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Status of the ^{10}B Absorption Cross Section*

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ABSTRACT

Recent measurements on the ^{10}B total, scattering, absorption, (n,α_0), and $(n,\alpha_1\gamma)$ are reviewed. In particular, the absorption cross sections betweem 1 and 500 keV are treated in detail and existing discrepancies in available data are noted. Experimental results on $(n,\alpha_1\gamma)$ are shown up to 4 MeV but thermal and low-energy measurements are not included in this survey.

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STATUS OF THE ^{10}B ABSORPTION CROSS SECTION

Although detector characteristics are very important to the measurement of neutron flux, this report will be confined to a discussion of standard neutron cross sections, in particular the absorption cross section of ^{10}B. For comparison of cross-section efficiency, Figure 1 displays the energy dependence of several cross sections often used as standards in the region from 1 keV to 10 MeV. Below 1 keV, the hydrogen scattering cross section is a constant, while the $^{3}He(n,p)T$, $^{6}Li(n,\alpha)T$, and $^{10}B(n,abs)$ are generally given by a $1/v$ dependence upon the inclusion of a small constant term, $\Delta\sigma$. A more precise representation of the absorption cross section is obtained from the low-energy S-wave expansion derived by Shapiro:[1]

$$\sigma_{ABS} = A/\sqrt{E_n} + \Delta\sigma + B\sqrt{E_n} + CE_n + \ldots \quad (1)$$

where the constants will be quoted with E in eV and σ in barns.

Much of the present data for σ_{ABS} have been obtained through fitting measurements of the total cross section[2,3] generally assuming that the constants B and C are zero. Recent measurements of the scattering cross section[4] have been combined with data on σ_{TOT} to obtain a value for the constant, $\Delta\sigma$, again assuming that B and C are negligible. A couple of years ago, however, Gubernator and Moret from GEEL[5] fitted all available data on σ_{TOT} and σ_{ABS} to obtain values of the parameters, A, $\Delta\sigma$, B, and C.

No attempt will be made here to analyze the large amount of information on the $n,\alpha_0/n,\alpha_1$ ratio or to review most of the absorption data in the keV range whose absolute values depend upon an assumed shape and magnitude of the cross section under study. For a treatment of these data, the reader is referred to recent and excellent papers by Gubernator and Moret,[5] Bogart and Nichols,[6] and Gibbons.[7] It is of interest to note, however, that Gubernator and Moret show that the recommended thermal ratio of 6.308 for $n,\alpha_0/n,\alpha$ is lower, on the average, than measured values in the energy range from 20 eV to 20 keV. For example, 15 measurements are above this extrapolated value, three are essentially on the line, and two are below; less than half the values above the "assumed" ratio show overlapping error flags.

Although ^{10}B has a large absorption cross section, it is important to note that, in addition to n,α_0 and n,α_1, the following reactions are energetically possible when thermal neutrons interact with ^{10}B: $^{10}B(n,\gamma)^{11}B$, $^{10}B(n,p)^{10}Be$, $^{10}B(n,t)^{8}Be$, and $^{10}B(n,t2\alpha)$. While it may be reasonable to assume that $\sigma_{ABS} = \sigma_{n,\alpha}$ at low neutron energies, some of the above channels could be slightly competitive in the range of a few keV. These other channels are commonly ignored and this practice, while not correct, is followed here. That is, it is generally assumed that $\sigma_{ABS} = \sigma_{TOT} - \sigma_{SCAT} = \sigma_{n,\alpha_0} + \sigma_{n,\alpha_1}$ in most of the comparisons which follow.

Besides having a large absorption cross section, ^{10}B is easily fabricated into a detector. An additional advantage results from the emission of a 480-keV γ ray in the decay of Li^{7*} from the $^{10}B(n,\alpha_1)Li^{7*}$ reaction; this latter interaction accounts for more than 90% of the thermal cross section thereby making γ-detection possible in the measurement of low-energy neutron fluxes.

Before employing ^{10}B as a flux monitor, it is worthwhile considering various experiments pertinent to the problems. First, Diment[2] measured the total cross section from 76 eV to 10 MeV and fitted the data below 10 keV with the following expression:

$$\sigma_{TOT} = 610.3/\sqrt{E_n} + 1.95 \text{ barns.} \qquad (2)$$

These results were then interpreted as an absorption cross section which goes as 1/v and a scattering cross section of 1.95 barns. Recently, however, Asami and Moxon[4] measured the scattering cross section from 0.47 to 127 keV. Using their own data and that of Diment and assuming $C\sqrt{E_n}$, of Eq. (1), to be zero, Asami and Moxon determined that $\Delta\sigma = -0.28$ barn. Gubernator and Moret[5] performed a least squares fit to all available data and derived the following constants for Eq. (1): $A = 609.5 \pm 2.25$, $\Delta\sigma = -0.32 \pm 0.05$, $B = (2.5 \pm 0.38) \times 10^{-3}$, and $C = (3.9 \pm 0.6) \times 10^{-6}$. Note that at 10 keV, the upper limit used for most fitting routines, the value of $B\sqrt{E_n}$ is approximately equal to $\Delta\sigma$, though opposite in sign; many analyses, however, find $\Delta\sigma$ finite while assuming $B = C = 0$.

The total cross section measurements above 10 keV by Diment[2] and Mooring[3] are compared in Fig. 2. The scattering cross sections measured by Mooring[3] and Asami and Moxon,[4] along with those "assumed" by Diment,[2] are shown in Fig. 3. While the comparison of the total cross sections is quite good, it should be noted that the slight rise above 30 keV found by Diment* is not repeated in Mooring's data. The scattering data of Asami and Moxon in Fig. 3 show an abrupt increase of approximately 250 mb (approximately the magnitude of $\Delta\sigma$†) above 30 keV. To emphasize more clearly the energy dependence, the data of Asami and Moxon are plotted in Fig. 4 over the entire range covered by their measurements.

Cox[8] reported values of σ_{ABS} from 10 to 250 keV in agreement with a 1/v extrapolation from thermal. These are plotted as $\sigma_{ABS}\sqrt{E}$ in Fig. 5. Note that a numerical average gives 669, far from the 610.3 Diment found by fitting his total cross sections below 10 keV.

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*At 30 keV, Diment changed his flight path from 120 to 300 meters.

†At 30 keV, the value of $(B\sqrt{E_n})$ found by the GEEL group is much larger in magnitude, though opposite in sign, than $\Delta\sigma$.

