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EVALUATION OF THE ^{10}B(n,α) CROSS SECTION AND BRANCHING RATIO

by

K. GUBERNATOR and H. MORET

1968

Joint Nuclear Research Center
Geel Establishment - Belgium

Central Bureau for Nuclear Measurements - CBNM

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Printed by Guyot, s.a.
Brussels, June 1968

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At thermal energy $\sigma^{o}_{n, \alpha} = (3835 \pm 14) b$ and $R^{o} = 6.308 \pm 0.012$ are recommended, the errors corresponding to confidence limits (95 %). From thermal energy to 100 keV best curves are recommended on the basis of least

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squares fits to the experimental data. The formula for $\sigma_{n,\alpha} = f(E)$ contains terms to correct for non-1/v behaviour from the eV-range up to 100 keV. The confidence interval gradually decreases from ± 14*b* (thermal) to ± 0.06 *b* (100 keV).

R = constant = 6.3 ± 0.3 up to 30 keV. From 30 to 100 keV higher order terms are proposed to fit the data. All recommended values and curves are summarized in the last chapter of this report, together with a set of numerical values.

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SUMMARY

Data available on the ^{10}B (n, α) cross section and the branching ratio in the range from thermal energy to 1 MeV are compiled. After a critical evaluation a set of data is selected to compute recommended values and best curves of the (n, α) cross section and the branching ratio, for neutron energies up to 100 keV. The σ_{n, α_1} cross section is derived from this.

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KEYWORDS

NUCLEAR REACTIONS
BORON 10
NEUTRON BEAMS
ALPHA PARTICLES
LITHIUM 7
CROSS SECTIONS
BRANCHING RATIO
KEV RANGE
NUMERICALS
THERMAL NEUTRONS
DIAGRAMS
EV RANGE
LEAST SQUARE FIT

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Figures

1. INTRODUCTION

From the data available in literature have been derived :

a. the best values of the $^{10}B(n,\alpha)$ cross section and branching ratio at thermal energy,

b. the energy dependence up to 100 keV of the (n,α) and (n,α_1) cross sections and of the branching ratio.

To these ends a compilation of data from thermal energy to 1 MeV is contained in this report, together with a critical evaluation, ending with a selection of those data wich enter into the calculations, required for the above-mentioned purposes. Of the energy range up to 1 MeV, the recommendations are limited to the interval between thermal energy and 100 keV as the latter is the most important region for practical use at the present time. Nevertheless, curves and formulae are also given above 100 keV, but the accuracy is much less in this energy interval.

Such an evaluation also required a discussion of non-(n,α)-reactions. It was considered useful to incorporate a chapter on isotopic composition as well. On several occasions published data had to be changed because of afterwards better known isotopic composition. Furthermore, for convenience of the reader, it might be useful to know which differences in isotopic composition of so-called natural samples may be expected, and - on the other hand - how accurate standard boron stocks have been defined and how and where standard samples may be obtained.

The ^{10}B cross sections have already been compiled and evaluated earlier (Hu 58, Bu 60, St 64, Sp 67, Ir 67). However, until now the most recent data and comments which help to clarify the situation have not all been taken into consideration.

On the other hand, in this evaluation the special aspects of ^{10}B as a neutron data standard have been considered. Chapter 6 summarizes the recommended values in such a way that it is expected to be of practical use in neutron measurements.

2. ISOTOPIC COMPOSITION OF NATURAL BORON

Until recent years the ^{10}B isotope concentration in "natural" boron has not been known accurately as is clear from the values given in table I.

Table I. Former measurements of the isotopic composition of natural boron

^{10}B atom %	Reference	^{10}B atom %	Reference
18.83	In 46	19.3	Be 58a
18.45 - 18.98	Th 48	19.27	Be 60
19.569	Os 50	19.7 - 19.9	Fi 61
19.05 - 19.61	Sh 56	19.83 - 20.00	Go 61
19.57	Se 57	19.72 - 19.84	Mu 61
19.65	Pa 58	19.80	Sh 63

Variations in the isotopic composition of natural boron appear also from a series of intercomparisons carried out by the Central Bureau for Nuclear Measurements in 1962 on reference stock used for neutron measurements by different nuclear institutes (table II). The values given in table II (De 63) have a precision of ± 0.5% relative but were uncorrected at that time for possible systematic errors (such as mass discrimination).
Table I shows that ^{10}B concentrations vary from 18.4 to 20.0 atom %, while it appears from table II that even reference stocks are not identical.
To eliminate this uncertainty and consequently the error contribution to $\sigma_{nA}(^{10}B)$, a long term effort at the Central Bureau for Nuclear Measurements has resulted in highly reproducible (< 0.1%) and accurate (0.1%) isotopic analysis of boron in boric acid. A small bias effect (mass discrimination) of (0.13 ± 0.07)% on the $^{10}B/^{11}B$ ratio thereby persisted in the measurements of known synthetic ^{10}B-^{11}B blends, all known systematic errors

Table II. 1962 Intercomparison of different natural boron stocks

Sample	^{10}B atom %
Argonne National Laboratory - stock I	19.80
Argonne National Laboratory - stock II (now transferred to NBS)	19.82
Central Bureau for Nuclear Measurements - stock I	19.81
Central Bureau for Nuclear Measurements - stock II	19.85
Chalk River	19.83
Allgemeine Elektrizitätsgesellschaft	19.81
Fontenay-aux-Roses	20.13
Harwell old stock (now destroyed)	20.13
Harwell new stock	19.78
Fontenay-aux-Roses - stock I	20.11
Fontenay-aux-Roses - stock II	20.07

being either eliminated or corrected for. This bias factor was constant over the concentration range 10% - 90% ^{10}B and hence was reliable to correct any boron isotopic measurement. Thus the ^{10}B concentration of the CBNM stock II of 200 kg boric acid (H_3BO_3) was redetermined, yielding an absolute value of (19.824 ± 0.020) atom % ^{10}B (De 68).

This standard is available for distribution provided with a certificate for the isotopic composition, either in the original crystalline H_3BO_3 form, or as solutions of the same with chemical concentration known to 0.1%. Furthermore, homogeneous evaporated metallic boron layers with known ^{10}B content (mass- and chemistry defined) can be prepared, the isotopic definition being relative to the standard. The U.S. Atomic Energy Commission Nuclear Cross Section Advisory Group and the European-American Nuclear Data Committee emphasize the desirability of measuring boron neutron cross sections on CBNM standard boron or on boron from the identical NBS stock (De 54).

3. NON-(n,α) REACTIONS

The total cross section σ_{nT} and scattering cross section σ_{nS} are not compiled in this report. However, some results of absorption cross section σ_{nA} are obtained by subtracting σ_{nS} from σ_{nT}. In the energy range of interest only elastic scattering is involved : $\sigma_{nS} = \sigma_{n,n}$.
In addition to the $^{10}B(n,\alpha)^{7}Li$ reaction, the following processes are energetically possible and could contribute to σ_{nA} :

$^{10}B(n,\gamma)^{11}B$, $^{10}B(n,p)^{10}Be$ and $^{10}B(n,t)2^{4}He$.
As appears from the following discussion of these competing absorption reactions, their contribution to σ_{nA} is too small to account for any significant deviation from the 1/v dependence below 100 keV (within the given accuracy limits) or to influence $\sigma_{n,\alpha}$ at thermal energies.

3.1. (n,n) Cross Section

$^{10}B(n,n)^{10}B$

Hi 50, Argonne
Scattering cross section measurements on enriched ^{10}B and normal B with epithermal B-filtered neutrons in the scattering chamber give 2.43 for ^{10}B.

Wi 55, Oak Ridge
Elastic scattering measurements with a proton recoil proportional counter on a cylindrical sample enriched in ^{10}B show angular distribution of scattered neutrons to be isotropic in the centre-of-mass system at E_n = 550 keV and 1 MeV and yield by integration $\sigma_{n,n}$ (corrected for neutron attenuation and multiple scattering). $\sigma_{n,n}$ = 3.71 b and 2.43 b, respectively.

Hu 58, Brookhaven

Quotes ^{10}B thermal neutron scattering cross section for the bound atom, calculated by multiplying the free atom cross section, σ_{free}, by the recoil correction factor:

$\sigma_{free}\left(\frac{A+1}{A}\right)^2 = (4.0 \pm 0.5)b.$

La 67, Argonne

Integration of differential scattering cross section, varying from 3 to 4 b in the region $80 \leq E_n \leq 500$ keV.

