

TOTAL NEUTRON CROSS-SECTIONS ON HYDROGEN AND
VARIOUS OTHER ELEMENTS IN THE 4-15 GeV/c RANGE

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ABSTRACT

Total neutron cross-sections were determined for the following elements: H, D, He, Li, Be, C, Al, Fe, Cu, Pb. The mean momentum of the spectrum of the incident neutrons was 10 GeV/c. Furthermore, measurements were made for hydrogen with lower neutron momentum down to 4 GeV/c. All cross-sections are in excellent agreement with corresponding proton total cross-sections.

Geneva - 18 July 1968
(Submitted to Physics Letters)

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Measurements of total cross-sections of very light nuclei are of considerable interest since they provide valuable tests for the strong interaction scattering theory. For heavier nuclei, the total cross-sections can be interpreted in terms of an optical model yielding interesting results on the structure of the nuclei. In the first part of this paper, a precise measurement of the neutron-proton total cross-section for an average neutron momentum of 10 GeV/c is reported. It could be shown that this cross-section agrees with the corresponding proton-proton cross-section. In the second part of the paper these measurements are extended to nuclei throughout the periodic system up to lead. Also, these results are in agreement with measurements of proton-nuclei total cross-sections, whereas previous measurements have indicated considerable differences.

Most of the information for neutron-proton total cross-sections has been obtained in the past from (pd) scattering by subtracting the (pp) contribution. However, in this procedure, screening corrections which have been calculated by Glauber¹⁾ and by Harrington²⁾ have to be applied, and these introduce an element of uncertainty. These data indicate that the (np) total cross-section is higher than the (pp) cross-section in the energy range between 8 and 20 GeV. Recent measurements of neutron-proton total cross-sections at various neutron momenta between 14 and 27 GeV/c have been reported by Kreisler et al.³⁾. These data show (np) cross-sections which are lower than the corresponding (pp) cross-sections at 14 GeV/c^{4,5)}, and are then rising slowly to the corresponding (pp) value at about 27 GeV/c. To solve this discrepancy the (np) total cross-section is determined absolutely for a mean neutron momentum of 10 GeV/c with a rather high precision in this experiment. In addition, the energy dependence was measured with lower accuracy.

The measurements were carried out during the tests for a neutron-proton elastic scattering experiment at the CERN Proton Synchrotron. A neutron beam was installed under an angle of -2.7° with respect to the tangent at the internal Be target. Since this beam left the target under a negative angle, it had to traverse the vacuum pipe of the machine three times under a rather shallow angle which attenuated the beam by a factor of about 50. The beam was constructed of a series of collimators and confined to a rectangular shape by the defining collimator at a distance of 29.5 m from the internal target. The aperture of this collimator was

12.94 mm horizontally by 28.42 mm vertically at the above distance, and it was tapered so that the walls aimed at the target position. The total number of neutrons was 30,000 per burst of 5×10^{11} protons. Gamma rays were attenuated very effectively by the vacuum pipe of the machine itself, and by an additional lead filter of 2.5 cm. Charged particles were removed by a sweeping magnet of 1.5 Wb/m bending strength. Contamination of neutral kaons was calculated to be $\sim 5\%$, in agreement with a survey done in a previous experiment in a similar geometric location⁶⁾.

A counter telescope looking at the internal target⁷⁾ was used as beam monitor which proved to be reliable. No other beam monitor was installed in the neutral beam because it was felt that thick counters might disturb the shape of the beam, whilst the thin counters that leave it undisturbed are, however, mostly sensitive to the small fraction of charged particles, originating anywhere.

Absorption measurements using this beam were carried out on the following elements and compounds: Group I: H₂, D₂, He; Group II: LiH, Be, C, Al; Group III: Fe, Cu, Pb. The experimental procedure and the analysis of the data differed somewhat from group to group.

Much effort was spent on performing the measurements with good geometry, including beam definition, and on correcting for small-angle scattering. Since the experiment was done on a parasitic basis, sufficient beam-time was available not only for obtaining a good statistical accuracy but also for eliminating systematic errors. On the other hand, the primary proton energy was chosen by the main user and could not be changed deliberately.

