Total Nuclear Photoabsorption Cross Sections and the Levinger's Factor (*)

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Very recently, Levinger([1]) has analysed the Saclay data ([2]) on total photoabsorption cross sections of lead in the energy range 35-106 MeV by using his modified quasi-deuteron model. In the present work, this analysis is reviewed and extended to the cross section data of lithium, beryllium, carbon, oxigen, aluminium and calcium in the energy range 40-150 MeV obtained in recent years by the Mainz group ([3]). It is shown that the available cross section data ([2,3]) provide physical evidence for an increase of the Levinger's factor L with increasing mass number, in accordance with the assumption made in a previous paper by us ([4]).

In its simplest form, the Levinger's model ([5]) describes a photonuclear reaction by the interaction between the incoming photon and correlated neutron-proton pairs (quasi-deuteron), and such a mechanism of interaction leads to a total nuclear photoabsorption cross section given by

$$\sigma^{t}_{qd}(E_{\gamma}) = L\,\frac{NZ}{A}\,\sigma_{d}(E_{\gamma}) \quad . \tag{1}$$

In this equation, $\sigma_d(E_\gamma)$ is the total photodisintegration cross section of a free deuteron ([6]), NZ is the number of neutron-proton pairs in a nucleus of mass number A, and L is a constant (the so-called Levinger's factor) which represents a measure of the relative probability of two nucleons being near each other in a complex nucleus compared with that of a free deuteron. For a given nucleus, the ratio LNZ/A can be thought of as the effective number of deuteron-like structures which take place in the primary photointeraction.

In the original version of his model, Levinger ([5])

deduced $L = 6.4$ by using a nuclear radius of 1.4 $A^{1/3}$ fm. Later, he found ([7]) $L = 8$ for a nucleus of radius parameter $r_0 = 1.2$ fm. On the other hand, several experimental investigations have indicated values of L not well defined (see table I). In addition a constant value $L \simeq 10$ (taken as being independent of A) has been assumed throughout Monte Carlo calculations of photon-induced intranuclear cascades in complex nuclei ([12,13]) aiming to study, in a systematic manner, (γ,nucleon), (γ,spallation), (γ,fission) and other photoreactions at intermediate energies.

Such a variety of L-values which emerge from both theoretical and experimental considerations led us to return at the original Levinger's quasi-deuteron model ([5]) in order to search for a dependence of L on the mass number A. We noted that the values of L are strongly dependent on the nuclear radius parameter r_0. We have assumed, following Elton ([14]), an A-dependence of r_0 according to

$$(2) \qquad r_0 = 1.12 + 2.35A^{-2/3} - 2.07A^{-4/3} \text{ fm} \quad ,$$

from which the following equation for L has been deduced ([4]):

$$(3) \qquad L = \frac{0.67}{NZ} A^{2.28} \quad .$$

The L values obtained in this way have been quite adequate in analysing intermediate-energy (γ,n) reaction cross sections of nuclei ranging from ^{12}C up to ^{238}U ([4,15]). At present, in our systematic study of the yields of true direct (γ,n) and (γ,p) reactions at intermediate energies ([16]), we have changed from eq. (3) into

(4) $$L = 2.1 \ln (1.3A)$$

to take into account the condition $L = 2$ for a deuterium target (values of L calculated from this equation, however, do not differ significantly from those obtained from eq. (3)). We shall see that the above assumption of an increase of L with increasing mass number as expressed by eqs. (3) and (4) is consistent with the results of the Mainz ([3]) and Saclay ([2]) experiments on total photoabsorption cross sections of lithium, beryllium, carbon, oxigen, aluminium and calcium in the energy range 40-150 MeV, and lead from 35 to 106 MeV photon energy, respectively.

The data for lead have been recently fitted by the Levinger's modified quasi-deuteron model ([1]) which gives a total absorption cross section for the nuclear photoeffect as

(5) $$\sigma^{t}_{mqd}(E_\gamma) = L \frac{NZ}{A} \sigma_d(E_\gamma) \exp(-D/E_\gamma) \quad .$$

The one-parameter factor $\exp(-D/E_\gamma)$ was introduced by Levinger into his original cross section formula to take into account some damping effects of the cross section $\sigma^{t}_{qd}(E_\gamma)$ due to Pauli blocking of final states for the neutron and/or proton emitted from the quasi-deuteron at incident photon energies comparable to the Fermi energy in the nucleus. By assuming $L = 8$, Levinger ([1]) has derived $D = 60$ MeV as the best value for the damping parameter, which fits rather well the Saclay data ([2]) on the total photoabsorption cross section in lead.