Di 67, Harwell

Least squares fit of measured σ_{nT} yields a constant scattering cross section $\sigma_{n,n} = (1.95 \pm 0.10)b$ for $E_n \leq 10$ keV.

As 68, Harwell

Scattering measurements relative to carbon between 1 keV and 130 keV neutron energy by TOF method, 93.0% enriched ^{10}B samples, ^6Li-glass detectors. Corrections applied for sample impurities and sample holder, detector efficiency and size, multiple scattering; errors arising from counting statistics, background normalization, angular uncertainty, multiple scattering. $\sigma_{n,n}$ appears to be constant below 20 keV, the average over energy region 1 to 10 keV being $\sigma_{n,n} = (2.20 \pm 0.06)b$. At higher energies agreement with the La 67 data is good. By comparison of the quoted $\sigma_{n,n} = 2.20$ b with the constant term of 1.95 b found by Di 67, authors conclude that the deviation from the 1/v dependence of $\sigma_{n,\alpha}(^{10}B)$ according to Be 58b, Sh 58 and Be 61 is given by a constant of $-(0.25 \pm 0.12)b$ (see further discussion in section 4.5).

Although the error on this small constant is 50% and further scattering measurements are needed, As 68 have led us to accept a deviation from the 1/v law (see 4.5) which below 100 keV remains within ± 4% from this law and which may need revision as soon as other measurements become available.

3.2. (n,γ) Cross Section

$^{10}B(n,\gamma)^{11}B$ $Q = + 11.464$ MeV

Ba 57, Chalk River

Measurement of the absolute intensity of the 4.47 MeV capture γ-line of ^{11}B with a pair spectrometer. The partial $\sigma_{n,\gamma}$ for the production of this γ-line by thermal neutrons was found to be $\sigma_{n,\gamma}(^{10}B) = (0.5 \pm 0.2)$b.

Bi 65, Oak Ridge

Investigation of $\sigma_{n,\gamma}$ in the neighbourhood of $E_n = 230$ keV, no γ-rays observed, upper limit on $\sigma_{n,\gamma}$ estimated to be 10 mb.

3.3. (n,p) Cross Section

$^{10}B(n,p)^{10}Be$ $Q = + 0.227$ MeV

Eg 48, Argonne

^{10}Be activity measured, produced by irradiating B in a fast-pile spectrum, estimated $<\sigma_{n,p}>(^{10}B) \approx 3$mb averaged over the spectrum. Mo 66 (see page 15) conclude from this $\sigma_{n,p} < 30$ mb as an average value over the interval 10 keV $\leq E_n \leq$ 500 keV.

Cr 56, Buenos Aires

Investigation of the formation of ^{10}Be from ^{10}B by thermal neutrons using radiochemical methods resulted in $\sigma_{n,p}(^{10}B) < 7$ mb.

Co 66, Aldermaston/Argonne

Mentions (without reference, however) a measurement with thermal neutrons yielding $\sigma_{n,p} < 0.2$ b.

3.4. (n,t) Cross Section

$^{10}B(n,t)2\,^{4}He$ $Q = + 0.328$ MeV

Kl 66, Argonne

Investigation of the (n,t) reaction near $E_n \approx 230$ keV, no tritium found in the irradiated B_2O_3 samples, estimated $\sigma_{n,t}(^{10}B) < 60$ mb at these energies.

4. (n,α) CROSS SECTION

$^{10}B(n,\alpha_0)^{7}Li$ $Q_0 = +\ (2800.8 \pm 7.6)$ keV

$^{10}B(n,\alpha_1)^{7}Li^{*}$ $Q_1 = +\ (2322.3 \pm 6.3)$ keV

$^{7}Li^{*} \rightarrow\ ^{7}Li$ $E_\gamma = (478.5 \pm 1.5)$ keV

4.1. Q-Values

The Q-values quoted above are taken from:

De 67a, Geel/Mol

15 $\mu g/cm^2$ ^{10}B layers together with a ^{239}Pu - ^{241}Am source of about 6000 dpm in front of an Au-Si surface barrier detector in a thermal neutron beam allowed simultaneous measurement of the $^{10}B(n,\alpha)^{7}Li$ reaction products and the α-particles of the source. This is essentially the only direct high precision measurement, the quoted error being one standard deviation. (The actually recommended value from La 66 is $Q_0 = +\ (2.792 \pm 2)$ keV).

4.2. (n,α) Cross Section at Thermal Energy

The cross section at the thermal energy of 0.02526 eV is denoted by σ^{o} throughout this report.

Sc 60, Oak Ridge $\sigma^{o}_{n,\alpha} = (3844 \pm 38)b$

Fast chopper time-of-flight spectrometer, transmission measurement in the range $0.018\ eV \leq E_n \leq 0.4\ eV$, B_2O_3 dissolved in D_2O, samples enriched in ^{10}B to $(99.89 \pm 0.05)\%$ and $(96.39 \pm 0.05)\%$, 6 BF_3 counters, multichannel analyser. Corrections applied for background in the counters, differences in D_2O content between different samples, presence of O and ^{11}B. Authors assume that σ^{o}_{nA} is equal to $\sigma^{o}_{nT} = (3848 \pm 38)b$. To arrive at the value quoted above, $\sigma^{o}_{nS}(^{10}B) \approx 4b$ (Hu 58) has been subtracted here. The error given is one standard deviation. Authors stress that the uncertainty in the analysis of the samples is the main source of error.

Sa 60, Columbia/Brookhaven $\sigma^{o}_{n,\gamma} = (3838 \pm 11)b$

Crystal spectrometer, transmission measurement in the range $0.00291\ eV \leq E_n \leq 0.1\ eV$, $NaBO_2$ dissolved in D_2O, samples enriched in ^{10}B to (99.88 ± 0.01) atom % and (92.84 ± 0.06) atom %. Corrections applied: $\sigma_{nA}(S)$ and $\sigma_{nS}(SO_4^{--})$ from the Na_2SO_4 reference sample, $\sigma_{nA}(^{11}B)$, $\sigma_{nS}(BO_2)$, difference in D_2O content between different samples. By subtracting $\sigma^\circ_{nS}(^{10}B) = (4.0 \pm 0.5)b$ (Hu 58) from their measured $\sigma^\circ_{nT}(^{10}B)$, authors obtain above-mentioned $\sigma^\circ_{nA} = \sigma^\circ_{n,\alpha}$ as a weighted average of the results for the two samples of (3849 ± 15)b and (3828 ± 15)b, respectively. The quoted errors are standard deviations.

Me 61, Argonne $\sigma^\circ_{n,\alpha} = (3843 \pm 17)b$

Neutron lifetime measurement in H_3BO_3 solutions in H_2O, sample enriched to (93.0 ± 0.3)% in ^{10}B, BF_3 counter. Corrections applied for dead time losses, background, changes in diffusion coefficient of the solution, macroscopic scattering cross section of the moderator, contribution of other elements in the compound. The quoted error is mainly statistical.

Bl 62, Oak Ridge $\sigma^\circ_{n,\alpha} = (3846 \pm 40)b$

This is essentially a revised version of Sc 60. Experimental data are fitted to $\sigma_{nT} - \sigma_{nS} = c_1 + c_2/\sqrt{E_n}$. Thus authors obtain $\sigma^\circ_{nT}(^{10}B) = (3850 \pm 40)b$, the error being standard deviation. From this, $\sigma^\circ_{nA} = (3846 \pm 40)b$ is re-evaluated here, taking $\sigma^\circ_{nS} = 4b$ according to Hu 58.

Pr 63, Geel/Mol $\sigma^\circ_{n,\alpha} = (3836 \pm 7)b$

Slow chopper time-of-flight spectrometer, transmission measurement in the range of $0.006\ eV \leq E_n \leq 0.082\ eV$, B_2O_3 dissolved in D_2O, natural B [(19.838 ± 0.030)mol % ^{10}B] and enriched [(96.525 ± 0.006)mol% ^{10}B] samples (De 67b, new absolute determination of isotopic composition); bank of BF_3 counters. Corrected for background and epicadmium neutrons, assumed $\sigma_{nS}(B_2O_3) = (21 \pm 2)b$, multiple scattering (<0.1%) neglected. σ_{nA} found to vary as 1/v. In the original paper Pr 63, authors quote $\sigma^\circ_{nA} = (3840 \pm 11)b$ for the natural B and $\sigma^\circ_{nA} = (3877 \pm 9)b$ for the enriched samples, the errors being standard deviations, with restriction for a possible small systematic error due to mass discrimination. Value given in the first line is the weighted mean of the two re-evaluated results (De 67b) with the standard deviation, i.e. $\sigma^{\circ}_{nA} = (3835 \pm 11)\,b$ for the natural B and $\sigma^{\circ}_{nA} = (3836 \pm 9)\,b$ for the enriched sample.