The experimental set-up is shown schematically in Fig. 1. The neutrons were converted by an iron slab of variable size (C1, ..., C5) and the shower detected by two scintillation counters, of 4 mm thickness, in coincidence. The sensitive area of the scintillation counters (S1, S2) could be varied and matched to the size of the iron converter by changing the amount of overlap between the two. The 2 cm thick iron converters had dimensions of (4.0 × 8.0) cm, (6.0 × 10.0) cm, (9.5 × 13.5) cm, (13.0 × 17.0) cm, and (16.0 × 20.0) cm. The beam dimensions were 4.2 × 8.5 cm at the place of the neutron detector. The scintillation counter S3 (dimensions 50 × 50 × 0.5 cm), placed 1.5 m upstream, served as an anticounter with which to remove charged particles from the scattered beam. No other anticounter was installed ahead of the targets, because it was found that more charged particles were produced with it than were present without it ($\leq 0.5\%$).

The liquid hydrogen target was mounted at a distance of 29.5 m from the neutron detector (position T2). The same target assembly was used for the deuterium measurements. The target was 50.1 ± 0.3 cm long and 8.0 cm in diameter. A commercial cylinder was used as a He target; this cylinder was filled with He gas at a pressure of 147.5 ± 0.5 atm, and the pressure gauge was calibrated against a standard.

All targets of Groups II and III were placed at position T1, 38.8 m from the neutron detector. A vacuum pipe of 20 cm diameter was installed, which covered most of the distance between the neutron detector and the two target positions.

The measuring procedure was as follows: Group I elements were measured with target full and empty. For each target state, measurements up to a statistical accuracy of $< 1\%$ were made with each of the five different converters of the neutron detector. The same was done for the elements and compounds of Groups II and III, but with the addition of three to five different target thicknesses which were generally of the order of 0.1 to 1.5 collision lengths. For the elements of Group III, additional absorption curves were taken in steps of 0.78 g/cm² for Fe, 0.89 g/cm² for Cu, and 1.1 g/cm² for Pb.

In all measurements the PS energy was 19.3 GeV. The neutron spectrum was determined independently with a total absorption spectrometer consisting of 30 cm Fe interspersed with 20 scintillator plates. Five photomultipliers viewed these scintillators. The dynode outputs were summed and analysed. A neutron was registered whenever the first two counters gave a signal. The calibration was done using the beam of variable energy as described below. The energy resolution was found to be $\sim 30\%$. The neutron spectrum thus determined agreed very well with calculations for protons based on a statistical model by Hagedorn and Ranft⁸⁾.

To extend the measurements to lower energies, a separate experiment was made when only $\sim 3\%$ of the beam intensity was available due to operation of the slow ejection of the PS. During the acceleration cycle of the PS, the internal Be target was flipped twice, producing short bursts of ~ 20 msec. The corresponding mean neutron momenta were 6 and 10 GeV/c.

Since the measuring time was rather long, the results are subject to larger systematic uncertainties which, however, are included in the error.

A second method consisted of changing the trigger conditions of the total absorption counter to a sixfold coincidence. This meant that the secondaries produced in the first iron plate were required to traverse the whole counter. According to the calibration, the threshold of the counter was then moved up to about 3 GeV/c neutrons, and it generally favoured neutrons of higher energy. The results for the different trigger conditions are given in Table 1b. The results show no change of the total cross-section down to neutron momenta of 4 GeV/c (see Table 1a).

The result for the main measurement for hydrogen with the full beam was 39.5 ± 0.5 mb. The total absorption spectrometer was not used here. No statistically significant change was found in the ratio $N_{\text{full}}/N_{\text{empty}}$ between the measurements with the different neutron converters. To prove this, a differential measurement was made with a small pencil-shaped (0.5×10.0 cm² area) scintillation counter with a 2 cm thick iron converter of the same shape in front of it. Within the statistical accuracy and the limitation of the reproducibility of the position of the counter, no significant contribution of small-angle scattered neutrons to the detected neutrons could be found.