Next, Mooring's absorption measurements on two different targets are plotted in Fig. 6; the "so-called average" values, denoted by the closed circles, have been used on the previous graphs. Note that the difference at some energies between the two datum sets is as large as 30%. That his "average" values show good agreement with the data of Diment and of Asami and Moxon is quite unexpected.

Absorption cross sections derived from the data of Diment,[2] Mooring,[3] Asami and Moxon[4] along with calculations by the Geel Group[5] are plotted in Figs. 7, 8, and 9 covering the energy range to 500 keV. It should be noted that, between 100-500 keV, several points by Mooring and one by Diment fall outside the graphical contour. The data of Cox have been ignored. Older measurements from Rice[9] along with recent results of Macklin and Gibbons[10] and Bogart and Nichols[8] have not been included since each depends upon some "assumed" shape and absolute normalization on a predetermined energy scale. For a treatment of these results, see Refs. 6, 7, and 10.

Recently, Nellis, Tucker, and Morgan[11] observed the γ-ray from the $^{10}B(n,\alpha\gamma)$ reaction and obtained an absolute cross section via a flux measurement using the hydrogen scattering cross section. These data, shown in Fig. 10, are therefore independent of a ^{10}B normalization. Measurements by Davis[9] and Macklin and Gibbons[10] are included along with a reconstruction* of the Bogart and Nichols results based on the assumption of "average" branching ratios between the α_0 and α_1 channels. While this comparison is not unique, it does show trends between various sets of data similar to those found at lower energies in the total absorption cross section. The smooth curve in Fig. 10 is based on an extrapolation using the recommended thermal cross section and thermal branching ratio.

It should be noted that a renormalization of the Davis results would bring all data into agreement with the exception of the Macklin and Gibbons results which are based on the inverse reaction and the assumption of a 1/v dependence at 30 keV. The Bogart and Nichols data are normalized to an average value of $\sqrt{E}\,\sigma$ below 80 keV, again assuming a 1/v dependence extrapolated from thermal. Suffice to say that more measurements are required in the keV range to determine both the shape and magnitude of the absorption and (n,α) cross sections with ^{10}B.

A few particular points are worthy of note: Macklin and Gibbons found that the n,α_0 is rising while the n,α_1 is falling well below 100 keV making the sum "look like" a 1/v dependence. It should be mentioned, however, that the Macklin and Gibbons data are based on a measurement of (n,α) while the Mooring data are a measurement of total absorption. If Mooring's data be correct, then the total absorption cross section is almost 10% below 1/v at 10 keV, rising to about 10% above 1/v near 200 keV and dropping to almost 20% below 1/v at 350 keV. This energy dependence of σ_{ABS} found by Mooring

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*These values for the data of Bogart and Nichols are taken directly from the paper by Nellis, Tucker, and Morgan; see Ref. 11.

is not substantiated by the measurements on n,α_0 or n,α_1. In addition, the total scattering cross section reaches a maximum value near the minimum in the absorption making a theoretical treatment of the data somewhat difficult.

Other measurements have been made on branching ratios of $^{10}B(n,ABS)$ to other absorption cross sections such as the $^{3}He(n,p)$ and the $^{6}Li(n,\alpha)$. Data on the former are treated in some detail by Gibbons in Ref. 7. Sowerby and Patrick[12] measured the ratios with respect to the $^{6}Li(n,\alpha)T$ reaction in the energy range 10 eV to 70 keV. When combined with other measurements on ^{10}B and resonance fits made by Uttley[13] to his measurements of σ_{TOT} for ^{6}Li, Sowerby and Patrick used the values derived by Uttley for the $^{6}Li(n,\alpha)$ reaction to further interpret their ratio data. Since tabular values of the ratios and ^{6}Li data are not presently available, some of the conclusions stated by Sowerby and Patrick are quoted herein for the benefit of the reader:

	1.	$\sigma_{ABS} = 610.3/\sqrt{E_n} - 0.22$ barns	($E < 20$ keV)
^{10}B	2.	Structure in σ_{ABS}	($E \sim 30$ keV)
	3.	$\sigma_{ABS} \sim 610.3/\sqrt{E_n}$	($E > 30$ keV)
	4.	"It is suggested that the $^{6}Li(n,\alpha)$ cross section be used as the primary standard for measuring neutron flux in the region below 100 keV.	

It should be pointed out, however, that the Sowerby and Patrick conclusions are based on a constant scattering cross section for ^{10}B of 2.17 barns below 10.3 keV and quote the Asami and Moxon results who, in turn, quote 2.23 barns. The lower value of the constant is not in very good agreement with the data shown in Fig. 4. In addition, Sowerby and Patrick base their conclusions on the assumption that the $B/\sqrt{E_n}$ and CE_n terms in Eq. (1) are zero. On the other hand, Moret and Gubernator find the contribution from $B/\sqrt{E_n}$ to be something like 250 mb at 10 keV, approximately the same value, but opposite in sign, to the $\Delta\sigma$ Asami and Moxon report by assuming that both $B/\sqrt{E_n}$ and CE_n are negligible. At 10 keV, $\sigma_{ABS} \sim 6$ barns therefore $B/\sqrt{E_n}$ may not be a negligible contribution above this energy, contrary to the interpretation by Sowerby and Patrick.

For the convenience of the reader, an effort has been made to summarize some of the important points derived from each reference in this paper. This information is presented in Table I.

In conclusion, the data from 5 to 500 keV need be verified, especially to verify the Harwell total cross section measurements over the region the flight path was changed; in addition the Mooring results show definite structure in this energy range and also imply a maximum in the scattering cross section. Certainly, the results show quite clearly that the 1/v dependence of the ^{10}B cross section is not well established in the keV range.

ACKNOWLEDGEMENTS

I wish to thank Don Nellis, Bill Tucker, and Ira Morgan of Texas Nuclear Corporation for sending their data described in Reference 11 prior to publication.

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13. C. A. Uttley, private communication to Sowerby and Patrick, reference 12.