Al 64, Risø $\qquad \sigma^{\circ}_{n,\alpha} = (3827 \pm 12)\,b$

Crystal spectrometer, transmission measurement in the range $0.0015\ eV \leq E_n \leq 0.10\ eV$; the same natural B sample used as in the Pr 63 measurements. Found σ_{nA} to vary as 1/v. Assumed $\sigma_{nS}(B_2O_3) = (21 \pm 2)\,b$. The above-mentioned $\sigma^{\circ}_{n,\alpha}(^{10}B)$ has been deduced here (according to new absolute determination of isotopic composition by De 67b) from the measured $\sigma^{\circ}_{nA}(B) = (759.1 \pm 2.0)\,b$. The quoted errors are standard deviations.

4.3. Recommended Thermal Cross Section

$$\boxed{\begin{array}{lll} \hat{\sigma}^{\circ}_{n,\alpha}(^{10}B) & = & (3835 \pm 14)\,b \\ \text{at} \quad E_n & = & 0.02526 \ \text{eV} \end{array}}$$

Since all other neutron absorbing reactions at thermal energy are negligible (see chapt.3), the absorption cross section is practically identical with the (n,α) cross section. The recommended value is the (weighted) mean of the final results of Sa 60, Pr 63 and Al 64. The error corresponds to confidence limits at 95% confidence level (C.L. 95% = ±14b or ±0.37%)*. The results of all other authors are in agreement with the recommended value; however, they have not been taken into consideration since their sample analysis is too poor and other shortcomings are evident.

4.4. (n,α) Cross Section from Thermal Energy to 1 MeV

All available data are represented in figs. 1 and 2 together with the $1/\sqrt{E}$ fit discussed in chapter 4.5.

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* Further denoted by: "errors are confidence limits...."

Bi 57, Rice

Modified long counter as flux monitor. NaI crystal and multichannel analyser for detecting the 0.478 MeV γ-radiation. B shielded proportional counter with $^{10}BF_3$, multichannel analyser, background effects taken into account. No details given on errors and corrections. Measured cross sections normalized at 20 keV (assuming $\sigma^{\circ}_{n,\alpha}$ = 4010b and validity of 1/v law between thermal energy and 20 keV). Authors conclude $\sigma_{n,\alpha} \sim 1/v$ up to 100 keV and assign a ± 25% error to their absolute values; their relative values presumably are more accurate. Data plotted in fig. 2 are renormalized to the new recommended thermal value (chapt. 4.3.); for clarity of presentation, error bars are not indicated. Recently (Bo 66, Sp 67) the assumed constant efficiency vs. energy of the modified long counter assigned by Bi 57 has been called in question.

Bi 60, Duke

Long counter as neutron monitor. 122° neutron collimation-detection system, 18 $^{10}BF_3$ proportional counters connected in parallel. Background effects taken into account. $\sigma_{n,\alpha}$ obtained by subtracting potential scattering $\sigma_{n,n}$ = 2.43 b (Hi 50) from σ_{nT} measured with the 122° collimator by Ro 60. Authors conclude that $\sigma_{n,\alpha} = 624/\sqrt{E}$ within statistical errors, corresponding to $\sigma^{\circ}_{n,\alpha}$ = 4036b, and that cross section curve indicates $\sigma_{n,\alpha} \sim 1/v$ up to 70 keV, ratio of BF_3- to long-counter counting rates (assuming constant efficiency) indicates $\sigma_{n,\alpha} \sim 1/v$ up to 250 keV. Recently (Ta 67) the assumed flat response of the Bi 60 long counter has been suspected to be a wrong assumption.

Da 61, Rice

Long counter as flux monitor, calibrated with Pu-Be sources. Cd-shielded grid-type ionization chamber with BF_3 enriched to 96% in ^{10}B. Wall effects and multi-channel analyser dead-time taken into account. Considered are the uncertainties of counting statistics, background corrections, geometry, amount of ^{10}B in the chamber, wall effects, neutron energy determination. Authors estimate their cross sections to be in error by ± 20%. Bogart comments in Sp 67 that with the Da 61 data there are difficulties in separating the (n,α_0) and (n,α_1) groups because of large epithermal background contribution, and that accuracy is poor as E_n is lowered to several hundred keV.

Mo 66, Argonne

Two collimated counting systems, each consisting of 34 BF_3 counters in a moderator medium, one system used as monitor, the other as counter. Natural B samples and samples enriched to 93% in ^{10}B. σ_{nT} and σ_{nT}/σ_{nS} have been measured and $\sigma_{nA} = \sigma_{nT} - \sigma_{nS}$ derived from this, taking σ_{nS} by integrating the differential scattering data of La 67. Authors conclude that σ_{nA} follows the 1/v law from 10 - 500 keV except for a resonance at $E_n \approx 230$ keV and a slight dip around 340 keV, and that $\sigma_{nA} - \sigma_{n,\alpha} <<$ 100 mb at any E_n in this interval. Error estimates assigned to the cross sections were obtained from a least squares fit to the measured quantities and vary for σ_{nA} from about ± 2% at 10 keV to ± 4% at 250 keV, 10 to 20% between 300 and 400 keV, and ± 5% between 400 and 500 keV.

In fig. 2 error bars are only shown when the uncertainty exceeds the size of the circle.

Co 66, Aldermaston

Spherical shell transmission method, B powder shell enriched in ^{10}B to 89.4%, either neutron source or detector in the centre of the shell, BF_3 counters. Corrections applied for variation of detector efficiency with neutron energy, finite counter size and source to detector distance, anisotropic neutron emission, multiple scattering and neutron energy loss using Monte Carlo and Carlson calculations. The values given are weighted means of different measurements with standard deviations. Author concludes that $\sigma_{n,\alpha} = \sigma_{nA}$ with a negligible error and that

$\sigma_{n,\alpha}$ follows quite well a 1/v extrapolation from a thermal value of (3840 ± 10)b up to 250 keV. Ma 67 comments that statistical and other errors of Co 66 are so large (varying from about 5% at 10 keV to 14% at 250 keV), that the three points between 100 and 160 keV whose error bars fall above the 1/v line are not considered a significant departure.

Di 67, Harwell

Transmission measurement by TOF method, flight path 120 m and 300 m, neutron burst width 140 ns. Detectors: Al can containing ^{10}B powder mixed with vaseline moderator for efficiency improvement. Samples: three (93.0 ± 0.2)% ^{10}B samples of different thickness. No corrections for competing processes applied. Background effects, sample impurities and counting corrections are taken into consideration. Mean root square errors calculated.

The measured σ_{nT} from 76 eV to 10 keV are least squares fitted by $\sigma_{nT} = (610.3 \pm 3.1)/\sqrt{E} + (1.95 \pm 0.10)b$, corresponding to an extrapolated $\sigma^{\circ}_{nT} = (3839 \pm 20)b$. The last term in the σ_{nT} formula is attributed to a constant potential scattering cross section $\sigma_{n,n} = (1.95 \pm 0.10)b$. By subtracting the $\sigma_{n,n}$ data of Mo 66/La 67 from the measured σ_{nT}, σ_{nA} values are obtained up to 500 keV. Author concludes that the $1/\sqrt{E}$ law is apparently followed up to about 300 keV to within the experimental errors which vary from ± 1% at a few hundred eV to ± 3% at about 100 keV and ± 7% at 500 keV.
In this report the σ_{nA} values below 25 keV are re-evaluated by subtracting the very recent As 68 $\sigma_{n,n}$ data from the measured Di 67 σ_{nT}.

The σ_{nA} data thus obtained are plotted in figs. 1 and 2, the errors being in the order of the triangles' size.

Ma 68, Oak Ridge

Measurement of the inverse reaction using the graphite sphere 4π neutron detector, determination of the $^{10}B(n,\alpha)$ cross section applying the reciprocity theorem and the

$^{10}B(n,\alpha)$ branching ratio. Thin metallic ^{7}Li Van de Graaff targets placed in the centre of the graphite sphere. Corrections applied for background effects, energy spread and target thickness. Normalization of the relative data by extrapolating $\sigma_{n,\alpha}(^{10}B)$ of Sc 60, Sa 60, Pr 63 and Al 64 (both uncorrected for new determination of isotopic composition) from thermal energy to 30 keV, and by the own branching ratio results. In this report the data are renormalized according to the recommended thermal value (chap. 4.3) and 1/v law (chap. 4.5). Author states that the $^{10}B(n,\alpha)$ data are consistent with a departure of less than 3% from $611/\sqrt{E_n}$ behaviour below 166 keV, whereas the separate ground state and excited state cross section show significant departure from a $1/\sqrt{E_n}$ dependence at and above 30 and 100 keV respectively.

