KERNFORSCHUNGSZENTRUM

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High Resolution Total Fast Neutron Cross Sections on Some Non-Fissible Nuclei in the Energy Range $0.5 \leqslant E_n \leqslant 30$ MeV

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The spectrometer at the Karlsruhe isochronous cyclotron has been used to measure fast neutron total cross sections of a number of nuclides ranging from C to Bi. Bursts of 45 MeV (average energy) deuterons of ~ 1 nsec duration striking a thick natural uranium target yield a broad neutron spectrum, capable to obtain useful neutron data between about 0,5 - 30 MeV. Neutrons were analysed by time-of-flight. The analysis system includes a 57 m flight path, a 9 cm diameter x 1 cm thick NE-213 liquid scintillator in connection with a zero-cross over tunnel diode time-mark circuit and a digital time analyzer coupled with a CDC-3100 on-line computer as the time recording system. The overall resolution in the present experiments was $\leq 0,03$ ns/m. The high neutron intensity from the cyclotron permits rapid data accumulation. Typically 1 % statistical accuracy was obtained in most of the 16000 data points in a 10 - 12 h running time.

In the energy dependent cross section significant fluctuations have been observed up to several MeV. In the light elements C, Q, Al, Na, S fluctuations outside the statistical uncertainty range up to 10 MeV or more, for the elements Ca and Fe fluctuations up to 6 - 8 MeV and for Bi and Tl up to 3 - 4 MeV were found. In order to investigate the effects of fluctuations a statistical analysis was performed in some cases.

1. Introduction

The objective of the study on high resolution cross-section is the acquisition of a systematic experimental knowledge and the approach of physical understanding of fast neutron scattering phenomena. One of the impulses of such measurements was given from fast reactor design requests and from shielding requirements. On the other hand, studies are chiefly maintained in order to provide a basic physical understanding to allow accurate predictions on unknown data by application of suitable semiempirical non-sophisticated models.

The extremely complicated structure of intermediate and heavy weight nuclei in the fast neutron region is a serious problem to the reactor and nuclear physicist. A microscopic resonance analysis of the resonance structure also in the region of non-overlapping levels if at all will be possible only in the lowest energy range covered by the present data. Therefore other physical interpretations leading to structure information and providing descriptions useful for applied calculations are necessary: useful physical approaches seem to be the concept of intermediate structure in the sense of Ericson1) or of Block and Feshbach.2) In the concept of Block and Feshbach the intermediate configurations represent short lived two-particle, one-hole configurations or more complex 'doorway state' configurations, which should appear as broad peaks in the excitation functions. According to Ericson fluctuations should be present also in the region of strongly overlapping levels as a consequence of the random phase approximation. Other useful concepts are the descriptions of cross-sections by average quantities such as the average spacings and average widths of compound nuclear levels.

In section 2 of this paper the high resolution time-of-flight spectrometer employed in this work and some experimental results are described, while in section 3 the analysis and comparisons with calculations based on statistical arguments and compound nuclear theory are outlined.

2. Experiments and results

The experimental procedure required high resolution and sensivity since all physically meaningful structure should be observed. On the other hand, the measurements required methods capable of the acquisition and processing of a large amount of experimental information Such requirements are essentially satisfied now by the existing time-of-flight spectrometer and the CDC-3100 on-line data acquisition system at the cyclotron and the extended data processing system of the IBM 7074 computer. The cyclotron provided with a particular 'deflection bunching' system described elsewhere[3)] was used to produce short (~ 1 nsec) intense bursts of neutrons with 20 kc/s repetition rate and a broad neutron spectrum. Neutron production was achieved by (d, nx) reactions in thick natural uranium targets by bombardment with 45 MeV deuterons from the internal beam. By timing of the neutrons over a 57 m flight path a resolution of $\leq 0,03$ nsec/m was obtained. Time-of-flight assignments were made with a digital time-sorter (LABEN UC-KB). Typically 2 x 8000 time channels of 1 nsec channel width were used. The presently used on-line program allows several automatical operations during the measurement (spectrum compatibilisation, dead time observation, etc.) and exerts a great deal of on-line-control of the overall-reliability of the time-of-flight apparatus. Unfortunately, however, the maximum input rate of 10^4 c/sec limits the rapid data accumulation at present.

Because of the limited memory capacity of the CDC-3100 the input data are preaccumulated in the memory separately for both sample positions. After each cycle for 'sample in' and 'open beam' position, for which typically a total period of 5 - 8 min was chosen, the information is stored on magnetic tape. Accumulation of the entire information belonging to the same run is accomplished after the measurements.

Total neutron cross-sections of 9 elements, C, O, Na, Al, S, Ca, Fe, Bi and Tl were measured at increasing energy intervals from about 0,5 - 30 MeV.