For the elements of Group II, the total cross-section was determined from the slope of the absorption line in a logarithmic plot. Again, the correction for small-angle scattering was negligible due to the good geometry.

The targets of Group III finally showed two effects which were not noticed for any of the others. For larger converters, the ratio $N_{\text{with}}/N_{\text{without}}$ increased in proportion corresponding to a scattering and probably a production of secondary neutrons. The absorption line in the logarithmic plot showed two distinctly different slopes corresponding to two different cross-sections. The kink in the slope appeared at about $1/10$ absorption length. Both effects increased with the atomic weight of the target, being strongest in Pb.

The measurements with the three smallest converters, and points collected with the above-mentioned pencil-counter, were used to extrapolate linearly to converter-size zero. The values thus obtained for the different

target thicknesses gave a straight line in the logarithmic plot. From this slope the total cross-section was derived.

The cross-sections for the different elements are plotted versus A in a logarithmic scale in Fig. 3. Empirically, a relation

$$\sigma_{\text{tot}} = 49.6 A^{0.8} \text{ mb}$$

was fitted for $A \geq 6$.

Comparing the hitherto known nucleon-nucleon total cross-sections (Fig. 2), one notices that around 25 GeV/c the (pp) and (np) cross-sections agree. However, the (pn) cross-sections inferred from the (pd) scattering increases with decreasing momentum, and they seem to lie systematically higher than the (pp) data. On the other hand, the directly measured (np) cross-sections of Kreisler et al. show a tendency to decrease with decreasing momentum, and they are consistently lower than the (pp) results. However, the (np) total cross-section, which has been measured with high precision at 10 GeV/c in this work, agrees excellently with the (pp) data. Also, no energy dependence was found within the error limits. We consider our results as a strong indication that the (pp) and (np) total cross-sections do not differ in this energy range.

The results for the total cross-sections of neutrons on nuclei at an average energy of 10 GeV are systematically higher than those reported previously at 27 GeV/c. Our results are, however, in very good agreement with the results for proton-nucleus scattering (see Table 2).

We appreciate the constant interest and support of Professors G. Cocconi and P. Preiswerk. We would like to thank the PS running staff, and especially Dr. J. Geibel, for their help. Mr. H. Keim and Mr. K. Ratz have contributed much to the success of the experiment by their diligence and enthusiasm. This work was supported by the Bundesministerium für wissenschaftliche Forschung.

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Table 1a

Relative (np) total cross-sections
as obtained with the low intensity beam and
different trigger conditions of the neutron detector