4.5. Analysis of Data and Recommended Best Curve

All available data are represented in figs. 1 and 2. At first sight the 1/v behaviour seems to be justified over a wide energy range, even up to 300 keV. For a more detailed analysis, however, four data sets were chosen from those reported in the preceding section. These four sets are Mo 66, Co 66, Di 67 and Ma 68, as these are the most accurate measurements in the energy range from thermal to about 300 keV. Moreover, Co 66 used a completely independent method.

The first step was to assume a

$$\sigma'_{n,\alpha} = C \cdot E_n^{-1/2}$$

in which C was computed from the recommended thermal cross section value of section 4.3., yielding

$$\boxed{C = (19.274 \pm 0.071)\ \mathrm{b \cdot keV^{1/2}}}$$

The error in C corresponds simply to the error of the recommended thermal cross section (i.e. C.L. 95% of ± 0.37%).

The next step was to compute the differences between this "1/v cross section" $\sigma'_{n,\alpha}$ and the measured cross sections $\sigma_{n,\alpha}$ (observed). These differences were plotted as a function of energy (fig. 3).

As it is clear that the scatter of the points is not uniform around the zero line, a weighted least squares fit was computed according to :

$$\delta(E_n) = A + B \cdot E_n^{+1/2} + D \cdot E_n \, , \qquad (1)$$

yielding the values

$A = -(0.32 \pm 0.05)\mathrm{b}$
$B = +(0.079 \pm 0.012)\mathrm{b} \cdot \mathrm{keV}^{-1/2}$
$D = -(0.0039 \pm 0.0006)\mathrm{b} \cdot \mathrm{keV}^{-1}$
Errors are standard deviations

The curve corresponding to this fit is traced in fig. 3. Formula (1) is in accordance with the model developed by Sh 58 and the shape of the curve seems to fit the experimental data fairly well. Even at 300 keV the agreement is still good. Earlier measurements below 30 keV by Be 58b and Be 61 based on the theoretical considerations of Sh 58 but neglecting the higher order coefficients B and D yielded a term α (equivalent with our A) = - 0.40b, whereas As 68 found a value of - 0.25 b.

Some recommended values $\hat{\sigma}_{n,\alpha} = \sigma'_{n,\alpha} + \delta$ (see (1)) are tabulated in Table III.

The errors $\Delta\sigma_{n,\alpha}$ in this table are confidence limits (P=95%), which were computed from three contributions:

- the uncertainty of the thermal value, which yields a corresponding error in the coefficient C (C.L. = ± 0.37%)
- the uncertainty in the scattering cross section
- the errors in the constants and coefficients of the least squares fit.

In the energy interval from thermal to 0.01 keV the main contribution is that of the error in C. Up to 10 keV the contributions are about equal in magnitude. From 10 to 40 keV the error in the least squares fit passes through a minimum; the contribution of the error in C decreases continually with increasing energy E_n. From 40 to 100 keV the final error is mainly determined by the uncertainties in the $\sigma_{n,n}$ correction and in the constants of the fit.

5. BRANCHING RATIO

By branching ratio is meant in this report the probability of the $^{10}B(n,\alpha)$ reaction going to the ground state of ^{7}Li. For practical reasons this probability is multiplied by 100, hence the sum of ground state and excited state (n,α) reaction probability should be 100 :

$$\boxed{\begin{aligned} &R = 100\ \sigma_{n,\alpha_0}/\sigma_{n,\alpha} \quad \text{with} \\ &\sigma_{n,\alpha} = \sigma_{n,\alpha_0} + \sigma_{n,\alpha_1} \end{aligned}}$$

The branching ratio at the thermal energy of 0.02526 eV is denoted here by R°.
In the literature this branching ratio is sometimes mixed up with the cross section ratio $\sigma_{n,\alpha_0}/\sigma_{n,\alpha_1}$, or even with its reciprocal, which is at the origin of some confusion.

5.1. Branching Ratio at Thermal Energy

Bo 45, Copenhagen $R^{\circ} = 6.3$

Cloud chamber, about 400 tracks evaluated. Value given in the paper is $\sigma_{n,\alpha_0}/\sigma_{n,\alpha_1} = 0.067$.

Gi 48, Cambridge $R^{\circ} = 8.6$

Cloud chamber with $B(OCH_3)$ gas, total ranges of Li- and α-particles measured, corrected for variations of stopping power.

Ha 50, Chalk River $R^{\circ} = 5.8 \pm 0.1$

Grid-type ionization chamber with BF_3, multichannel analyser, wall effects not taken into consideration. Author comments that the error quoted is an attempt to give reasonable limits of error, the reproducibility of the measurement being considerably better.

Cu 51, Strasbourg R° = 4.08 ± 0.15

Borate charged nuclear emulsions, 30531 tracks measured. Value given in the paper is $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1} = 0.0427 \pm 0.0015$, the uncertainty obviously representing only the statistical error.

Bi 52, Basel R° = 6.5 ± 0.7

Parallel plates ionization chamber with BF_3, wall effects neglected, photographic pulse-height spectrograph and multichannel analyser. Only statistical error considered. Value given in the paper is $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1} = 0.070 \pm 0.007$.

Ha 52, Göttingen R° = 5.8 ± 0.1

$B(CH_3)_3$ proportional counter in paraffin, Ra-Be neutron source, 16-channel analyser. No corrections applied.

Rh52, Pennsylvania R° = 5.9 ± 0.9

Cylindrical ionization chamber with thin B layer enriched to 96% in ^{10}B, photographic pulse-height spectrograph, wall effects and layer thickness taken into account. Value given in the paper is $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1} = 0.063 \pm 0.009$.

De 54, Washington R° = 6.52 ± 0.05

Two pulse-ionization chambers with thin B films, three-channel discriminator. Integral measurements. Exposure in the NBS standard slow-neutron flux, Cd difference method. Effects of geometry and film thickness taken into account. The error quoted is the statistical probable error.

Se 57, Aligarh R° = 3.8 ± 0.14

BF_3 proportional counter. Measurement obviously erroneous by systematic errors. Value given in the paper is $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1} = 0.040 \pm 0.0015$.

Bu 58, Debrecen R° = 7.9 ± 0.9

B-loaded nuclear emulsion, exposed to a Ra-Be source in paraffin. 1230 tracks measured with a microscope. Geometrical corrections taken into account. Value given in the paper is $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1} = 0.086 \pm 0.009$.

Br 60, Rossendorf $R^\circ = 6.51 \pm 0.05$

Proportional counter with BF_3, collimated beam from thermal column of RFR reactor, Cd difference method, 70-channel analyser, γ-ray effects on the counting plateau taken into account. Measurement errors due to radiation from Al and Cu counting tubes are negligible.

Ma 63, Studsvik $R^\circ = 6.08 \pm 0.07$

Proportional counter with $^{10}BF_3$, multichannel analyser. Pulse-height resolution 2.6%, statistical accuracy <1%. Author quotes that the average value of 10 measurements give the ratio to ± 0.0005 and that, with an estimate of systematical errors to ± 0.0005, $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1} = 0.0647 \pm 0.0007$.

Ma 65, Oak Ridge $R^\circ = 6.3 \pm 0.2$

Two face-to-face Si surface-barrier detectors with $^{10}B_2H_6$, coincidence, multichannel analyser. Thermal neutron spectrum (wax moderator). Value given in the paper is $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1} = 0.067 \pm 0.002$ as an average of four measurements.

To 66, North Carolina $R^\circ = 6.43 \pm 0.11$

Semiconductor detector with thin ^{10}B converter film, 200-channel analyser, thermal neutron beam, epi-cadmium check. Standard error assumed to be entirely statistical.

De 67a, Mol/Geel $R^\circ = 6.3082 \pm 0.0064$

Thin ^{10}B layer on Au-coated quartz disk in front of an Au-Si surface barrier detector, thermal neutron beam, Cd-difference method, 400-channel analyser. Due to the geometry, backscattering and selfabsorption are eliminated. 20 runs evaluated taking into account all error contributions, corrected for epi-Cd data. The error indicated is one standard deviation of the mean.

