KERNFORSCHUNGSZENTRUM

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INTERNATIONAL ATOMIC ENERGY AGENCY

CONFERENCE ON NUCLEAR DATA-
MICROSCOPIC CROSS SECTIONS AND OTHER
DATA BASIC FOR REACTORS

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MEASUREMENTS OF EFFECTIVE (RESONANCE-SHIELDED) NEUTRON CROSS SECTIONS IN THE KEV REGION [1)]

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1. Introduction

The knowledge of effective neutron cross sections is fundamental for Doppler coefficient calculations in fast reactor design. In the low keV region, which is most important for the Doppler effect, the resonances of the cross sections of fertile and fissile materials are narrow and seperated but are still experimentally unresolved.

In the following measurements the pulsed method which has been proved for measuring capture and transport cross sections in the thermal energy range is extended to the keV region. Beghian et al. /1/ used the fast pulsed method to determine nonelastic cross sections in lead, uranium, bismuth, and iron in the MeV range.

2. Principles of Measurement

In the present work, a short burst (1 or 10 ns) of nearly monoenergetic neutrons with energies below the threshold for inelastic scattering is injected into assemblies of lead and

1) This work was performed within the framework of the association EURATOM-Gesellschaft für Kernforschung m.b.H. in the field of fast reactor development.

uranium (parallelepipeds of 10 to 20 cm side length) and the decay of the neutron field in the block is measured. For very heavy materials, moderation effects are negligible, so that the diffusion process can be described by the usual one-group theory and the neutron field decays exponentially with a time constant

$$\alpha_o = v_o \Sigma_a^{eff} + \frac{v_o}{3\Sigma_{tr}^{eff}} B^2 + C_T B^4, \qquad (1)$$

where:

v_o = injection velocity

$$B^2 = \pi^2 \left\{ \frac{1}{(a+1{,}42/\Sigma_{tr}^{eff})^2} + \frac{1}{(b+1{,}42/\Sigma_{tr}^{eff})^2} + \frac{1}{(c+1{,}42/\Sigma_{tr}^{eff})^2} \right\} \qquad (2)$$

the buckling of the assembly (side lengths a,b,c)

$C_T = \frac{v_o}{45 \cdot \Sigma_t^3}$ correction term due to transport theory

Σ_t = macroscopic total cross section

Σ_{tr} = macroscopic transport cross section

Σ_a = macroscopic absorption cross section.

The detailed treatment of the pulsed neutron field including the resonance structure of the cross sections [2] leads to self-shielded cross sections which are identical with effective values defined by Abagjan et al. [3].

$$\sigma_a^{eff} = \frac{\left\langle \frac{\sigma_a}{\sigma_t} \right\rangle}{\left\langle \frac{1}{\sigma_t} \right\rangle} = f_a \cdot \langle \sigma_a \rangle \qquad (3)$$

$$\sigma_{tr}^{eff} = \frac{\left\langle \frac{1}{\sigma_t} \right\rangle}{\left\langle \frac{1}{\sigma_t \cdot \sigma_{tr}} \right\rangle} = f_t \cdot \langle \sigma_{tr} \rangle \qquad (4)$$

The brackets designate averages over an energy interval that is large enough to contain many resonances, but is smaller than the average energy loss per elastic collision. Values of the

self-shielding factors f_a and f_t have been calculated for many nuclides [3].

If the resonance absorber is diluted by a potential scatterer (e.g. Pb), the resonance self-shielding is reduced and can be described by f factors depending on σ_o, which is the potential corss section of the non resonant material referred to a resonance nucleus, that is:

$$\sigma_o = \frac{\Sigma_{pot}}{N_r} - \sigma_{potr} \qquad (5)$$

Σ_{pot} is the macroscopic potential cross section of the mixture, σ_{potr} the microscopic potential cross section of the resonance absorber, N_r the number of resonance nuclei per cm^3. $f_a(\sigma_o)$ and $f_t(\sigma_o)$ are also calculated in Ref. [3].