In the present analysis, use has been made of eq. (5) in order to determine both the L and D parameters by least-squares fitting the available cross section data $\sigma_{exp}(E_\gamma)$ from the Mainz and Saclay experiments. The quantity $\ell n(\sigma_{exp}(E_\gamma)/\sigma_d(E_\gamma))$ has been plotted against $1/E_\gamma$ in the energy range 40-150 MeV for Li, Be, C, O, Al and Ca, and for Pb from 35 to 106 MeV. For each nucleus under consideration, the great majority of points lies, within the current errors, on a straight line from which the values of L and D could be deduced. Except for the case of lead (for wich D = (61±4) MeV and L = 8.3±0.6, in a quite complete agreement with the values reported by Levinger ([1])), no damping parameter ($D \simeq 0$) resulted for the nuclei we considered. This is probably due to the small values of the Fermi energies E_F for neutrons and protons in nuclei up to $A \simeq 40$ ($E_F \lesssim 30$ MeV) as compared with the range of incident photon energies ($E_\gamma \gtrsim 40$ MeV). As regards the parameter L, the following values were obtained from our analysis: 5.3±1.2 for Li, 4.5±1.1 for Be, 5.8±1.5 for C, 6.8±2.5 for O, 7.3±1.9 for Al, and 7.1±2.9 for Ca. These L-values, together with the obtained one for Pb, are plotted in fig. 1 as a function of the mass number. We point out the remarkable increase of LNZ/A with increasing A. The points have been treated by a least-squares method to give

$$L \simeq \frac{A^{2.147}}{NZ} \tag{6}$$

which compares, for $A \lesssim 100$, reasonably well (a maximum of about 20% deviation) with the L-values deduced from our previous formula (3). For $A \gtrsim 100$, eq. (3) (dashed line in fig. 1) gives L-values which differ from the present ones (eq. (6) and solid line) by less than about 40% (this quantity referring to ^{238}U). In any way, an A-dependence of the Levinger's factor L is well established from the experiment, and eq. (6) may be used in the context of the Levinger's modified quasi-deuteron model. Therefore, we replace formula (5) by the new one

$$(7) \qquad \sigma^{t}_{mqd}(E_\gamma) \simeq A^{1.147}\, \sigma_d(E_\gamma)\exp(-\mathcal{D}/E_\gamma) \quad ,$$

with $\mathcal{D} \simeq 60$ MeV for Pb and $\mathcal{D} \simeq 0$ for nuclei with $A \lesssim 40$.

We have compared, in a systematic manner, the total absorption cross sections for the nuclear photoeffect calculated by means of eq. (7) with nearly 300 experimentally determined cross sections by the Mainz and Saclay groups (see fig. 2). About 80% of the measured cross sections are reproduced within a factor of two by the proposed formula (7) (this factor drops to 1.3 in the case of lead). The agreement between calculated and measured cross sections might be considered good if one considers either the large errors involved in individual measurements or fluctuations of the measured cross sections from a smoothed trend in the whole photon-energy interval (2,3) (the smallness of the cross sections makes precise measurements to be very difficult). Therefore, for photons of intermediate energies (say 150 MeV $\lesssim E_\gamma \lesssim$ 400 MeV), it is very adequate to use the Levinger's modified formula (eq. (5)) with LNZ/A given by $\simeq A^{1.147}$ in estimating the contribution coming from the quasi-deuteron mechanism of photon absorption to the total photonuclear reaction cross section.

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TABLE I. - *Values of L deduced from photodisintegration experiments.*