Ma 68, Oak Ridge $R^\circ = 6.32 \pm 0.03$

Considerable improvement of the Ma 65 measurements using self-supporting ^{10}B foils of 80 - 100 μg/cm^2 between the two face-to-face surface barrier silicon detectors. Calculated energy losses in the foils. Thermal neutrons from wax moderator. Error quoted by the authors combines the statistical standard deviation and the effect of uncertainty in identifying the 478 keV energy difference from the spectra.

5.2. Recommended Thermal Branching Ratio

$$\boxed{\begin{array}{l} \hat{R}^{\circ} = 6.308 \pm 0.012 \\ \text{at } E_n = 0.02526 \text{ eV} \end{array}}$$

The De 67a result is recommended as thermal value, since its precision is about one order of magnitude or more better than that of all previous measurements. It is in agreement with the latest solid state detector data of Ma 65, To 66 and Ma 68, but disagrees with the most precise previous results of De 54, Br 60 and Ma 63. The above mentioned error gives confidence limits (P=95%), derived from the standard deviation quoted by De 67a.

5.3. Branching Ratio from Thermal Energy to 1 MeV

All available data are represented in figs. 4 and 5, together with the recommended best curve.

Pe 51, Wisconsin

Cd-shielded proportional counter with $^{10}BF_3$, wall effect corrections, photographic recording. Considered are the uncertainties of concentration of ^{10}B in the counter, background corrections, counting statistics, neutron energy determination. In the paper are presented the $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1}$ values, the total uncertainty of which is, according to the authors, somewhat greater than the statistical uncertainty indicated in the graph.

Bi 52, Basel

B-shielded parallel plates ionization chamber with BF_3, wall effects neglected, photographic pulse-height spectrograph. Considered are the uncertainties of evaluation of the pulse-height spectrum, statistics, neutron energy. It concerns a single value at 500 keV which is quoted in the paper as $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1} = 0.31 \pm 0.04$, the total error of 13 % being composed of a 8% statistical error and a 10% uncertainty in evaluation.

Da 61, Rice

Cd-shielded grid-type ionization chamber with BF_3 enriched to 96% in ^{10}B, wall effects and multichannel analyser dead-time were corrected. Considered are the uncertainties of counting statistics, background corrections, geometry, amount of ^{10}B in the chamber, wall effects, neutron energy determination. Measured are both σ_{n,α_0} and σ_{n,α_1} with estimated errors of ± 20%. Bogart comments in Sp'67 that with the Da 61 data there are difficulties in separating the α_0 and α_1 groups because of large epithermal background contributions and that accuracy is poor, as E_n is lowered to several hundred keV.

Ma 65, Oak Ridge

Two face-to-face Si surface-barrier detectors with $^{10}B_2H_6$, detection of ^7Li and α-particles from the reaction in coincidence, multichannel analyser. No details given on corrections and errors. Energy uncertainties are only mentioned for 30, 110 and 160 keV. In the paper are presented $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1}$ values. Authors comment that above 160 keV the pulse height resolution became progressively worse (most due to longer exposure of the detector to $^{10}B_2H_6$) and difficulty was experienced in determining the ratio.

So 66, Harwell

Proportional counter with BF_3 enriched to 90% in ^{10}B, and end wall effects taken into consideration. Time-of-flight technique with 35 m (open circles o) and 52 m (open triangles ∧) flight paths, resp., two-dimensional multichannel analyser. Background neutrons proved to be negligible. Horizontal bars on measuring points indicate energy intervals (not errors in energy determination). Vertical bars include all uncertainties in corrected ratios. Author comments that the ratio is constant with a value of 6.5 ± 0.5 up to about 100 - 130 keV but above this energy the values given may be in error because the wall effects may alter appreciably with energy.

Mo 66, Argonne

$\sigma_{n,\alpha_1} / \sigma_{n,\alpha_0}$ used in a detailed-balance calculation for a comparison of $\sigma_{n,\alpha}(^{10}B)$ of Mo 66 with the $^7Li(\alpha,n)^{10}B$ cross section of Gi 59. No indication on errors.

Ma 68, Oak Ridge

Considerable improvement of the Ma 65 measurements using self-supporting ^{10}B foils of 80 - 100 µg/cm^2 between the two face-to-face surface barrier Si detectors. Calculated energy losses in the foils, small thermal neutron contribution taken into account. In the paper $\sigma_{n,\alpha_0} / \sigma_{n,\alpha_1}$ values are quoted, the errors combining the statistical standard deviation and the effect of uncertainty in identifying the 478 keV energy difference from the spectra. Authors point to the difficulty of ratio measurements in the 100-300 keV range, as neutron source strength is low and thermalized neutron effects important and difficult to measure.

5.4. Analysis of Data and Recommended Curve

The curve of figs. 4 and 5 suggests a constant branching ratio from thermal energy up to about 30 keV.
The (unweighted) mean of all data out of the data sets Mo 66, So 66 and Ma 68 - which were chosen for the same reasons as indicated in section 4.5 - in the energy interval 20 eV $< E_n <$ 30 keV is R=6.3 with a standard deviation of 0.13.
With a recommended thermal value of $\hat{R}^\circ = 6.308$ (confidence limit $\Delta\hat{R}=0.012$) it is recommended to assume the branching ratio

$$\boxed{\begin{array}{l}\hat{R} = 6.3. \pm 0.3 \text{ (C.L. 95\%)} \\ \text{above thermal to 30 keV}\end{array}}$$

Above 30 keV a weighted (based on the standard deviations quoted by the authors) least squares fit was computed according to the model :

$$100\sigma_{n,\alpha_0}/\sigma_{n,\alpha} = C + A(E_n-30)^2 + B(E_n - 30)^3 \;, \qquad (2)$$

where E_n is expressed in keV. C was fixed at 6.3. A significance test showed that terms of an order higher than 3 gave no significant improvement (F-test, 5% level) in the interval $E_n < 300$ keV. So it is recommended to accept for 30 keV $< E_n <$ 100 keV formula (2) with the following constants :

$C = 6.3 \pm 0.1$
$A = (2.1 \pm 0.1)10^{-4}\ \mathrm{keV}^{-2}$
$B = -(3.6 \pm 0.6)10^{-7}\ \mathrm{keV}^{-3}$
Errors are standard deviations

Some numerical values of $\hat{R}$ and the confidence limits $\Delta\hat{R}$ are tabulated in Table III. From the quoted $\hat{\sigma}_{n,\alpha}$ and $\hat{R}$, $\hat{\sigma}_{n,\alpha_1}$ is computed by

$$\hat{\sigma}_{n,\alpha_1} = \hat{\sigma}_{n,\alpha}\,(1 - \hat{R}/100) \qquad (3)$$

and the confidence limit $\Delta\hat{R}$ is deduced from the propagation of error law, which can be applied here as far as $\sigma_{n,\alpha}$ and R have been independently measured.

Some numerical values of both $\hat{\sigma}_{n,\alpha_1}$ and $\Delta\hat{\sigma}_{n,\alpha_1}$ are also to be found in Table III.

6. APPLICATION OF THE RECOMMENDED DATA AS STANDARDS FOR NEUTRON MEASUREMENTS

As a result of the present evaluation, some recommended values of the ^{10}B cross sections $\hat{\sigma}_{n,\alpha}$ and $\hat{\sigma}_{n,\alpha_1}$ together with the branching ratio $\hat{R} = 100\ \sigma_{n,\alpha_0}/\sigma_{n,\alpha}$ are tabulated with the corresponding confidence limits Δ from thermal energy to 100 keV (see Table III).

Values at thermal energy with their confidence limits (P = 95%) are quoted as evaluated in sections 4.3 and 5.2.