Eq. (1) is exactly valid only in the absence of moderation effects. It can be shown that, even for materials as heavy as lead and uranium, the moderation is not negligible. According to Eq. (1) the moderation causes a decrease of α with v during the decay, which is therefore not exactly exponential. However, it is possible to calculate the moderation effect and to eliminate it from each decay spectrum. This treatment makes use of the fact that, in the case of heavy materials after pulse injection of nearly monoenergetic neutrons, the spectrum remains sharp during the moderation; its maximum lies near the spectrum-averaged lethargy, which increases with time. It can be shown [2,4] that the decay process can be described as follows

$$N(t) \sim \exp\left[-\left(\alpha_o t + a\frac{t^2}{2} + \ldots\right)\right], \qquad (6)$$

where N(t) is the total (energy-integrated) neutron density, which is measured by a 1/v detector, α_o is the decay constant at injection energy and corresponds to the decay constant that would appear in the absence of moderation. Using a correction function $F(t) = \exp\left(-a\frac{t^2}{2}\right)$ moderation effects are eliminated in the following way:

$$\frac{N(t)}{F(t)} \sim \exp(-\alpha_o t), \qquad (7)$$

where F(t) can be calculated from the buckling, the injection velocity, the mass number of the material and the cross sections. However, for this correction, the cross sections need only be known to first order.

If α_o is measured as a function of the buckling, the cross sections Σ_a^{eff} and Σ_{tr}^{eff} can be obtained according to Eq. (1). The big advantage of this method is that it yields absolute values of the cross sections and no flux determination is necessary.

3. Measurements and Results

The experimental setup is shown in Fig. 1. The neutrons are produced by a pulsed 3-MeV van de Graaff (pulse length 1 or 10 ns, repetition rate 1 or 0,5 Mc/s). The pulsed proton beam passes through an electrostatic pick up system which provides the zero timing pulse. The $Li^7(p,n)\,Be^7$ reaction yields 30 keV neutrons near threshold (the energy spread is $\pm$ 6 keV); the $Sc^{45}(p,n)\,Ti^{45}$ reaction yields neutrons of 7.5 keV with an energy spread of $\pm$ 0.8 keV at the lowest resonance of the(p,n) cross section.

The decay of the neutron field in the assembly is measured with the detector A, which is either a Li^6-loaded glass scintillator (time resolution $\lesssim$ 8 ns) or a LiI crystal (time resolution $\lesssim$ 20 ns) in connection with 56 - AVP photo-multipliers.

The latter detector is used for the measurements on uranium, because of its better discrimination against the gamma radiation from radioactive decay of the uranium. Detector B (Li^6-loaded glass scintillator with a photo-multiplier) as a time-of-flight spectrometer, controls the energy of the neutrons of the Sc reaction.

Measurements of the decay time in assemblies of lead, uranium, and a homogeneous mixture of both have been made.

Fig. 2 shows a typical decay curve of a 30 keV neutron field in uranium. An inspection of the decay curve after background substraction shows that it is not exponential. But the division of the background corrected spectrum by F(t) leads to a decay which is exactly exponential over about 3 decades. However, for the evaluation of α_o, only about 2 decades are used. Within this region, F(t) is smaller than 2 and the accuracy of the Taylor expansion is good enough. Though F(t) is rather large, the difference of the slopes of corrected and uncorrected curve (if we restrict ourselves to the nearly exponential region) is less than 10 %, corresponding to an α correction of the same order. The decay constants obtained have been found to be independent of the detector position.

Figs. 3, 4 and 5 are plots of α_o vs B^2 curves for lead at a neutron energy of 30 keV and uranium at 30 keV and 7.5 keV respectively. The full curves are least squares fits according to Eq. (1), where B^2 is an implicit function of Σ_{tr}^{eff} /Eq. (2)/. Σ_a^{eff} and Σ_{tr}^{eff} are obtained from an iterative procedure which yields a best fit for $\alpha_o(B^2)$. Since C is very small, its theoretical value is used.

Table I shows the measured effective cross sections. Since no similar experimental values exist at present, the measured effective cross sections can be compared with $\langle\sigma\rangle$ values of other authors only after division by the calculated self-shielding factors /3/ according to Eqs. (3) and (4). Lead shows no resonance self-shielding in the keV region (the number of resonances is too small) and the f factor is equal 1. The capture cross section ($\approx$3 mb) is too small to be measured by this method. The transport cross section conforms very well with other measurements. For uranium the resonance self-shielding is still small at 30 keV ($f \approx 1$) but is already considerable at 7.5 keV. The agreement of the measured effective capture cross sections after division by

f_a is good both for 30 keV and 7.5 keV. The transport cross section at 7.5 keV agrees very well with other measurements, but at 30 keV this cross section is about 10 % higher than other values.