$$\Delta\sigma_T/\sigma_T (4.3 - 6.5 \text{ GeV/c}) = (1.8 \pm 3.5)\%$$

$$\Delta\sigma_T/\sigma_T (6.6 - 10.0 \text{ GeV/c}) = (4.0 \pm 6.0)\%$$

Table 1b

(np) total cross-sections as obtained
with the low intensity beam

Momentum [GeV/c]	σ_T [mb]
4.3	40.4 ± 1.9
6.5	38.6 ± 1.4

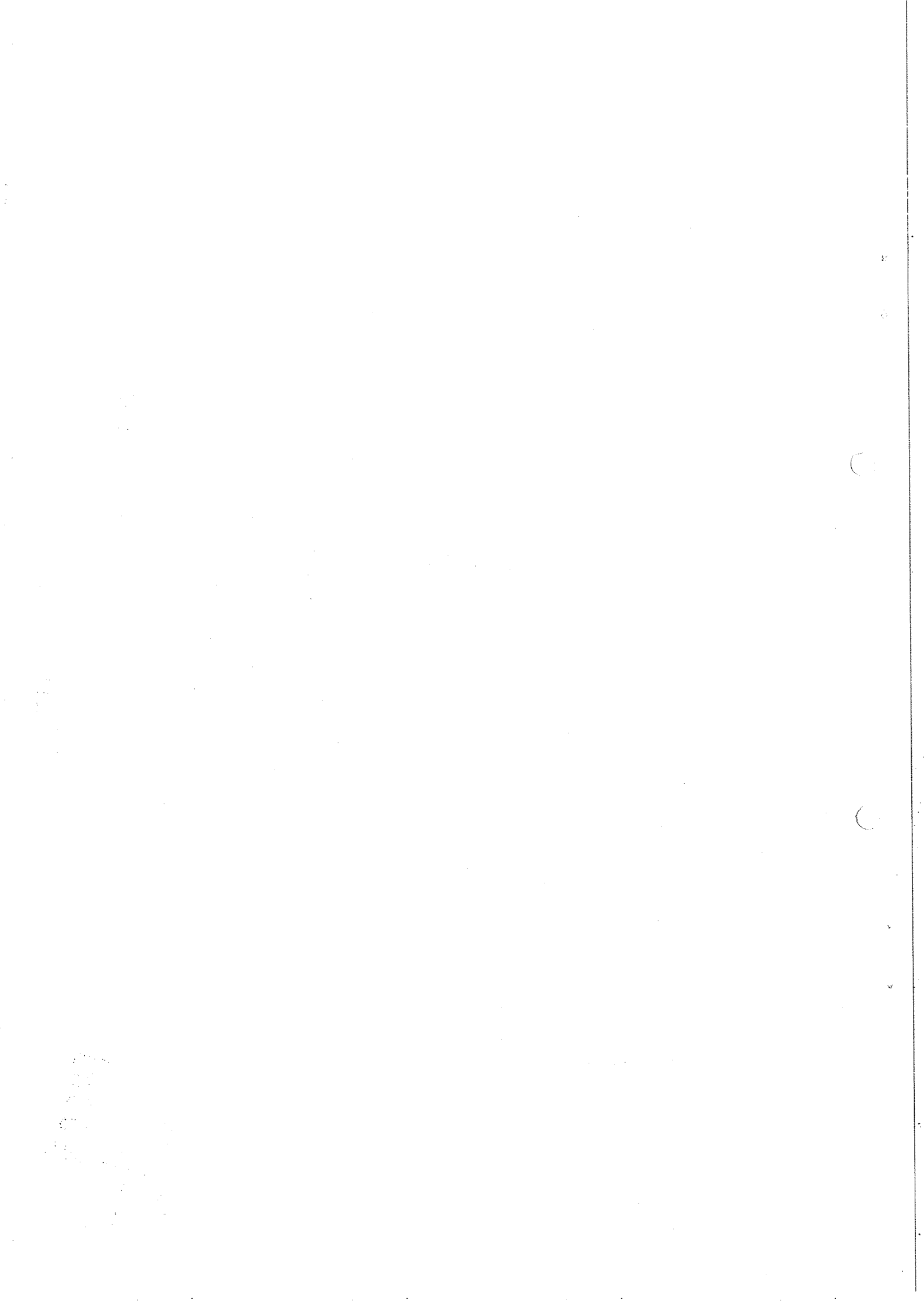
Table 2

Total cross-sections for nuclei

Nucleus	A	σ_T [mb] 10 GeV/c neutrons [this experiment]	σ_T [mb] 27 GeV/c neutrons [Jones et al. ¹²⁾]	σ_T [mb] 20 GeV/c protons [Bellettini et al. ¹³⁾]	σ_T [mb] 10 GeV/c protons [Galbraith et al. ⁴⁾]
H	1	39.5 ± 0.5	38.9 ± 0.6	38.9 ± 0.3	39.9 ± 0.6
D	2	73.3 ± 1.1	69.7 ± 0.7	74.1 ± 0.7	75.8 ± 1.3
He	4	141 ± 6	-	-	-
Li	7	237 ± 7	-	250 ± 5	-
Be	9	271 ± 6	255 ± 5	278 ± 4	-
C	12	340 ± 3	308 ± 6	335 ± 5	-
Al	26.9	683 ± 3	585 ± 10	687 ± 10	-
Fe	55.8	1204 ± 8	1060 ± 20	-	-
Cu	63.5	1344 ± 9	1135 ± 22	1360 ± 20	-
Pb	207.2	3245 ± 13	2800 ± 100	3290 ± 100	-

Figure captions

- Fig. 1 : Layout of the experimental arrangement at the CERN Proton Synchrotron. The distances from PS internal Be target are given in square brackets below the beam line.
- Fig. 2 : (pp) and (np) total cross-sections at various incident momenta. The dashed line was fitted to (pn) cross-sections calculated from (pd) data taken from Ref. 4. The solid line shows the results from (pp) measurements as taken from Ref. 5. The accuracy of these data is represented by some typical errors. All other points are taken from direct (np) measurements.
- Fig. 3 : Total cross-sections σ_T for neutrons on various nuclei. The curve $\sigma_T \sim A^{2/3}$ is taken from a simple optical model.