Between thermal energy and 0.001 keV values may be computed from:

$$\hat{\sigma}_{n,\alpha} = 19.274\ E_n^{-1/2}\ \mathrm{b}(E_n \text{ in keV})$$

$$\Delta\hat{\sigma}_{n,\alpha} = \pm\ 0.0037\ \hat{\sigma}_{n,\alpha}\ \mathrm{b}$$

$$\hat{\sigma}_{n,\alpha_1} = \hat{\sigma}_{n,\alpha}(1 - \hat{R}/100)\ \mathrm{b}$$

$$\Delta\hat{\sigma}_{n,\alpha_1} = \pm\ [(\Delta\hat{\sigma}_{n,\alpha})^2 + 10^{-5}(\hat{\sigma}_{n,\alpha})^2]^{1/2}\mathrm{b}$$

$$\hat{R} = 6.3$$

$$\Delta\hat{R} = \pm\ 0.3$$

(the errors ∧ are conf.limits (P=95%))

Above 0.001 keV values may be calculated from:

$$\hat{\sigma}_{n,\alpha} = 19.274\ E_n^{-1/2} - 0.32 + 0.079\ E_n^{1/2} - 0.0039\ E_n\ \mathrm{b}(E_n \text{ in keV})$$

$$\hat{\sigma}_{n,\alpha_1} = \hat{\sigma}_{n,\alpha}(1 - \hat{R}/100)\ \mathrm{b}$$

$$\hat{R} = 6.3 + 2.1 \times 10^{-4}(E_n - 30)^2 - 3.6 \times 10^{-7}(E_n - 30)^3(E_n \text{ in keV})$$

Confidence limits Δ are easily obtained directly from Table III

<u>Table III</u> : Some recommended values of the ^{10}B cross sections $\sigma_{n,\alpha}$ and σ_{n,α_1}, the branching ratio $R = 100\ \sigma_{n,\alpha_1}/\sigma_{n,\alpha}$ and the corresponding confidence limits (P=95%) ∧ . Linear interpolation of $\hat{\sigma}_{n,\alpha}$ and $\hat{\sigma}_{n,\alpha_1}$ is not justified!

E_n (keV)	$\hat{\sigma}_{n,\alpha}$ (b)	$\Delta\hat{\sigma}_{n,\alpha}$ (b)	$\hat{\sigma}_{n,\alpha_1}$ (b)	$\Delta\hat{\sigma}_{n,\alpha_1}$ (b)	$\hat{R}$	$\Delta\hat{R}$
$0.25258 \cdot 10^{-4}$	3.835	± 14	3.593	± 14	6.308	± 0.012
0.001	609.2	2.3	570.8	± 3.0	6.3	± 0.3
0.002	430.7	1.6	403.5	2.1		
0.003	351.6	1.3	329.4	1.7		
0.004	304.4	1.1	285.2	1.5		
0.005	272.3	1.0	255.1	1.3		
0.006	248.5	0.9	232.8	1.2		

$\hat{E}_n$ (keV)	$\hat{\sigma}_{n,\alpha}$ (b)	$\wedge\hat{\sigma}_{n,\alpha}$ (b)	$\hat{\sigma}_{n,\alpha_1}$ (b)	$\wedge\hat{\sigma}_{n,\alpha_1}$ (b)	$\hat{R}$	$\wedge\hat{R}$
0.007	230.0	± 0.9	215.6	± 1.2	6.3	± 0.3
0.008	215.2	0.8	201.6	± 1.1		
0.009	202.8	0.8	190.1	1.0		
0.01	192.4	0.8	180.3	0.9		
0.02	136.0	0.5	127.4	0.7		
0.03	111.0	0.5	104.0	0.6		
0.04	96.1	0.4	90.0	0.5		
0.05	85.9	0.4	80.5	0.5		
0.06	78.4	0.3	73.4	0.4		
0.07	72.6	0.3	68.0	0.4		
0.08	67.8	0.3	63.6	0.4		
0.09	64.0	0.3	60.0	0.4		
0.1	60.6	0.3	56.8	0.4		
0.2	42.8	0.2	40.1	0.2		
0.3	34.9	0.2	32.7	0.2		
0.4	30.2	0.2	28.3	0.2		
0.5	26.99	0.2	25.29	0.2		
0.6	24.62	0.2	23.07	0.2		
0.7	22.78	0.2	21.35	0.2		
0.8	21.30	0.2	19.96	0.2		
0.9	20.07	0.2	18.80	0.2		
1.0	19.03	0.15	17.83	0.15		
2.0	13.41	0.12	12.57	0.12		
3.0	10.93	0.12	10.24	0.12		
4.0	9.46	0.12	8.86	0.12		
5.0	8.46	0.10	7.92	0.10		
6.0	7.72	0.09	7.23	0.09		
7.0	7.15	0.08	6.70	0.08		
8.0	6.69	0.08	6.27	0.08		
9.0	6.31	0.07	5.91	0.07		
10.0	5.99	0.06	5.61	0.06		
20.0	4.27	0.06	4.00	0.06		
30.0	3.52	0.06	3.29	0.06		
40.0	3.07	0.06	2.88	0.06		

E_n (keV)	$\hat{\sigma}_{n,\alpha}$ (b)	$\Delta\hat{\sigma}_{n,\alpha}$ (b)	$\hat{\sigma}_{n,\alpha_1}$ (b)	$\Delta\hat{\sigma}_{n,\alpha_1}$ (b)	$\hat{R}$	$\Delta\hat{R}$
50.0	2.77	± 0.06	2.59	± 0.06	6.4	± 0.3
60.0	2.55	0.06	2.38	0.06	6.5	0.3
70.0	2.37	0.06	2.22	0.06	6.6	0.3
80.0	2.23	0.06	2.08	0.06	6.8	0.4
90.0	2.11	0.06	1.96	0.06	7.0	0.4
100.0	2.01	0.06	1.87	0.06	7.2	0.4

Acknowledgements

The authors wish to express their appreciation to Dr. J. Spaepen who has suggested and initiated the present evaluation, for many valuable discussions and for his continuous interest in this work. Thanks are also due to Dr. P. De Bièvre for his contribution to chapt. 2 and to Dr. G. Nastri who took charge of the computations.

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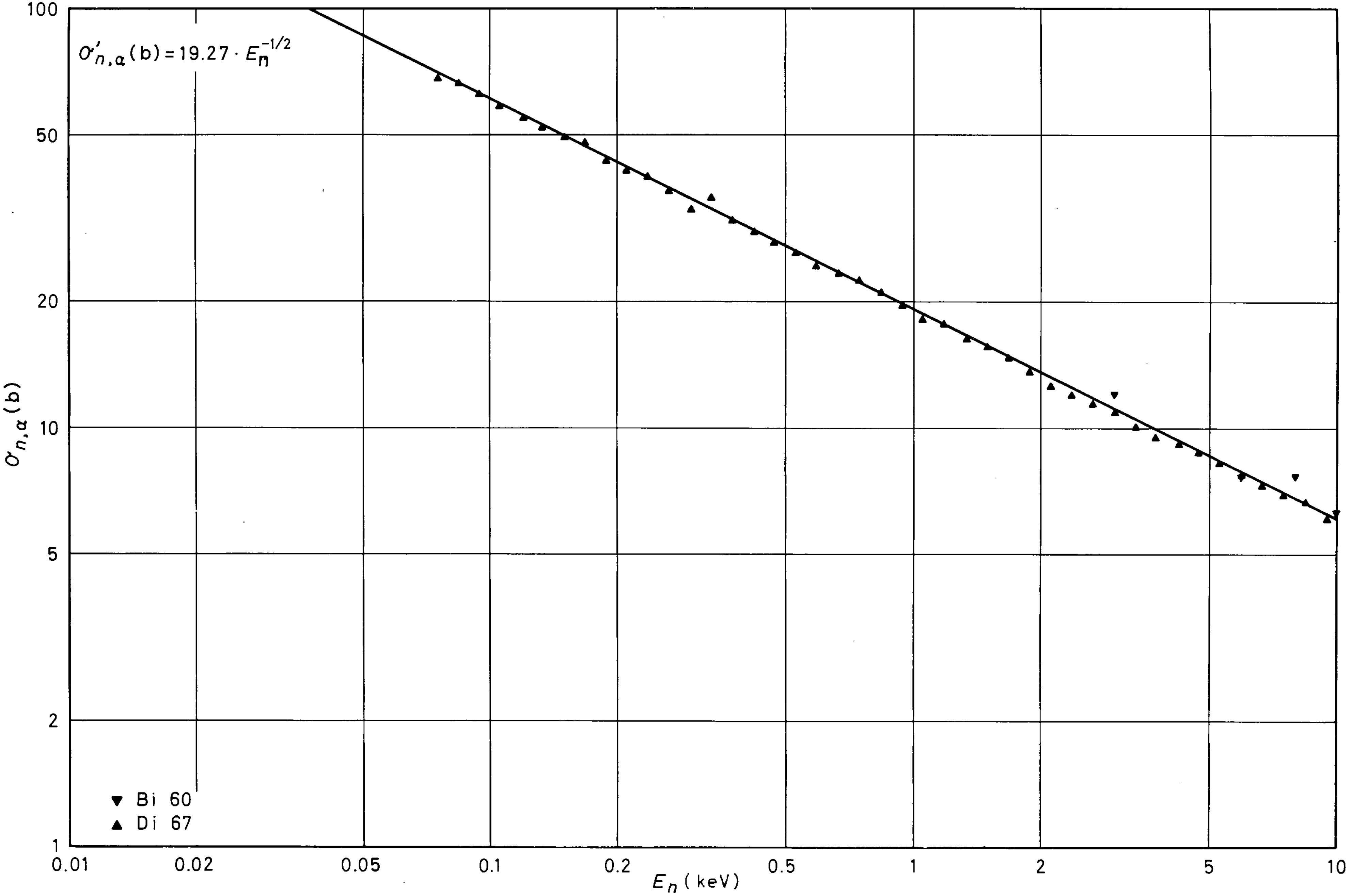

Fig.1. $^{10}B(n,\alpha)$ cross section from 0.07 to 10 keV.