Measurements on diluted systems are not yet concluded. Fig. 6 is a plot of f_a vs σ_o for uranium for 7.5 keV neutrons, calculated from Ref. /3/ using an interpolation formula /13/. The upper abscissa gives the corresponding volume ratios of a U^{238}-Pb mixture related to σ_o by Eq. (5). Preliminary on diluted systems measured f factures, obtained by measured σ_a^{eff} values after division by $\langle \sigma_a \rangle$ given in Ref. /8/ are consistent with Fig. 6.

The effective cross sections measured by the fast pulsed method agree with values computed from calculated f factors and $\langle\sigma\rangle$ values measured by other authors. The present method can be used to determine f factors, if $\langle\sigma\rangle$ values are obtained by other methods. Further it is possible to investigate the self-shielding in mixtures of materials, e.g., a resonance absorber(U^{238}) and a potential scatterer (Pb), which permits the study of dilution effects, or two resonance absorbers (U^{238} and Pu^{239}).

Table I: Comparison of Measured σ^{eff} Values with $\langle\sigma\rangle$ Values of Other Authors

Material	Neutron-energy /keV/	σ_a^{eff} /b/	f_a /3/	$\frac{\sigma_a^{eff}}{f_a}$ /b/	$\langle\sigma_a\rangle$ /b/	σ_{tr}^{eff} /b/	f_t /3/	$\frac{\sigma_{tr}^{eff}}{f_t}$ /b/	$\langle\sigma_{tr}\rangle$ /b/
Pb	30 ± 6	-	-	-	-	10,1±0,2	1,00	10,1	10,0/5/
U^{238}	30 ± 6	0,50±0,03	0,92	0,54	0,38/6/ 0,47/7/ 0,50/8/ 0,53/9/	14,65±0,5	0,97	15,1	13,6/10/ 13,4/8/ 13,7/11/ 12,0/12/
U^{238}	7,5±0,8	0,40±0,02	0,65	0,61	0,63/7/ 0,64/8/	11,92±0,4	0,75	15,9	15,8/11/ 15,3/8/

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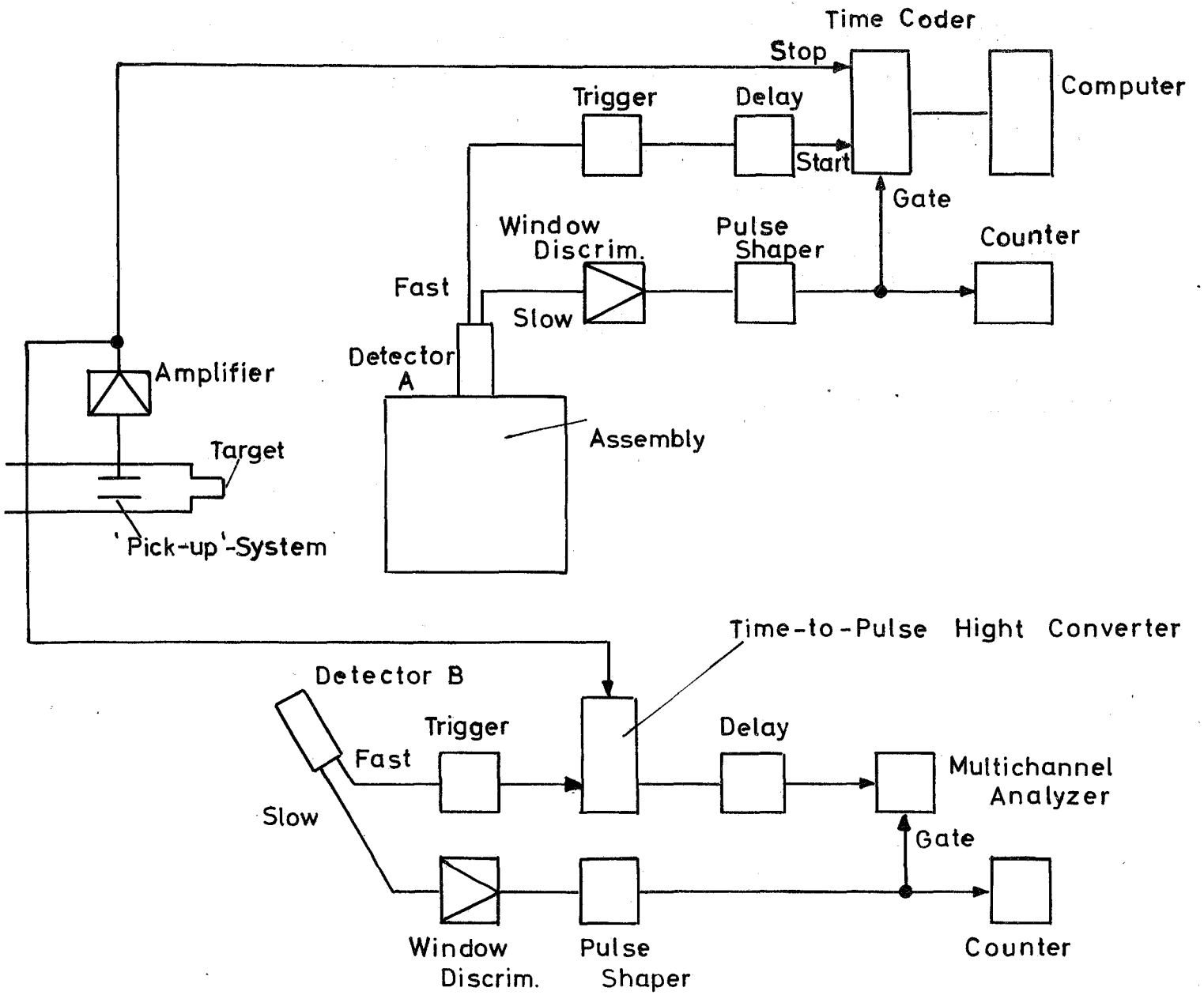