Table I. SUMMARY OF RECENT DATA DISCUSSED IN THIS REPORT

Reference	Measured	Assumed	Derived	Author's Conclusions
Diment Ref. 2 (1967)	σ_{TOT} 0.076 keV to 1 MeV; Author plots data up to 10 MeV.	< 10 keV; $\sigma_{TOT} = \frac{A}{\sqrt{E_n}}$ + Constant > 10 keV; Mooring's σ_{SCAT}.	$\sigma_{ABS} = 610.3/\sqrt{E_n}$ σ_{SCAT} = 1.95 b to 10 keV	Mooring's scattering data are in good agreement with fit.
Mooring, Monahan and Huddleston Ref. 3 (1966)	σ_{TOT} and σ_{SCAT} 10 to 500 keV		Values of σ_{ABS}	$\sigma_{ABS} - \sigma_{n,\alpha} \ll 100$ mb $\sigma_{ABS} \sim 1/v$ except near 230 and 340 keV
Asami and Moxon Ref. 4 (1969)	σ_{SCAT} 0.47 to 127 keV	Diment's fit to σ_{TOT}; σ_{SCAT} = 2.23 b < 10 keV; B = C = 0 (Eq. 1).	$\Delta\sigma$ = 0.28 b (Eq. 1)	σ_{SCAT} = constant = 2.23 b up to 10.3 keV; agreement with Mooring's scattering data.
Gubernator and Moret Ref. 5 (1968)	Evaluation Thermal to 1 MeV	$\sigma_{ABS} = \sigma_{n,\alpha}$; $\sigma_{ABS} = A/\sqrt{E_n} + \Delta\sigma + B\sqrt{E_n} + CE_n$.	$\sigma_{n,\alpha}$ Branching Ratio { Thermal to 1 MeV Parameters A, $\Delta\sigma$, B and C.	See paper
Bogart and Nichols Ref. 6 (1969)	$\sigma_{n,\alpha}$ 30 to 800 keV	1/v normalization to an average value below 80 keV.		1/v below 100 keV

Table I. Continued

Reference	Measured	Assumed	Derived	Author's Conclusions
Cox and Ponet Ref. 8 (1967)	σ_{ABS} 10 to 250 keV		Numerical average of $\sqrt{E_n}\ \sigma = 669$ up to 250 keV	$\sigma_{ABS} \sim 1/v$ up to 250 keV
Davis, Gabbard Bonner and Bass Ref. 9 (1961)	σ_{n,α_0} and/or σ_{n,α_1} Sum 200 keV to 7.5 MeV	$\sigma_{n,\alpha} = \sigma_{ABS}$ goes as 1/v for normalization		
Macklin and Gibbons Ref. 10 (1968)	$n,\alpha_0/n,\alpha_1$ $^7Li(\alpha_0,n)^{10}B$ ~ 30 to 300 keV	Ratio and Inverse could be used to normalize to 1/v at 30 keV.	σ_{n,α_0} σ_{n,α_1} Sum	α_0/α_1 ratios deviate from 1/v below 100 keV; sharp rise seen in α_1 ~ 140 keV.
Nellis, Tucker, and Morgan Ref. 11 (1969)	$\sigma_{n,\alpha_1\gamma}$ 50 keV to 5 MeV; also 14.8 MeV			Departure from 1/v above 100 keV
Sowerby and Patrick Ref. 12 (1968)	$^6Li(n,\alpha)/^{10}B(n,\alpha)$ 10 eV to 2 keV; $^6Li(n,\alpha)/^{10}B(n,\alpha_1\gamma)$ 50 eV to 70 keV	$^6Li(n,\alpha)$ cross section obtained from fit to Uttley's σ_{TOT} ; σ_{SCAT} from Asami and Moxon; Diment's σ_{TOT} ; and branching ratios > 50 eV	Energy dependence of $^{10}B(n,\alpha)$ with B = C = 0 for both ^6Li and ^{10}B.	See paper

Fig. 1. Comparison of a few "standard" cross sections above 1 keV. The curves shown do not, necessarily, represent the best evaluated set for each isotope.