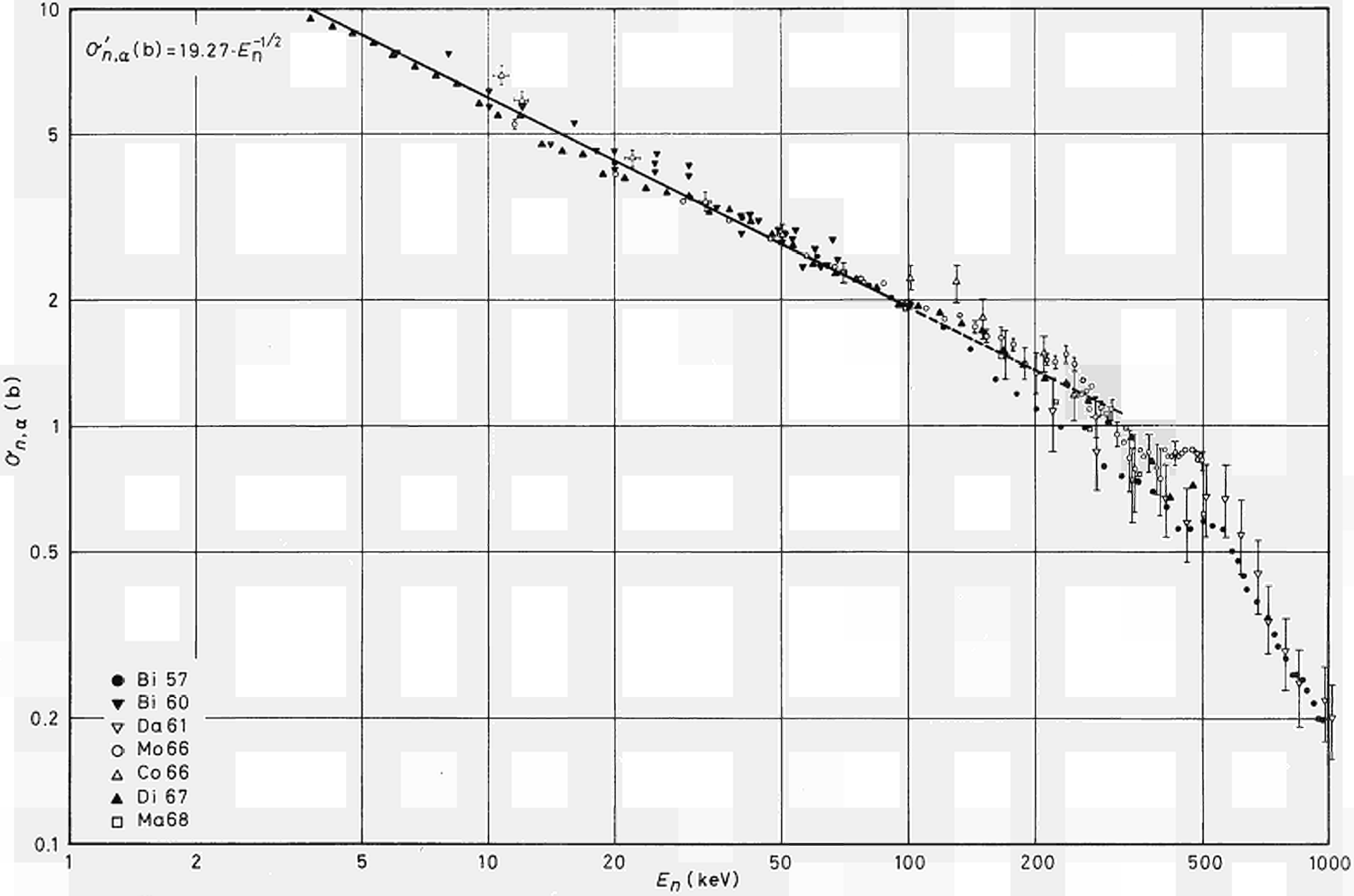

Fig. 2. $^{10}B\ (n,\alpha)$ cross section from 3 to 1000 keV.

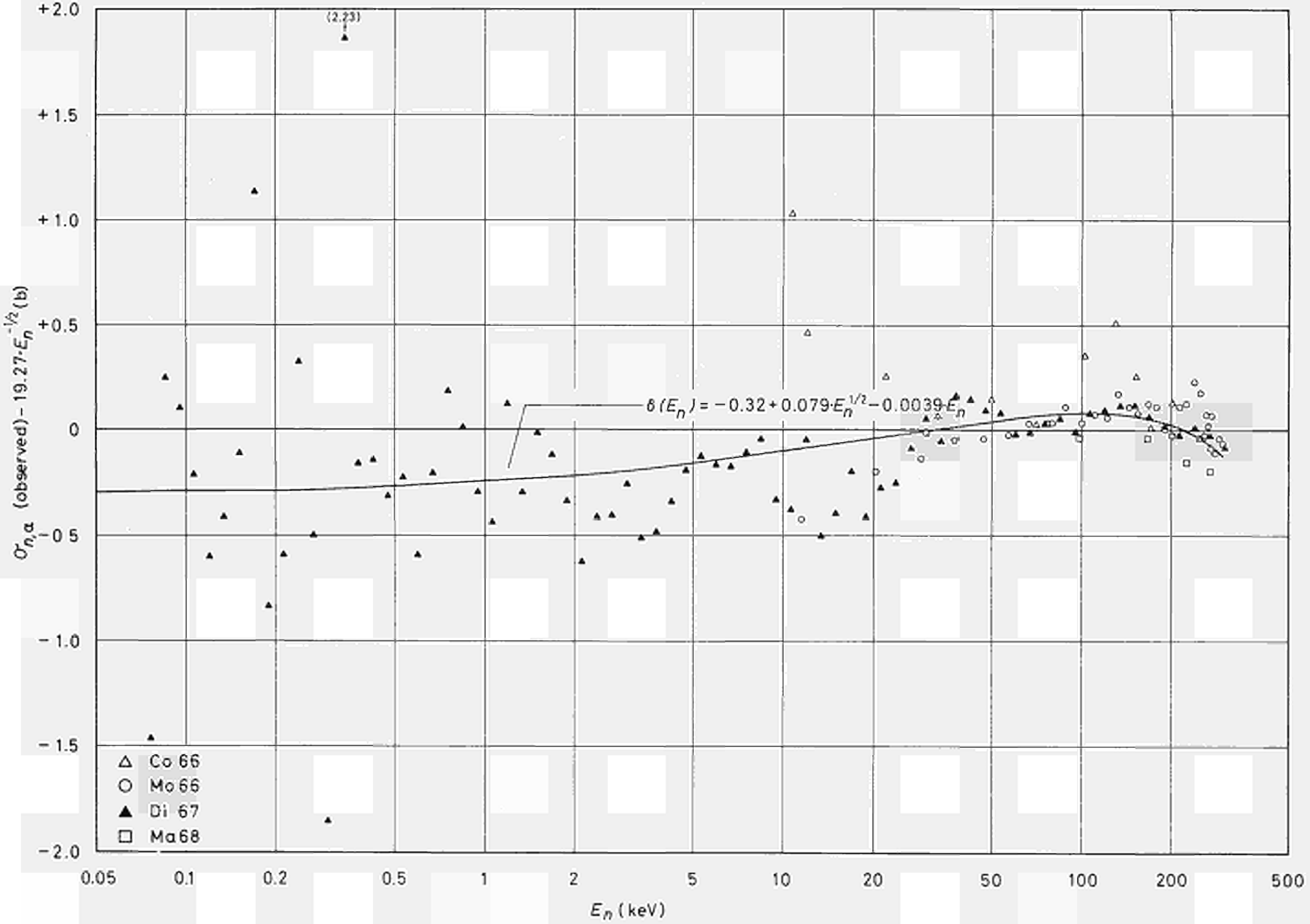

Fig. 3. Deviation of $\sigma_{n,\alpha}$ (^{10}B) from $19.27 \cdot E_n^{-1/2}$ between 70 eV and 300 keV.