Fig. 1 Experimental Set-up

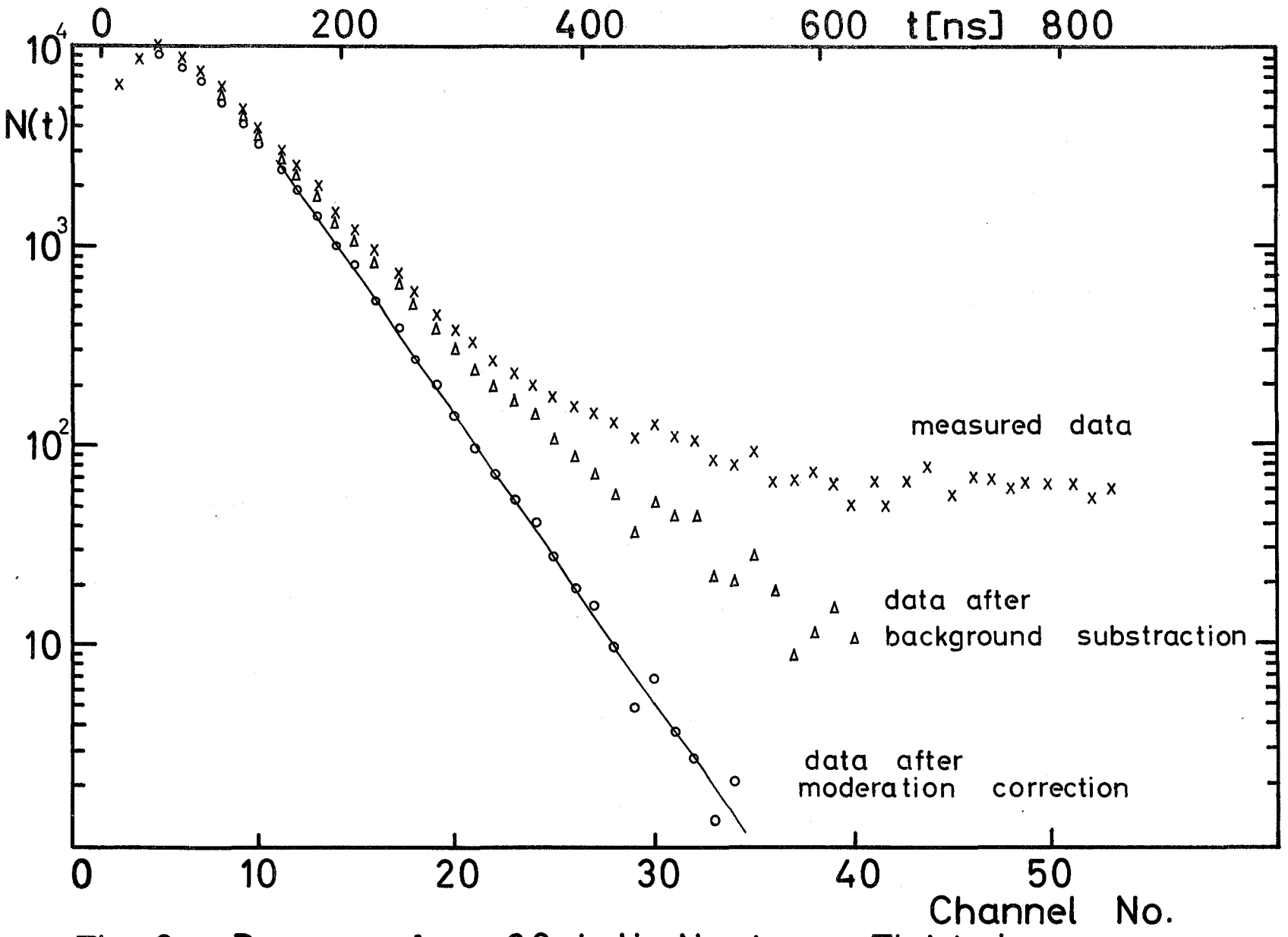

Fig. 2 Decay of a 30 keV Neutron Field in a 15.3×15.3×15.2 cm^3 Block of Natural Uranium