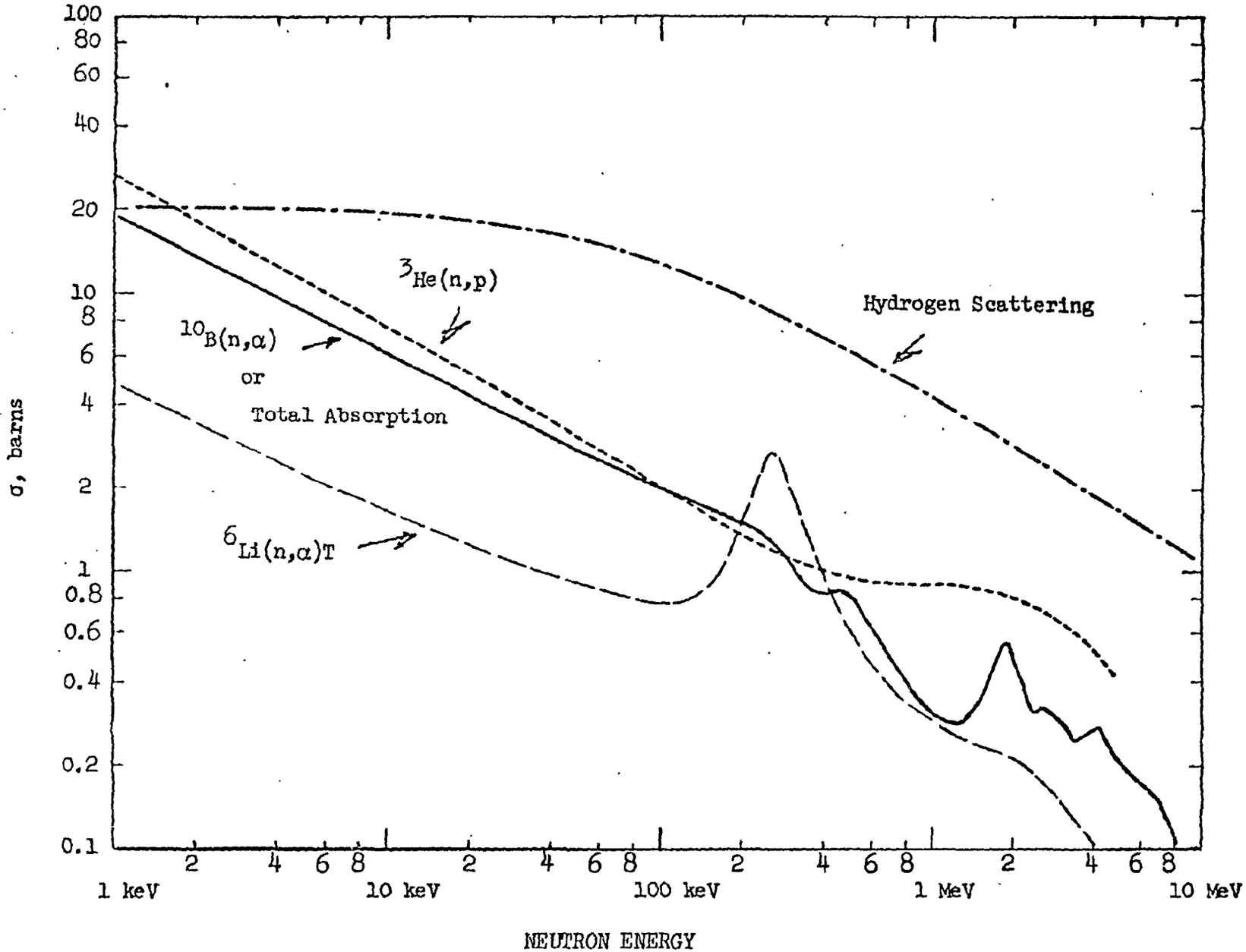


Figure 2

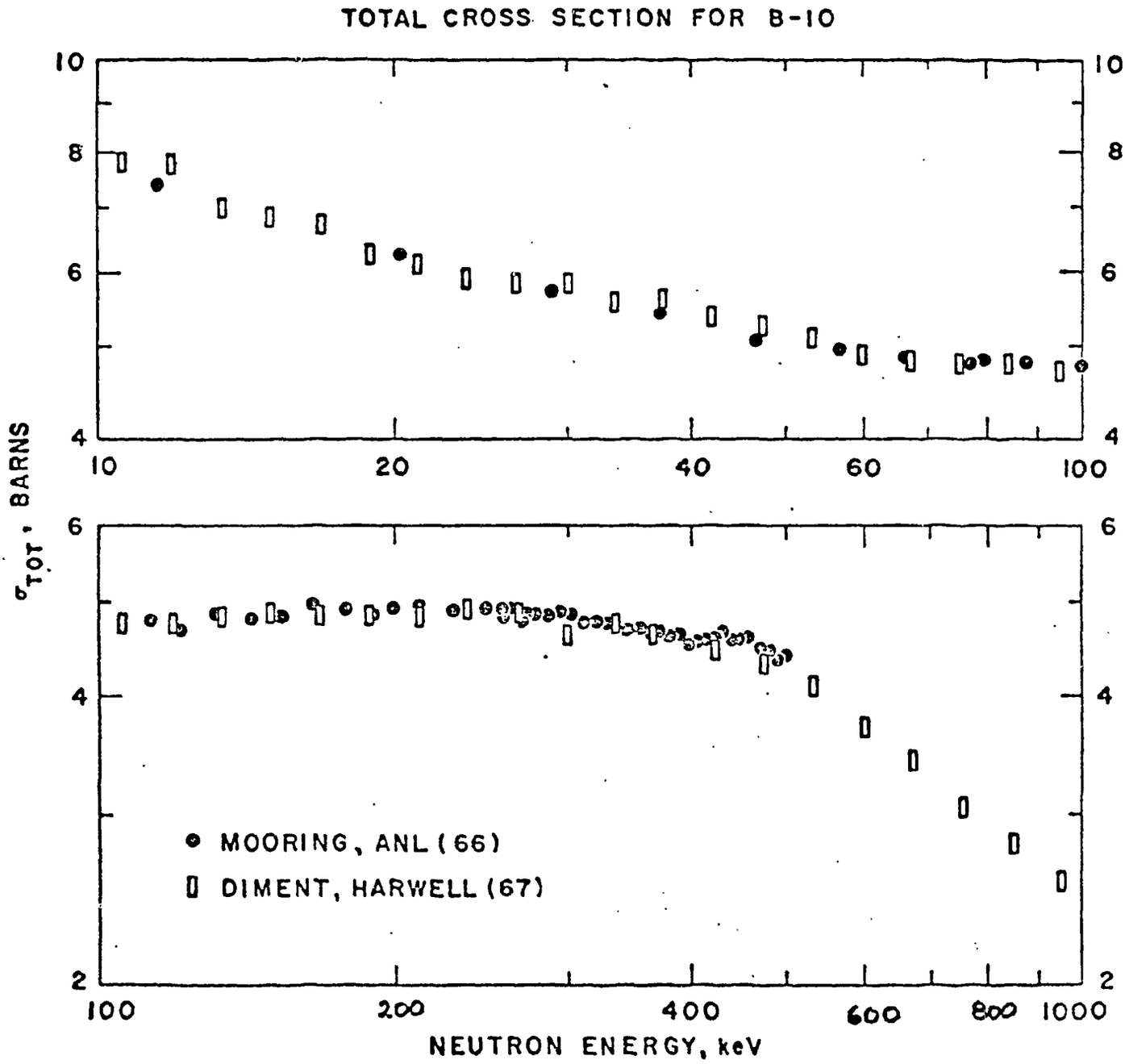
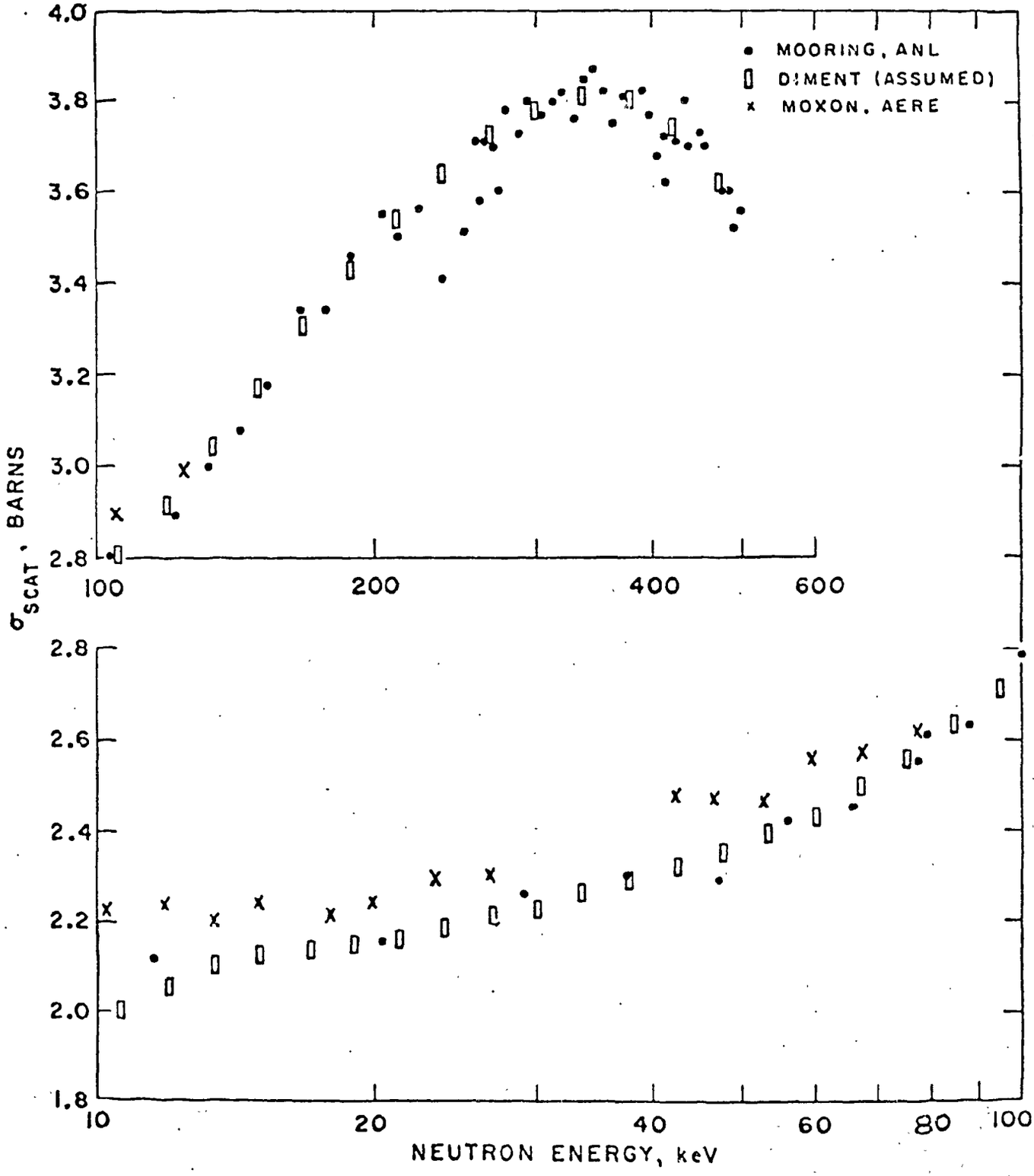