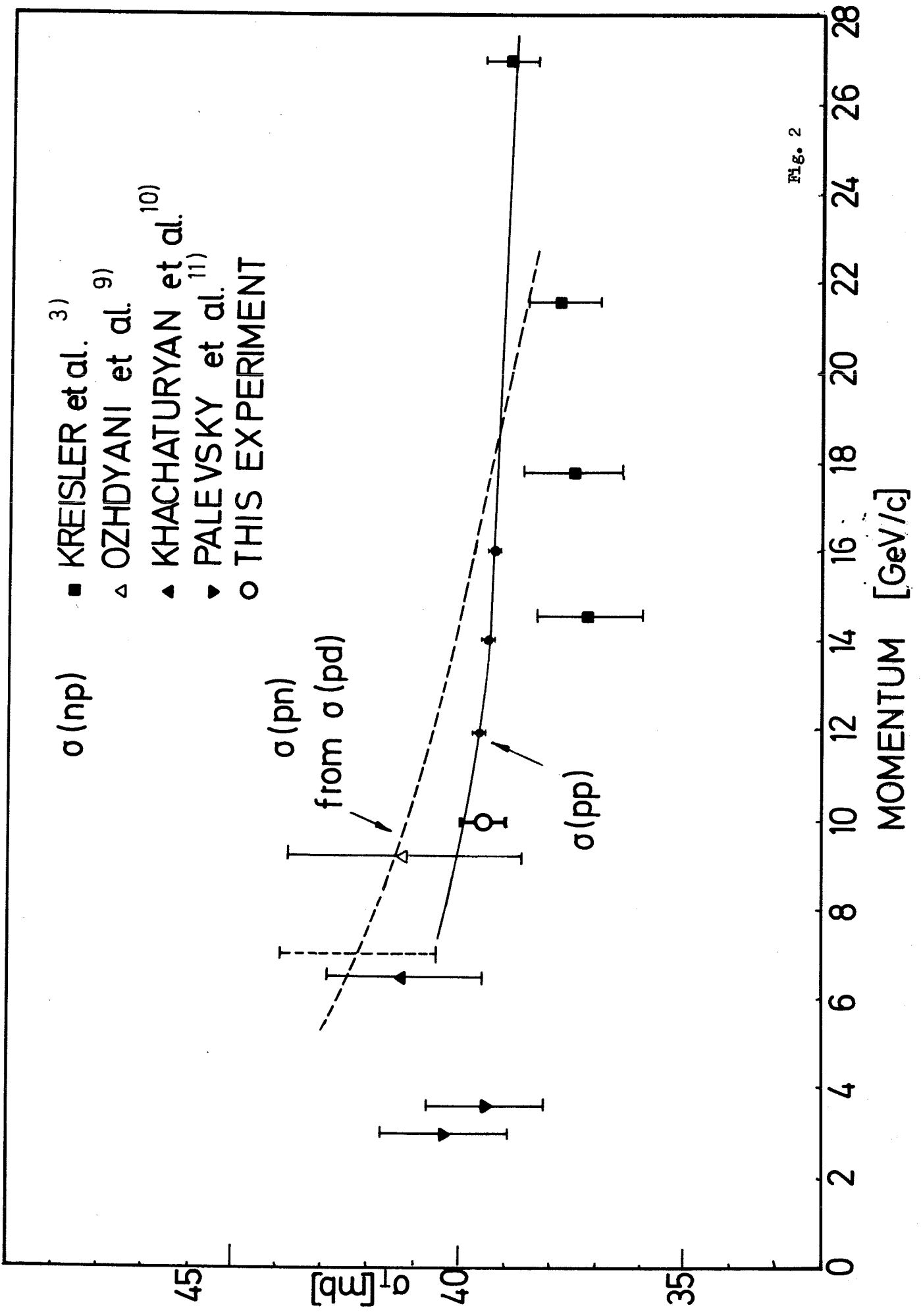