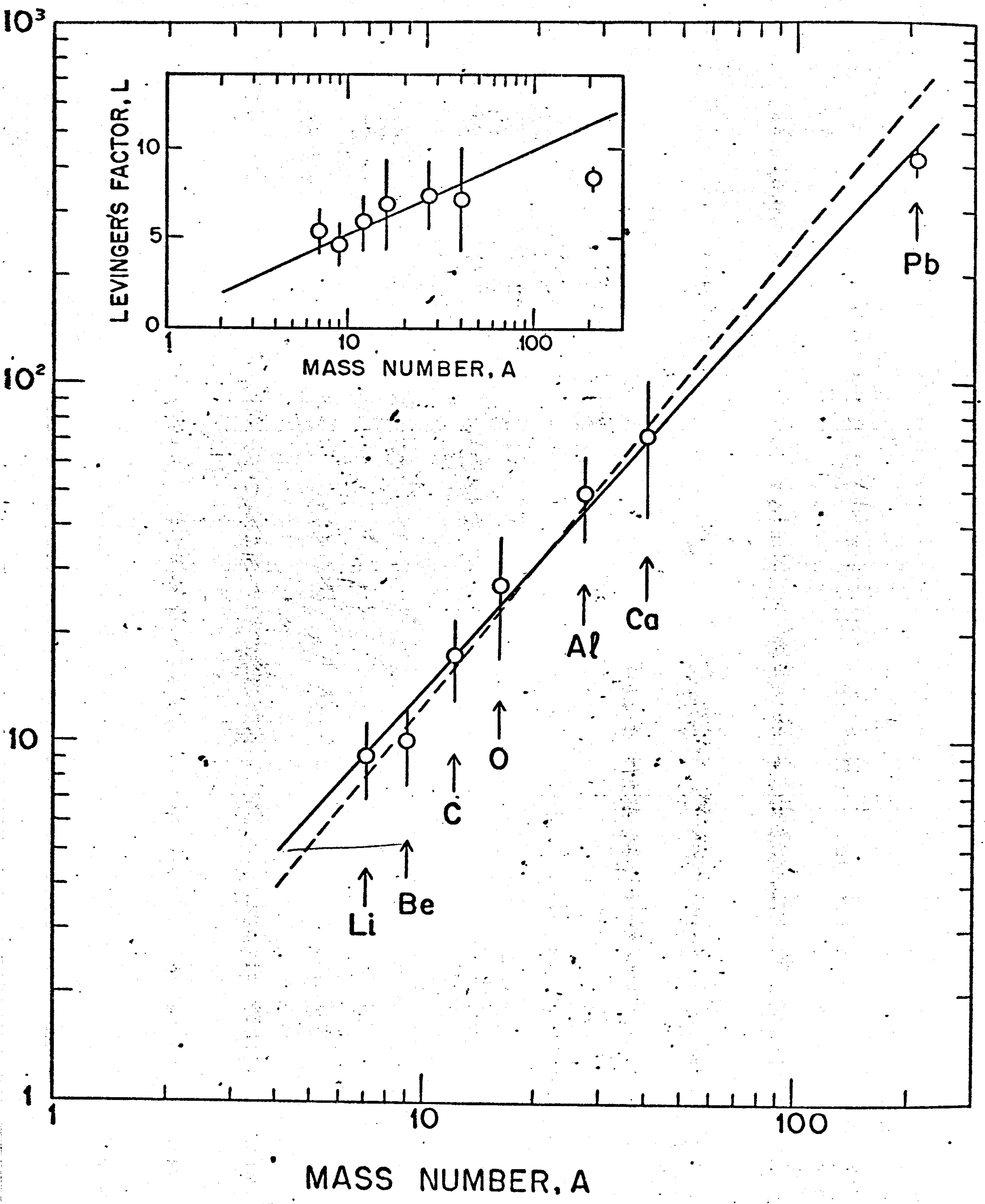
Reaction	Bremsstrahlung energy (MeV)	Nucleus	Ref.	L
(γ,np)	320	Li-Pb	[8]	≈3
				4.9 [a]
	300	^{16}O	[9]	10.3 ± 2.6
	150-250	^{7}Li	[10]	9.6 ± 2.3
		^{12}C	[10]	12.4 ± 3.0
		^{40}Ca	[10]	8.7 ± 2.1
(γ,p)	100	^{6}Li	[11]	4.5 ± 1.0

[a] Calculated value.

Figure Captions

Fig. 1. Effective number of deuteron-like agregates, LNZ/A, plotted against mass number A. The points represent the results by least-squares fitting the measured total photoabsorption cross sections for Li, Be, C, O, Al and Ca in the energy range 40-150 MeV ([3]) and for Pb from 35 to 106 MeV ([2]), as indicated in the text. The full line, whose equation reads $LNZ/A = A^{1.147}$, is the result of a least-squares fit through the calculated points, and the dashed line is the A-dependence of LNZ/A assumed previously by us (eq. (3)). For the sake of comparison, the inserted figure shows the correspon-ding values of L (points) and the A-dependence $L \doteq 2.1\ \ell n\ (1.3A)$ (full line) which has been assumed very recently by us ([16]).