TOTAL CROSS SECTION FOR B-10
σ_{TOT}, BARNS
10
8
6
4
10
20
40
60
100
6
4
2
100
200
400
600
800
1000
MOORING, ANL (66)
DIMENT, HARWELL (67)
NEUTRON ENERGY, keV

Figure 3 SCATTERING CROSS SECTION for ^{10}B



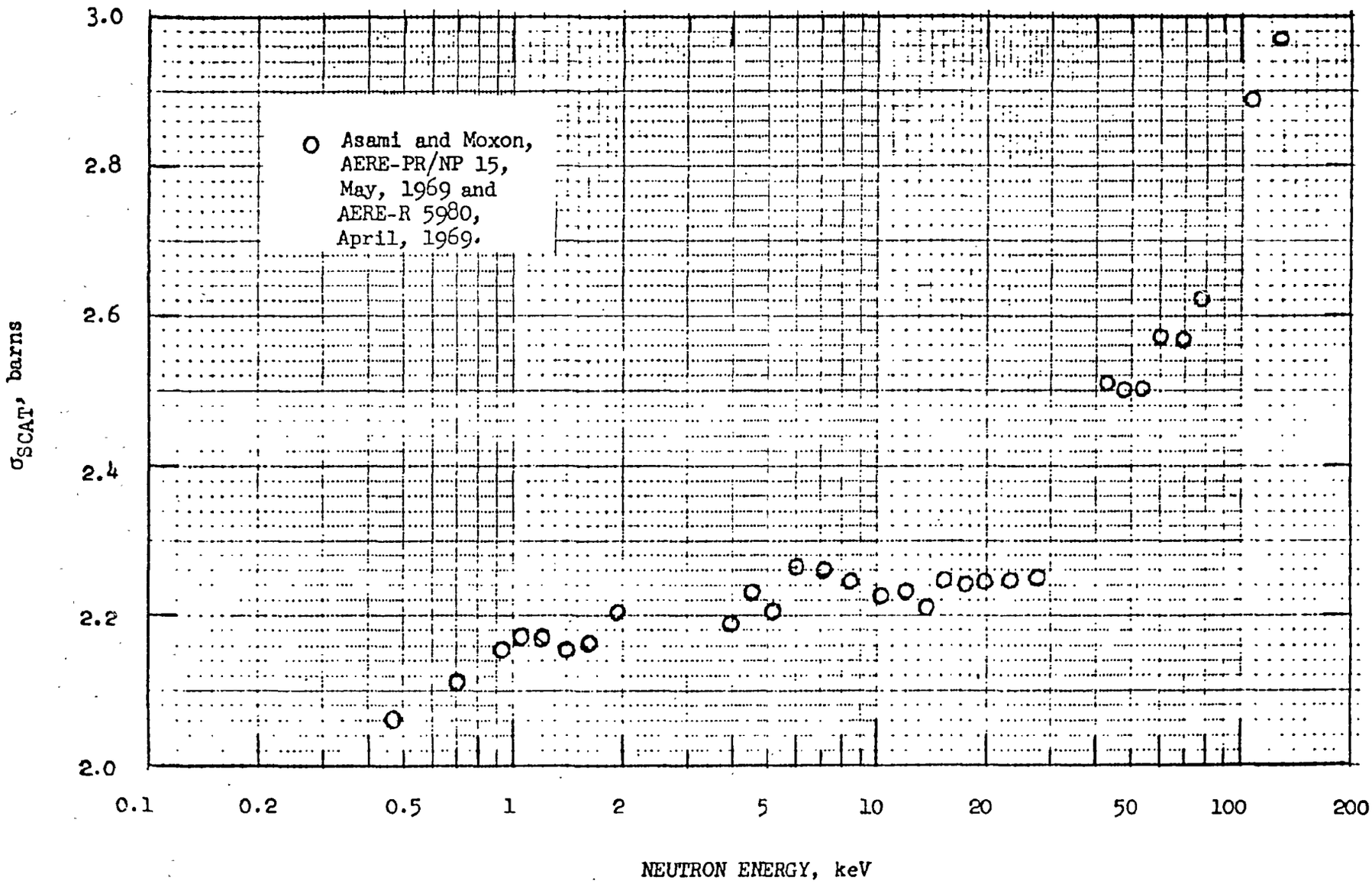


Fig. 4. The Scattering Cross Section for ^{10}B as Measured by Asami and Moxon

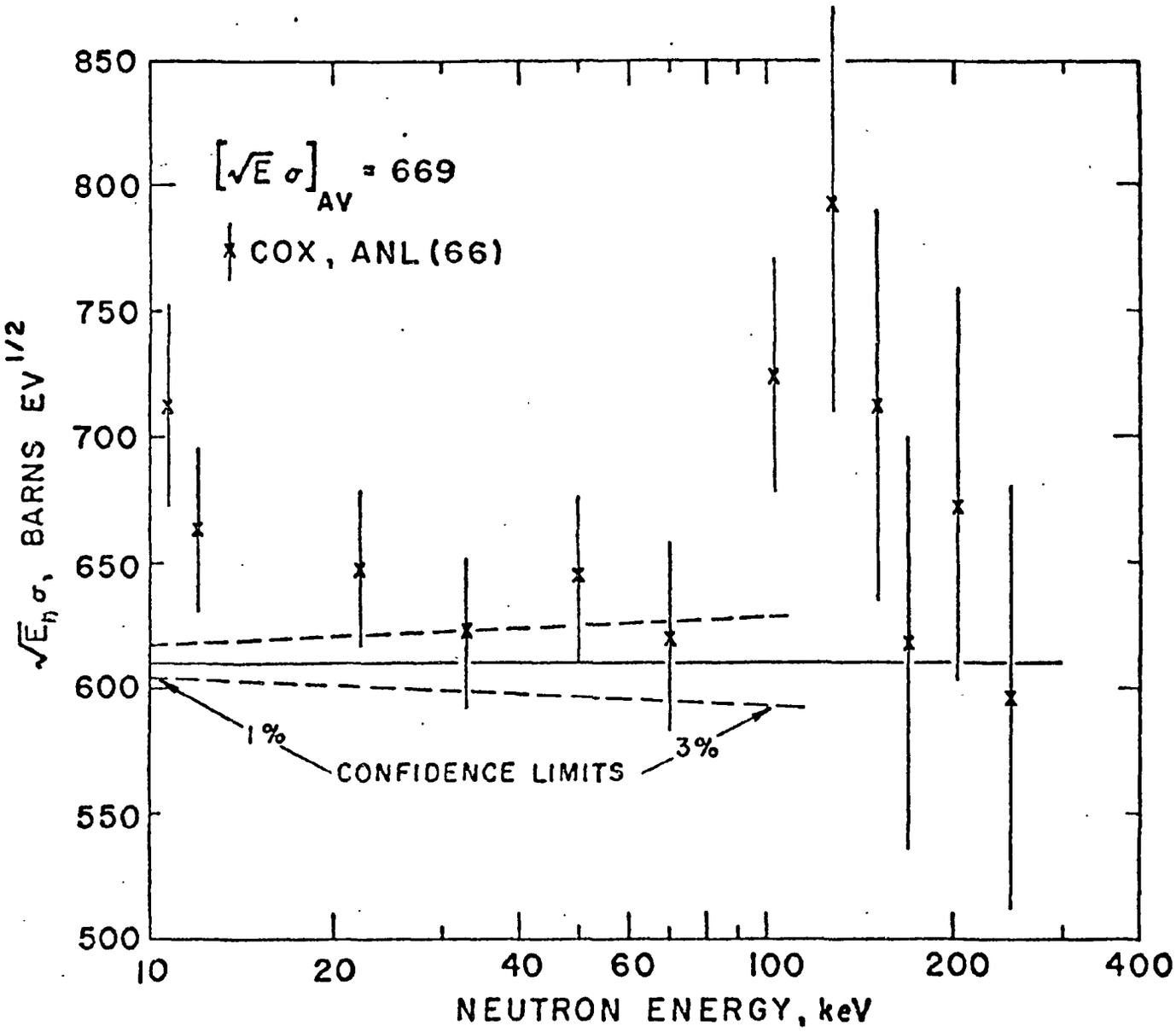
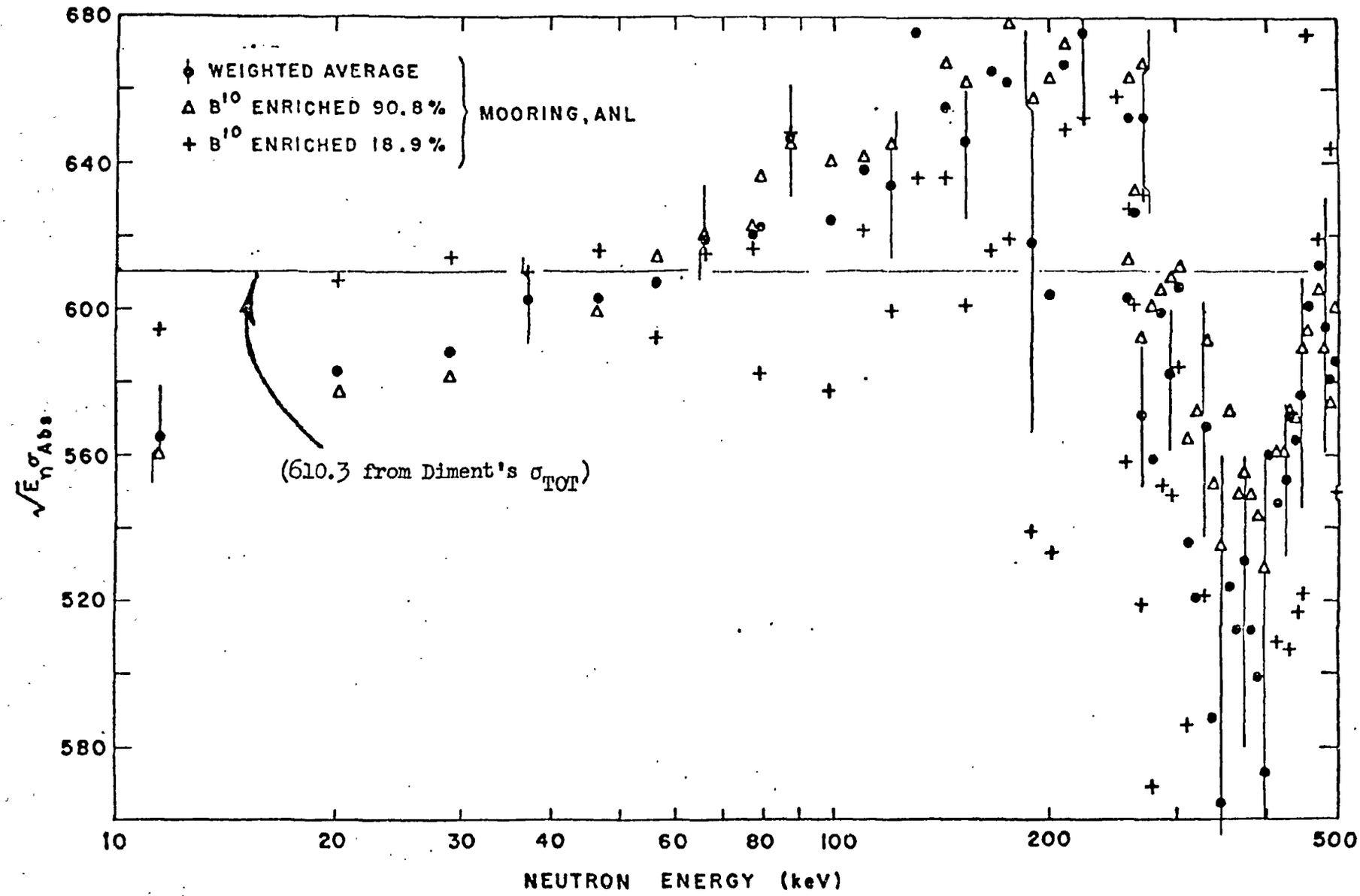