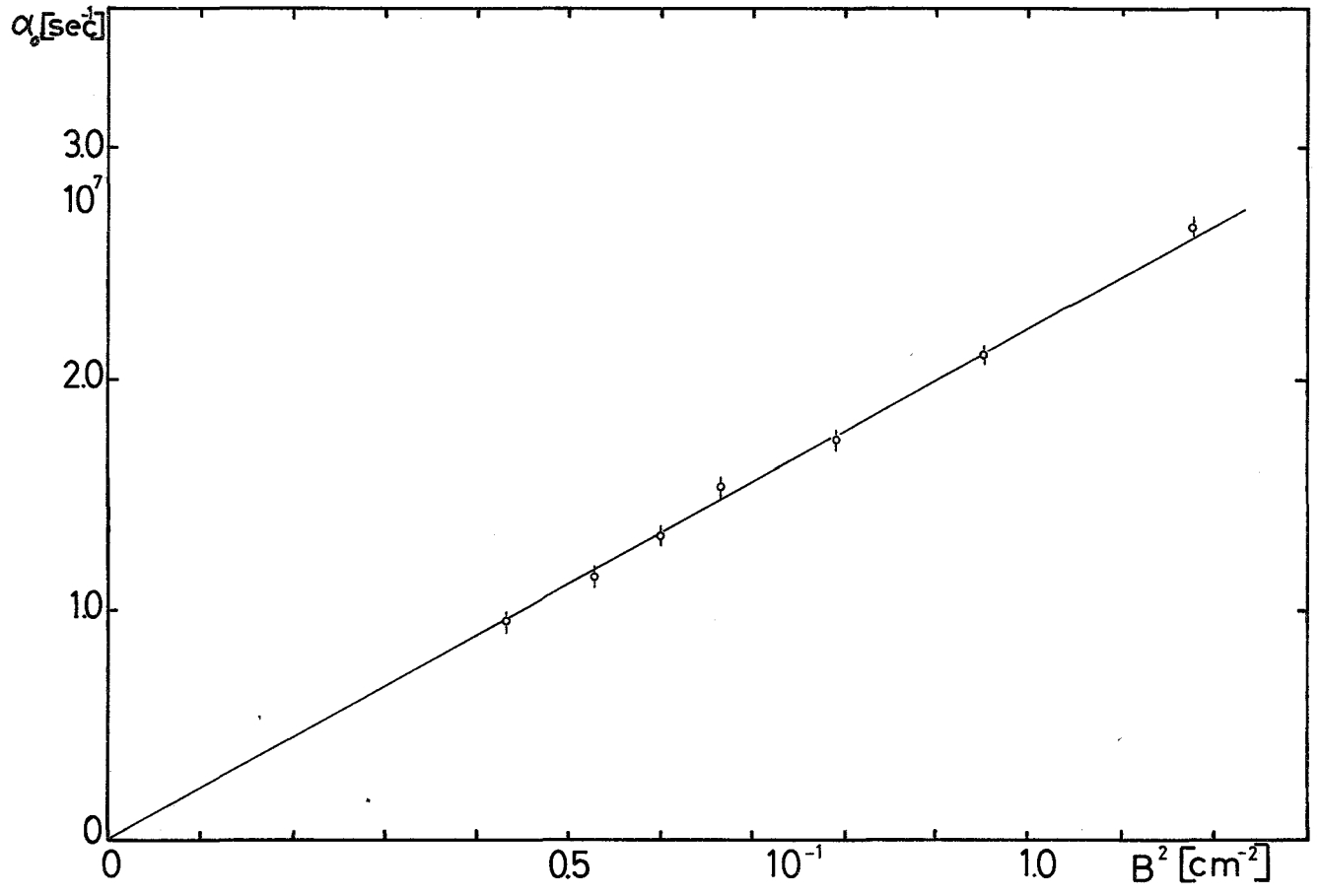

Fig. 3 Decay Constant vs Buckling for 30 keV Neutrons in Lead.