Fig. 2. Frequency distribution of the ratio between calculated total photoabsorption cross sections according to eq.(7) and measured cross sections ([2,3]). Damping parameters are: $D \simeq 0$ for Li, Be, C, O, Al and Ca, and $D \simeq 60$ MeV for Pb.



LEVINGER'S FACTOR, L
MASS NUMBER, A
Li
Be
C
O
Al
Ca
Pb
MASS NUMBER, A

Fig. 1

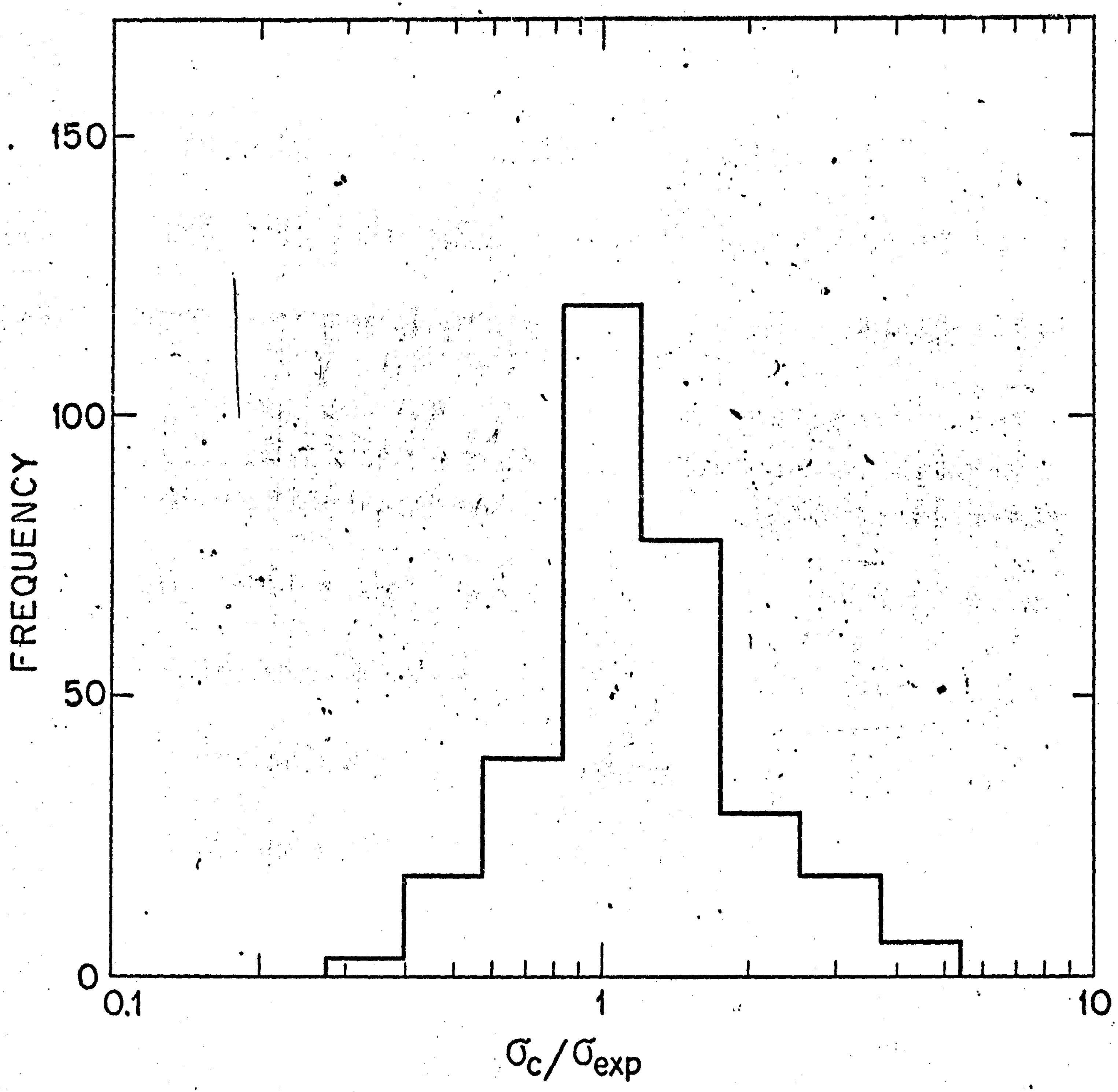


Fig. 2