Figure 5. $\sqrt{E_n}\,\sigma_{ABS}$ for ^{10}B as Measured by Cox

Figure 6. $\sqrt{E_n}\ \sigma_{ABS}$ for ^{10}B from Mooring's Data Using Different Targets



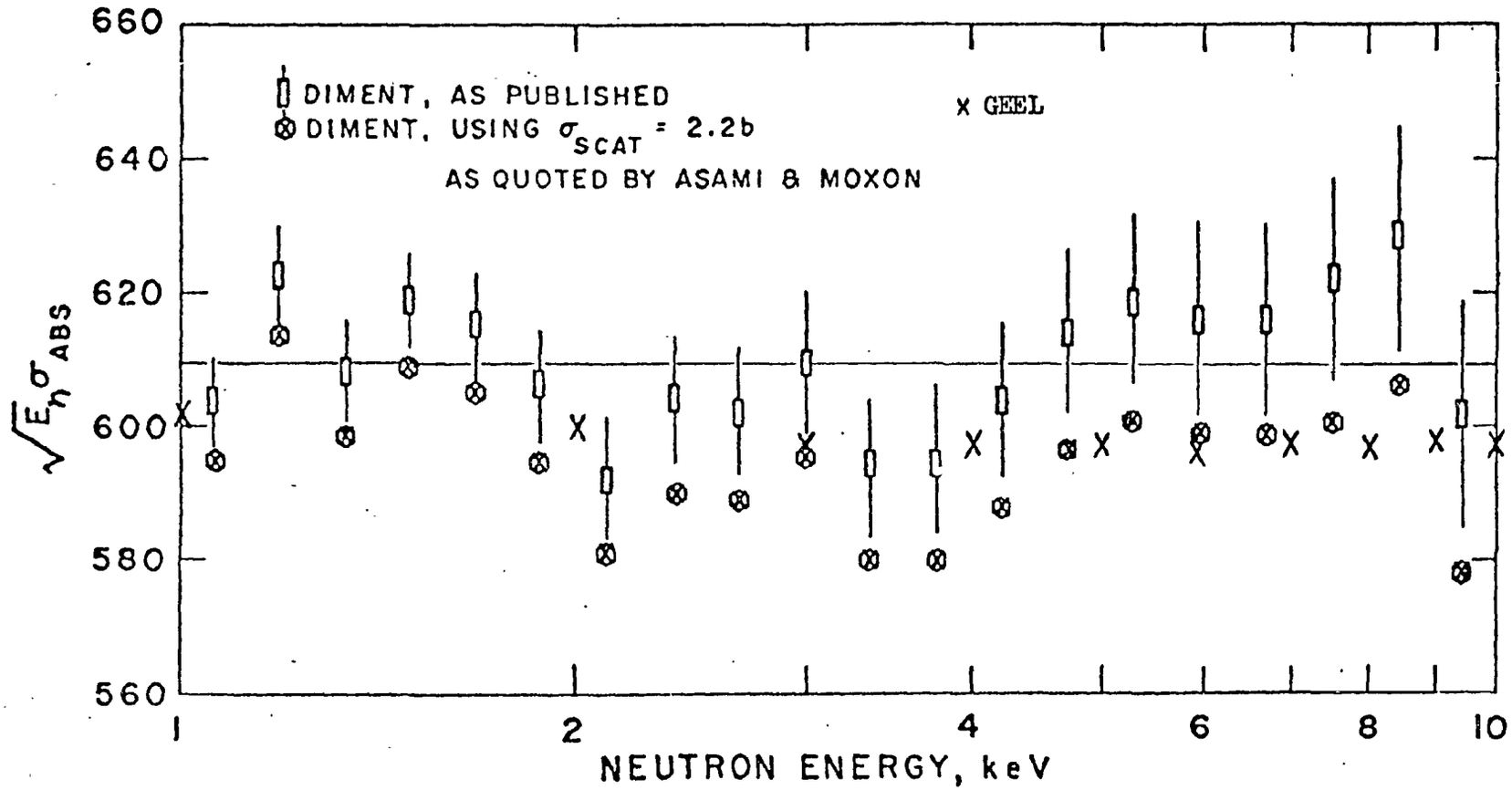
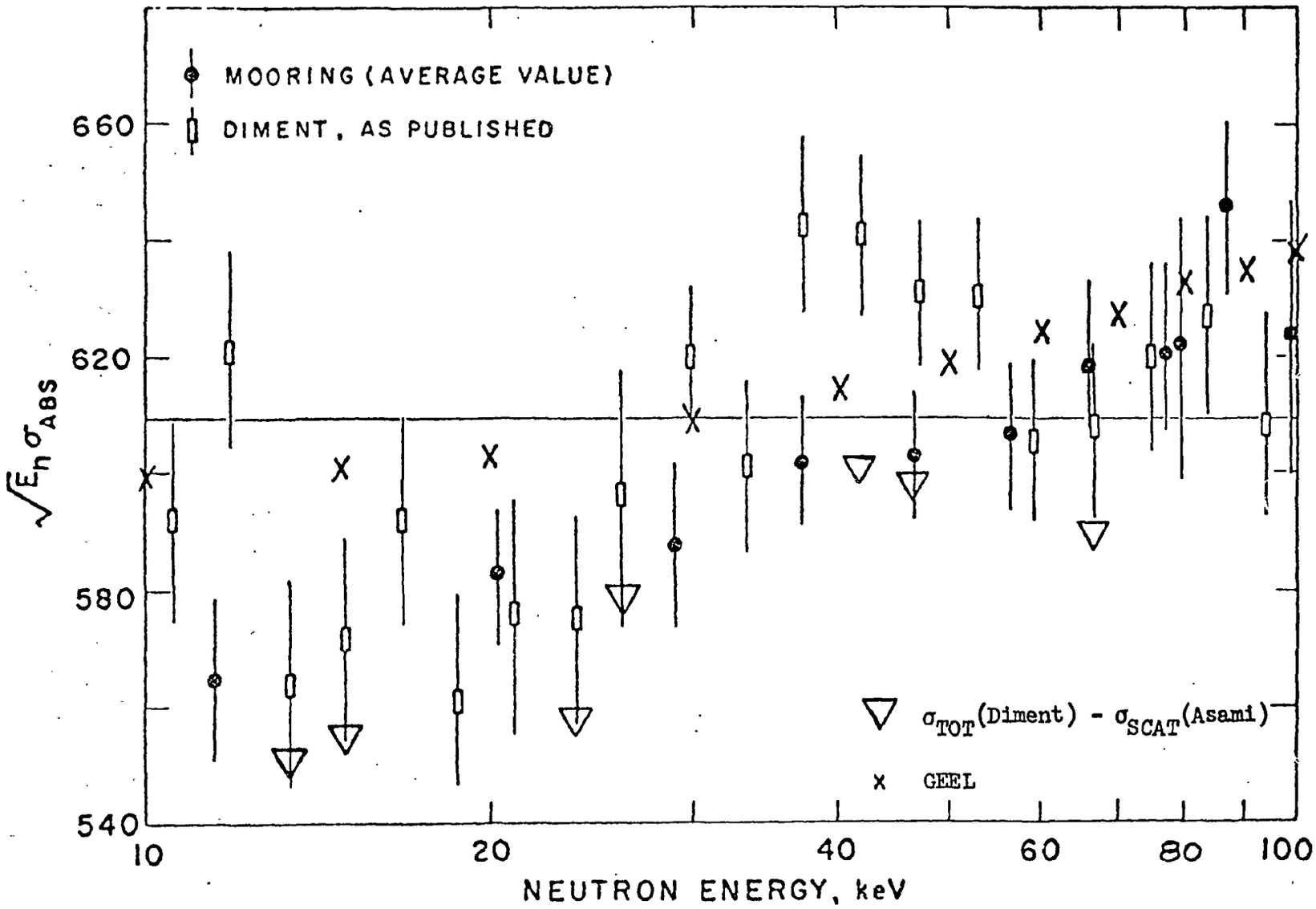


