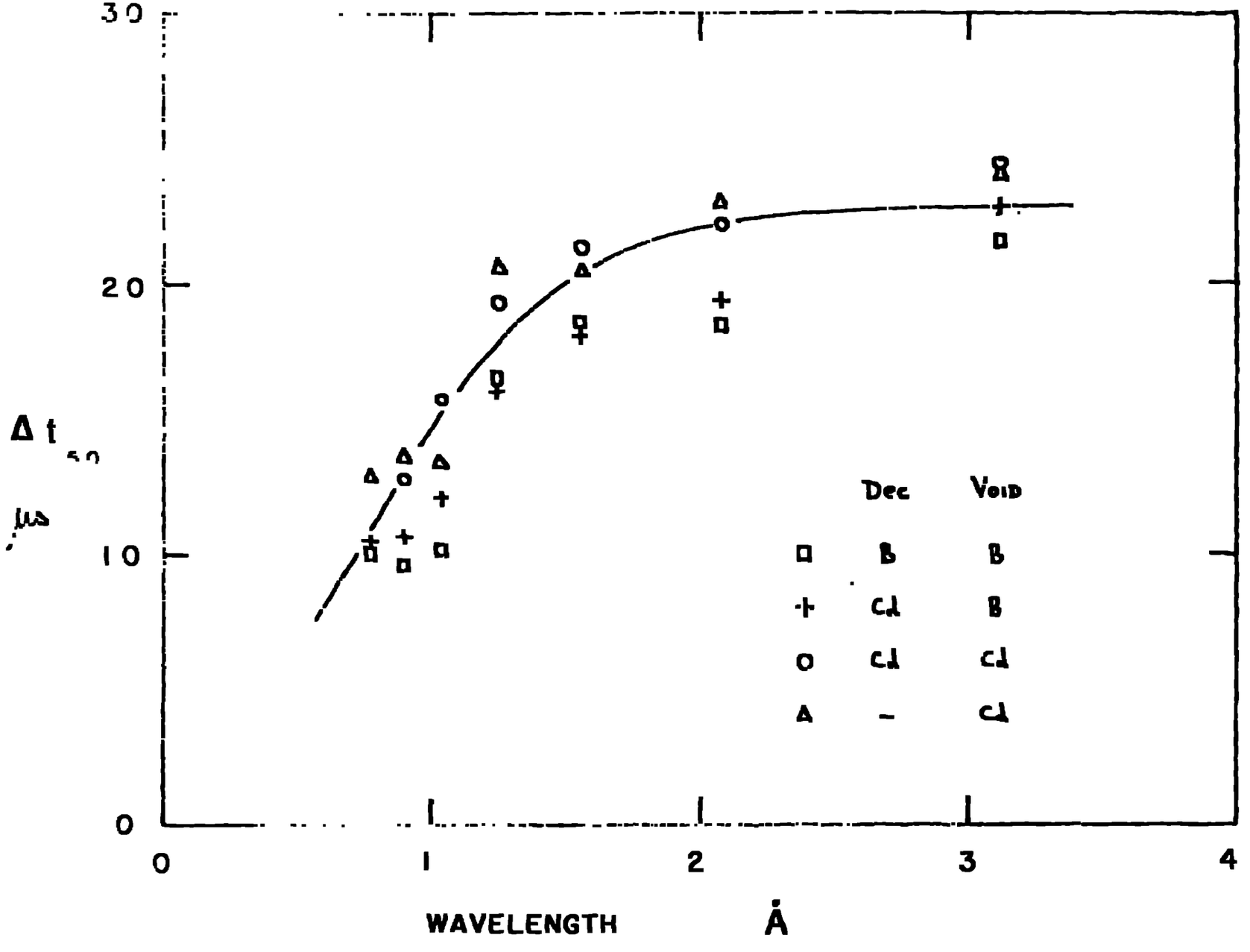
LONG TIME DECAY




REFLECTOR
TARGET
DECOUPLER
PREMODERATOR
MODERATOR

LONG TIME DECAY MODE




30
20
10
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Δ t