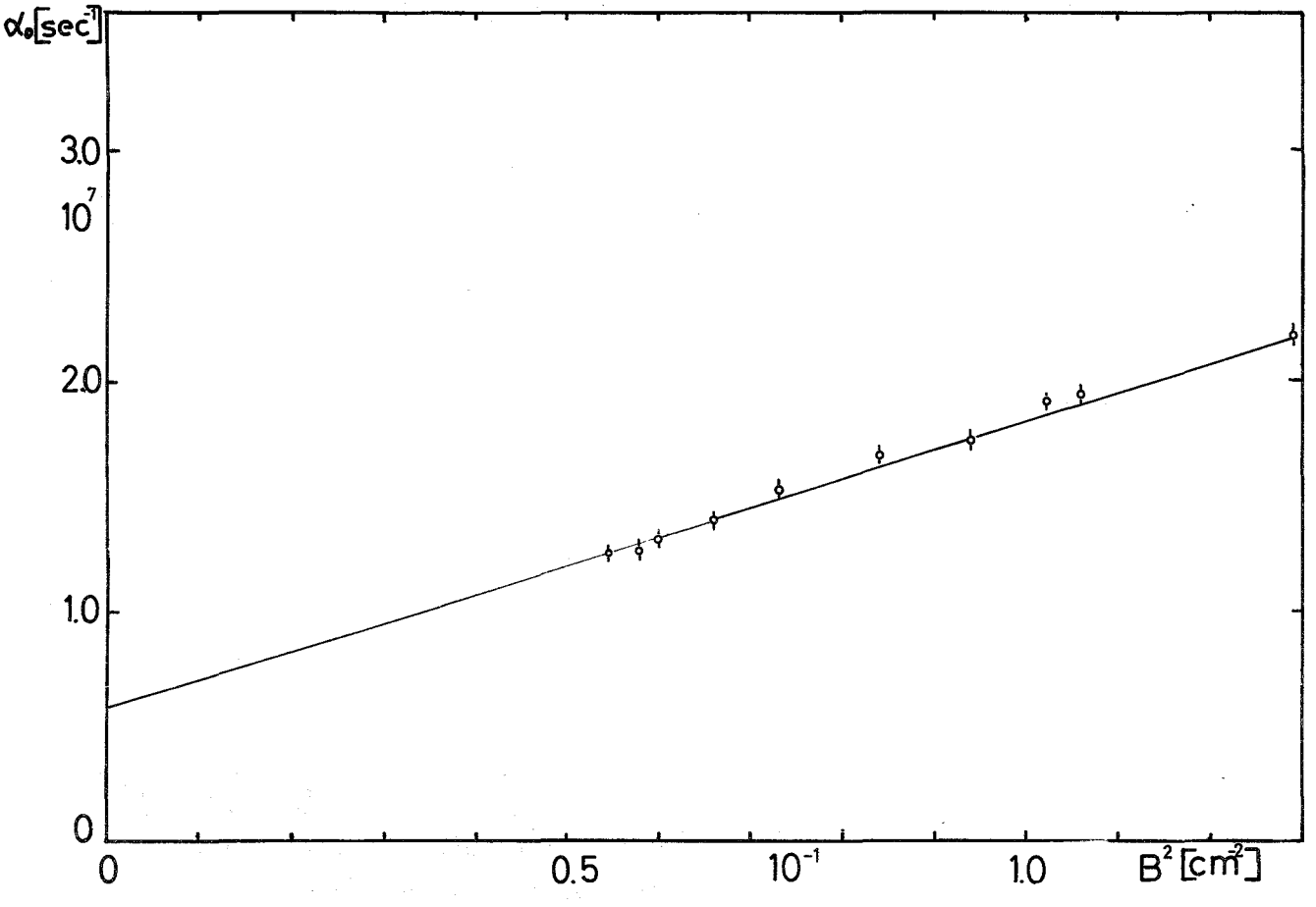

Fig. 4 . Decay Constant vs Buckling for 30 keV Neutrons in Natural Uranium.