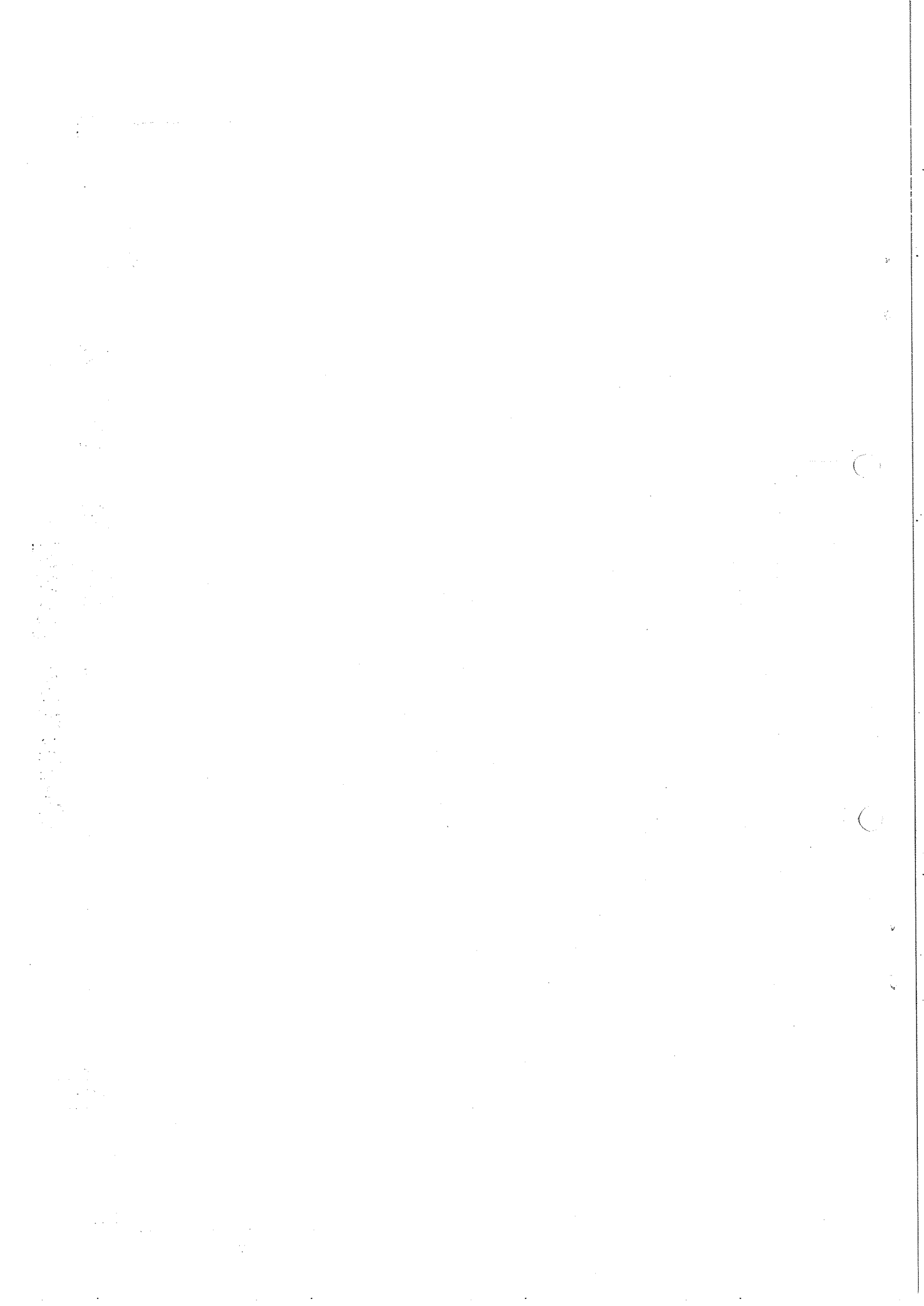