Fig. 7. $\sqrt{E_n}\,\sigma_{ABS}$ for ^{10}B, 1-10 keV

Fig. 8. $\sqrt{E_n}\,\sigma_{ABS}$ for ^{10}B, 10-100 keV



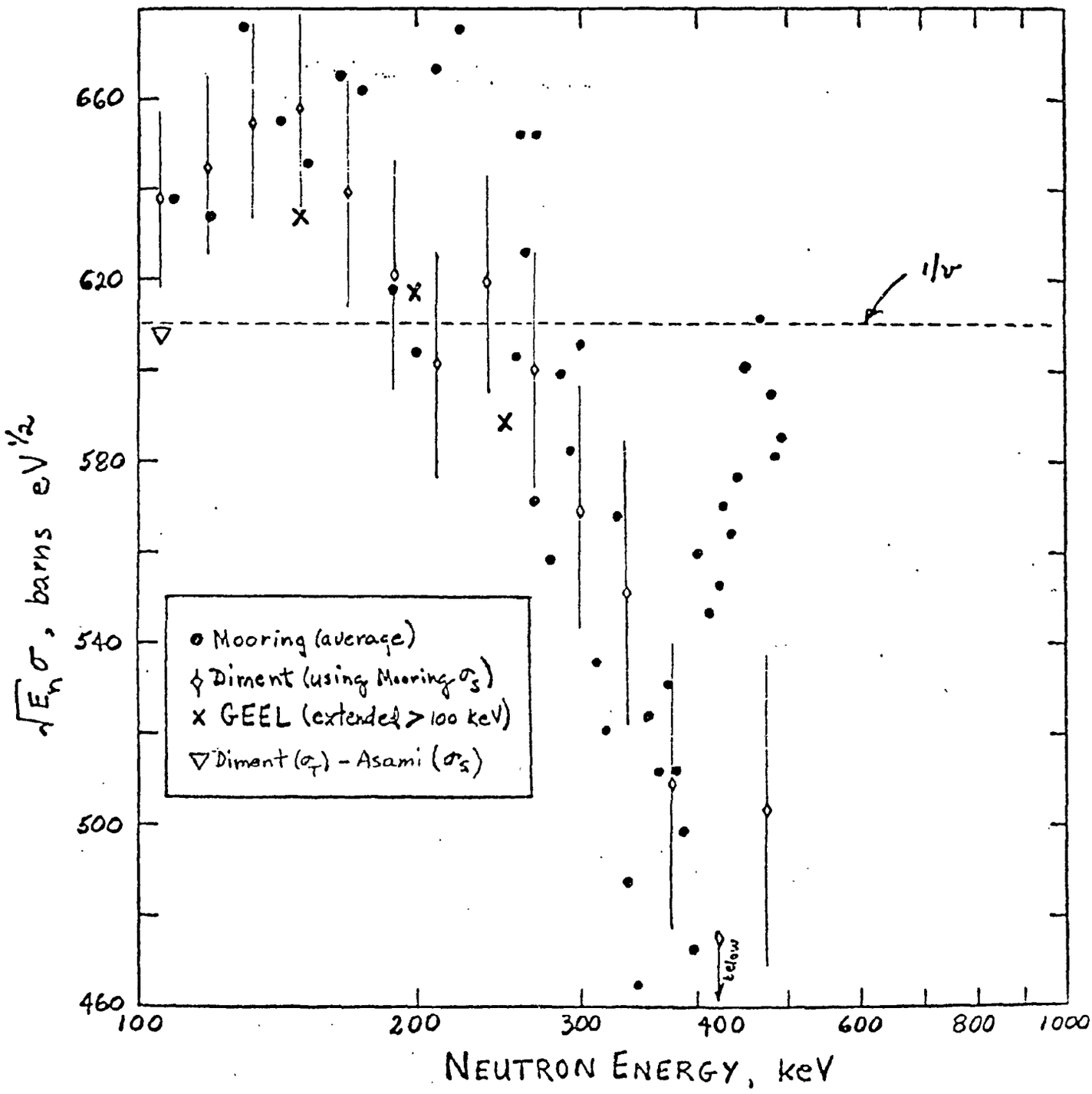


Fig. 9. $\sqrt{E_n}\,\sigma_{ABS}$ for ^{10}B, 100-500 keV

Fig. 10. Cross Section for the $^{10}B(n,\alpha_1\gamma)$ Reaction from 10 keV to 4.5 MeV