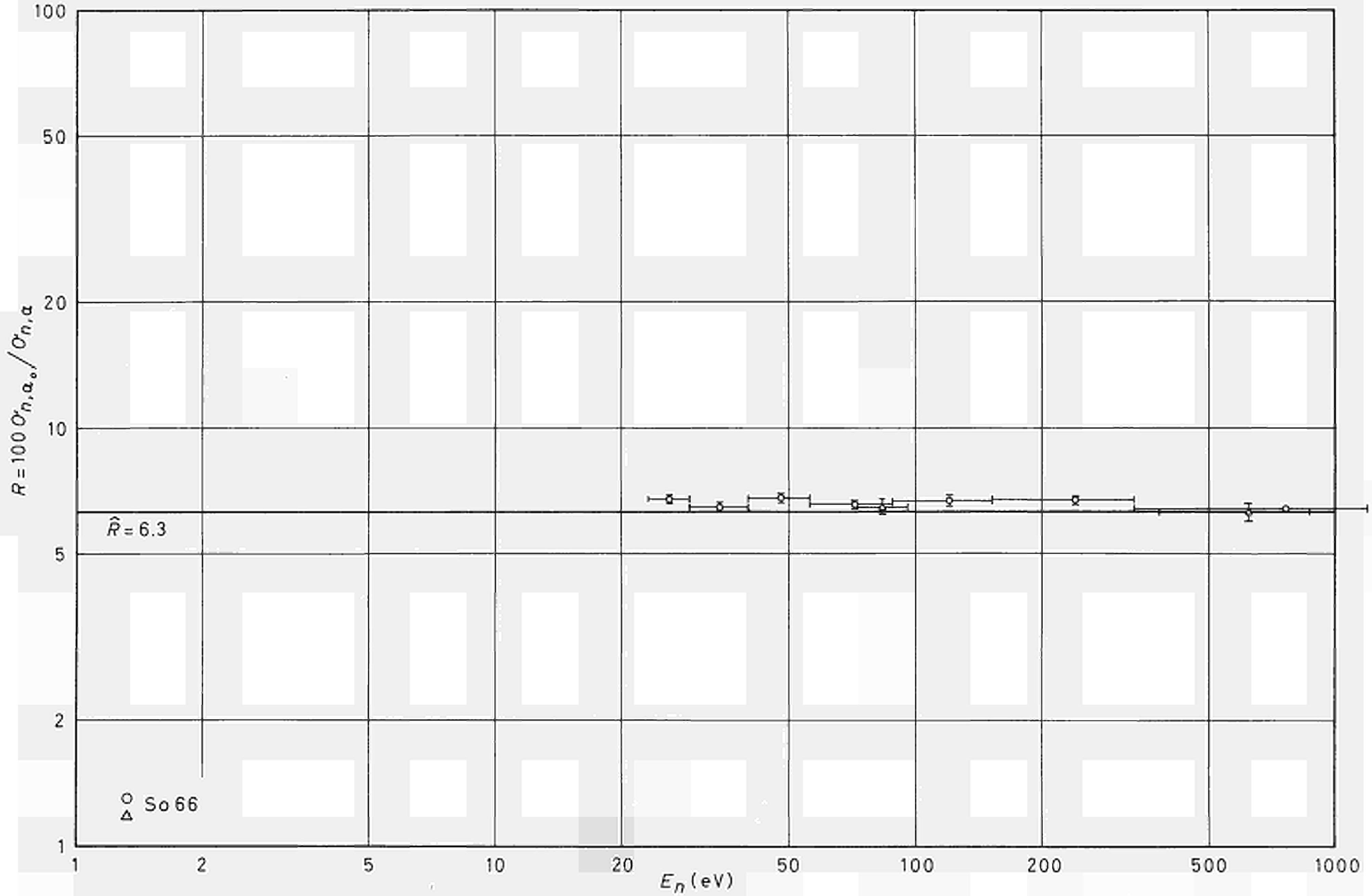

Fig.4. $^{10}B\,(n,\alpha)$ branching ratio from 20 to 1000 eV.

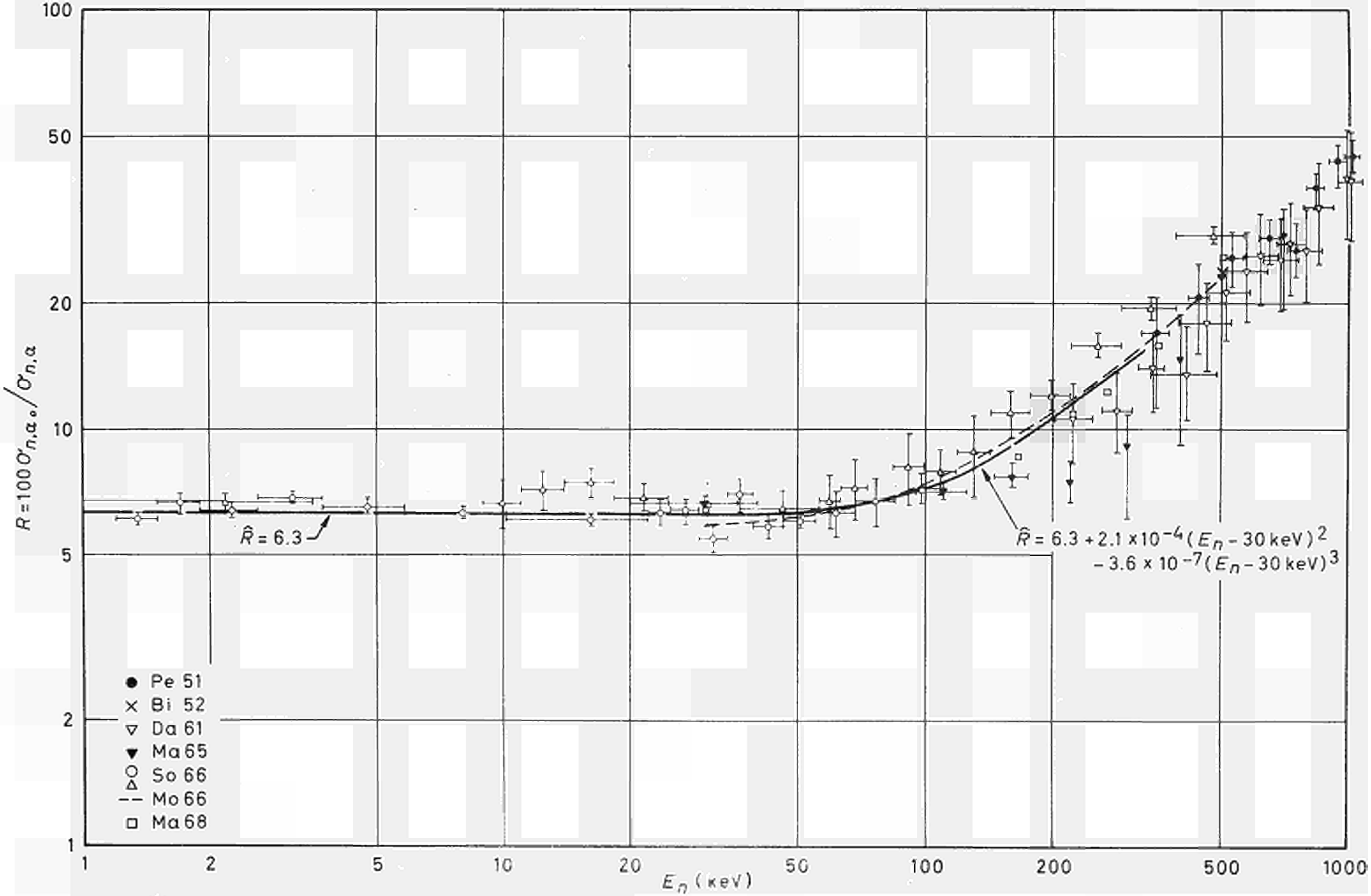

Fig.5. $^{10}B(n,\alpha)$ branching ratio from 1 to 1000 keV

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