Fig. 2



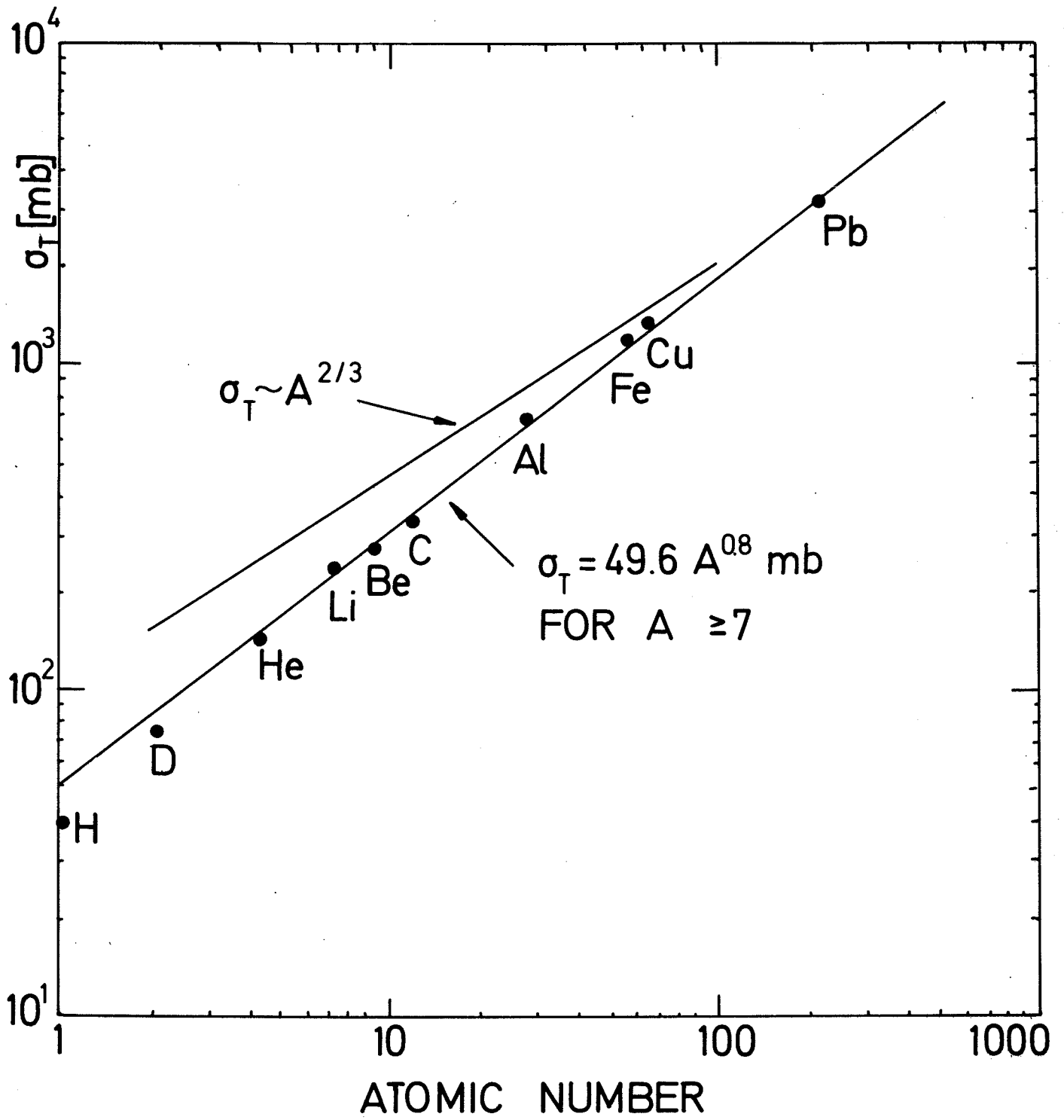


Fig. 3