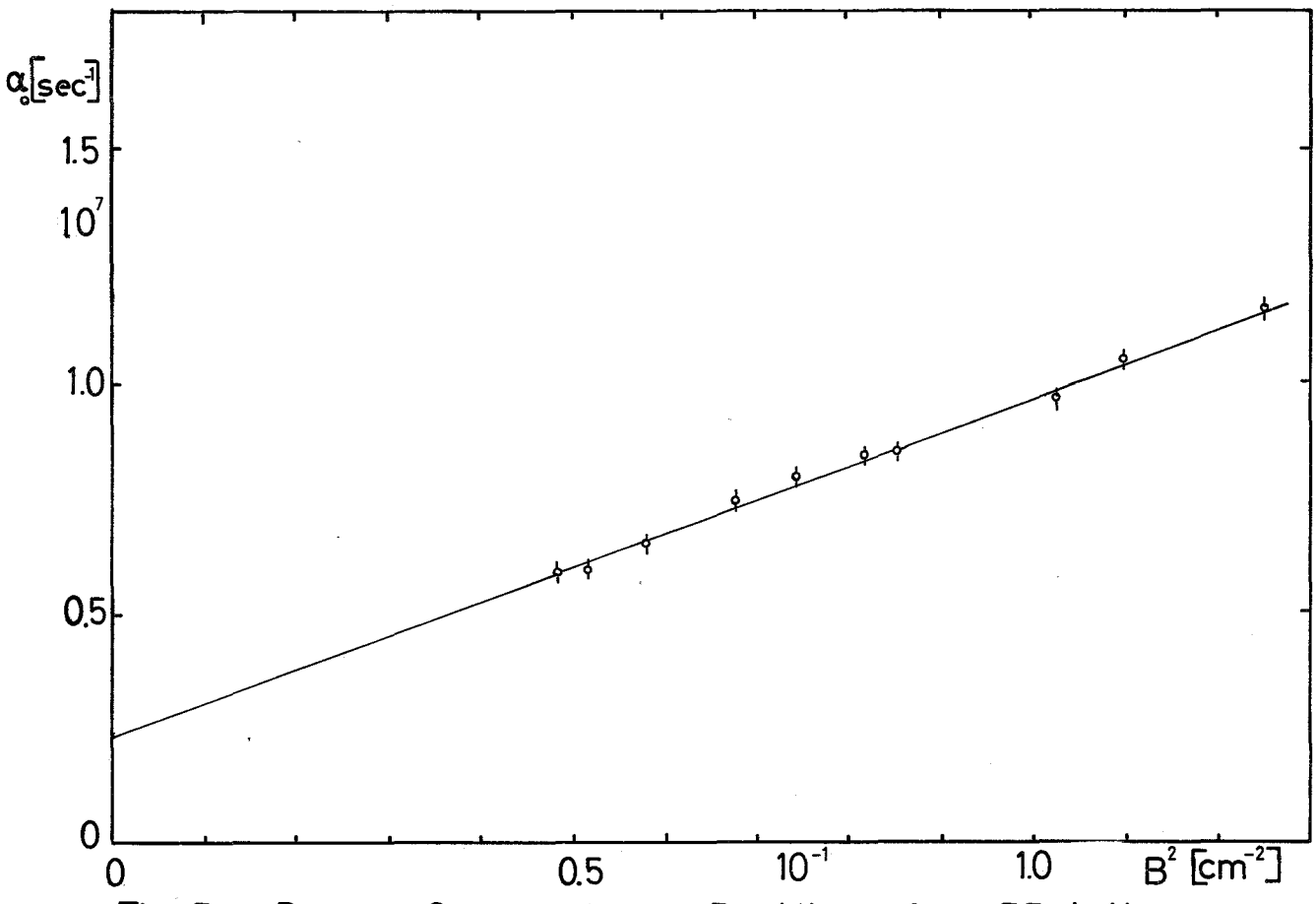

Fig. 5 Decay Constant vs Buckling for 7.5 keV Neutrons in Natural Uranium.

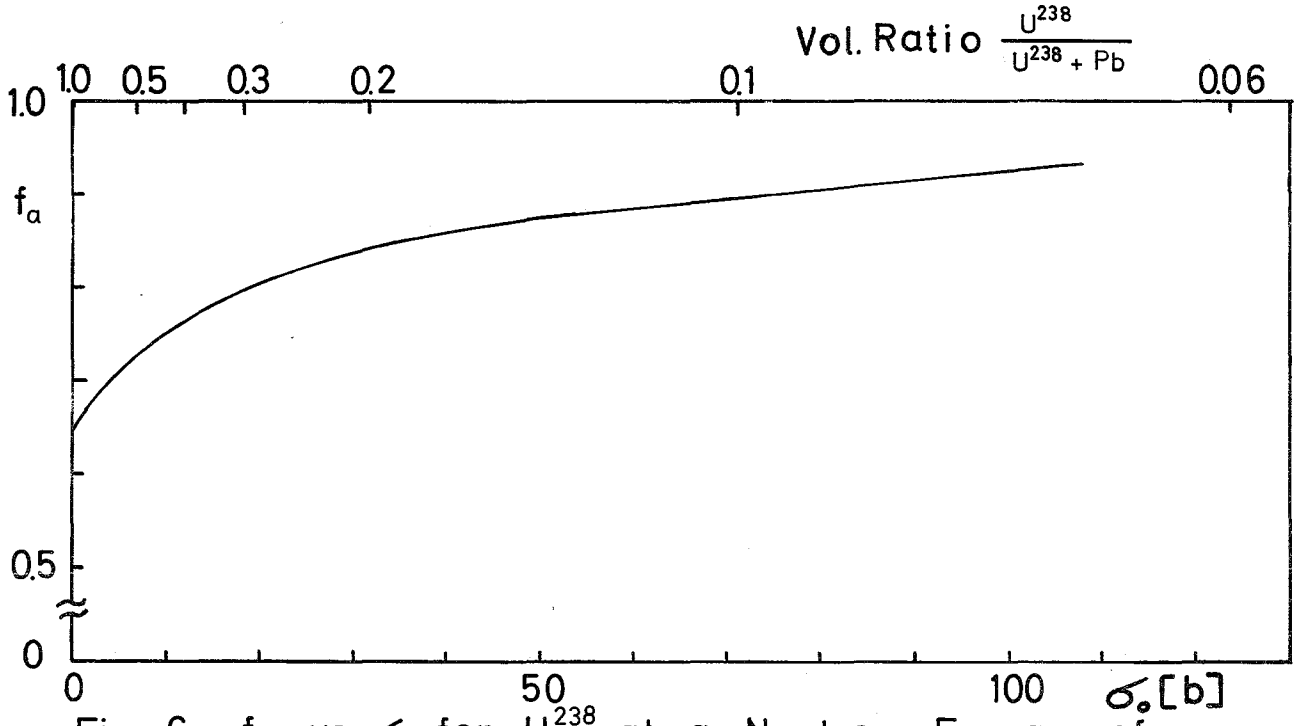

Fig. 6 f_a vs σ_o for U^{238} at a Neutron Energy of 7.5 keV. The Upper Abscissa gives the Corresponding Volume Ratios of a U^{238}-Pb Mixture.