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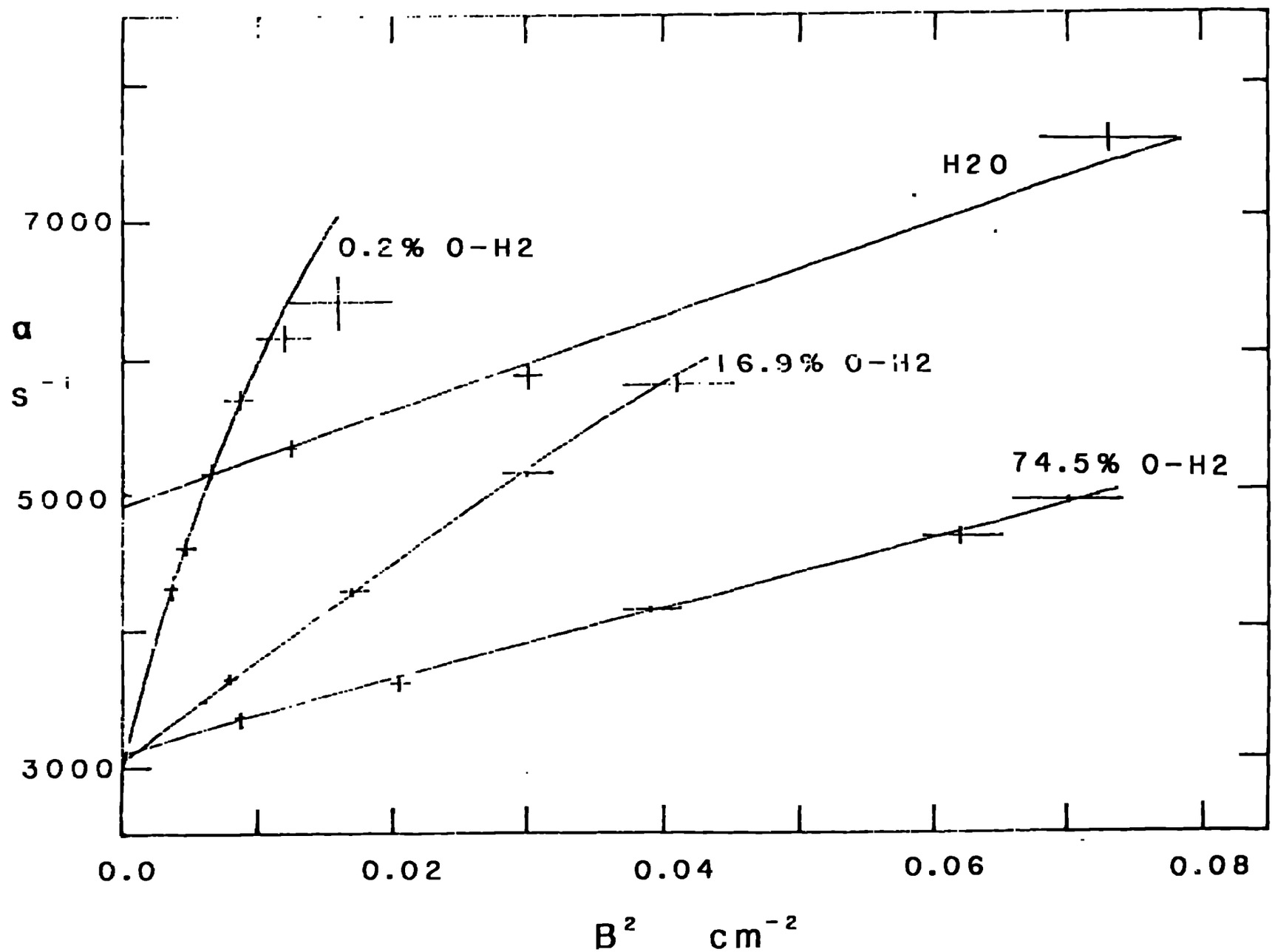
LONG TIME DECAY
H2O
0.2% O-H2
16.9% O-H2
74.5% O-H2
7000
5000
3000
α
S⁻¹
0.0
0.02
0.04
0.06
0.08
B² cm⁻²