In figures 1 - 5 total neutron cross-sections on C, Na and S are shown in different subintervals. The energy resolution is believed to be 2 channels at all energies. The statistical uncertainties in most of the data-points are between 1 - 3 %. Absolute uncertainties are less than 3 %. The data had been compared with selected published data (not shown) from various laboratories 5)-10). In general, the agreement with published work is good. In several energy regions the data exhibit more structure than was observed in the earlier measurements. The differences in structure can be attributed mainly to the difference in energy resolutions. If our curves are smoothed by using average intervals equivalent to the energy resolution of the previous measurements, the remaining structure agrees with that observed in other laboratories, There are, however, still some discrepancies: Comparing (e. g.) the data on C in the energy region around 2.8 MeV (fig. 1) with data reported by Willard et. al. 11), there is a discrepancy concerning the sharp resonance of ~ 5 keV (f. w. h. m.) observed in our measurements. This resonance could not be observed by Willard, Bair and Cohn in a 5 keV resolution measurement. We have been unable to identify any error in our data which could be responsible for this disagreement. But the level at 2,817 MeV was observed also in the C^{12} (d, p) C^{13} reaction 12). So we believe that this is the same resonance as we found in our total neutron cross section measurement.

The sodium data (figures 2 to 4) can be compared mainly with the recent measurements of Langsford et al. 13) which, however, shows poorer statistical accuracy than our data. The average cross-sections agree well with these measurements. Over a wide energy range we observed more structure which fact can be attributed to our higher energy resolution. Above 6 MeV we do not agree at all with the details of structure even if the different energy spreads are taken into account. But in this range the Hanford data are in good agreement with our and other data 14).

Similar arguments -i.e. good agreement with other published data 15) 16) was found for comparable energy spreads-applies for the sulfur results.

These data are an example for what happens in the MeV region of intermediate weight nuclei. While in the lowest energy region the rapid fluctuations are due to individual levels, these levels start overlapping more and more at increasing energies. At about several MeV the average widths become comparable to the average spacings and finally we enter the region of Ericson fluctuations where $\Gamma_J/D_{J\pi} \gg 1$. It is this situation where the arguments mentioned earlier i. e. the need of interpretation leading to structure information and the need of providing descriptions useful for applied calculations, become meaningful.

3. Analysis and discussion

Causes of fluctuations which were considered are mainly intermediate structure. Additionally Ericson fluctuations and fluctuations of neutron widths and spacings of compound nuclear levels have been included in some cases.

In order to investigate whether a broad structure is present in addition to the fine structure the analysis proposed by Pappalardo17) was performed for Al, Na, S, Ca and Fe in the energy regions in which fluctuations were observed. This occured mostly in the region between 0,8 - 8 MeV. For each element the analysis was performed separately for four quarters of the total range. The correlations functions $C(0, \delta)$ i. e. unnormalized variance for Al are shown in fig. 6. The subintervalls over which the data were taken are from 0,8 - 2, 2 - 4, 4 - 6 and 6 - 8 MeV respectively. The error bars are deduced from the finite number of fluctuations.

The presence of a second rise in the variance curves is taken as an evidence that a broader structure exists. From the curves in fig. 6 such a structure must be assumed for aluminium at least in the two lower energy subintervalls. Similar results were obtained for the other elements in some energy regions. To conclude anything about the nature of the structure from these results it is necessary to go into more details. It has been shown by some authors18) that intermediate structure can also be explained in terms of statistical fluctuations in the parameters that describe compound nuclear levels, i.e.

such structure must not necessarily be interpreted as doorwaystate structure. We have also considered the possibility of such an interpretation which was done by an analysis similar to the theory of Agodi et al.[19) Assuming various conventional distributions for level spacings and level widths this theory yields values for the number of levels of given spin and parity that can exist in an average interval and still give rise to the observed intermediate structure. In several cases it is difficult to justify the discrepancy between the number of levels found and the number of levels that would be necessary to explain the observed intermediate structure in terms of level statistics. Although somewhat tenuous, this arguments suggest that the broader structure involves the type associated with doorway states. Further evidence for this interpretation comes from a rough calculation of average level distances for two particle, one-hole states from the shell modell which have been made in the cases of Al, Ca and Fe and which gave order of magnitude agreement with the experiment. We would, however, point out that the energy dependence of average distances is in qualitative disagreement. While from the calculation a decrease of the level distances is predicted, the average distances of the broader maxima in the cross section curves seem to increase with increasing energies.

The analysis applied in this work also provides values for the auto-correlations functions which are used in the theory of Ericson fluctuations. This enables us to deduce level densities and average level widths if the condition $\Gamma_I/D_{J\pi} \gg 1$ is fulfilled. There is, however, some doubt that this condition holds, especially for the lighter nuclei, even at higher energies.

Nevertheless it was proved that in various subintervalls the calculated curves follow the theoretical dependence of $C(I,\delta)$ on δ if the average is taken over the fine structure only. The values obtained for level spacings and level widths are largely in agreement with other reported values[10).

Finally, it should be mentioned that a statistical analysis provides a method to deduce level densities applying the theory of Agodi and Pappalardo[19]. The first results which have been obtained till now are consistent with available estimates of level densities. In the regions of non-strongly overlapping levels it is this method from which most reliable results can be expected.

Summarising this paper it can be stated: In general individual quantities of compound nuclear levels can not be observed in MeV neutron experiments except for the lightest nuclei or at lowest energies for some medium weight nuclei. Mainly average quantities can be deduced from high resolution measurements the more accurately the more all physically meaningful structure has been observed. But these quantities will be most important for applied calculations. For reactor requirements it is especially the broader structure in the cross section curves which may not be at all negligible. Therefore a better understanding of intermediate structure phenomena may be of great importance. Valuable additional information can be obtained from partial cross-section measurements. Therefore we try an attack also on this kind of experiments at present.

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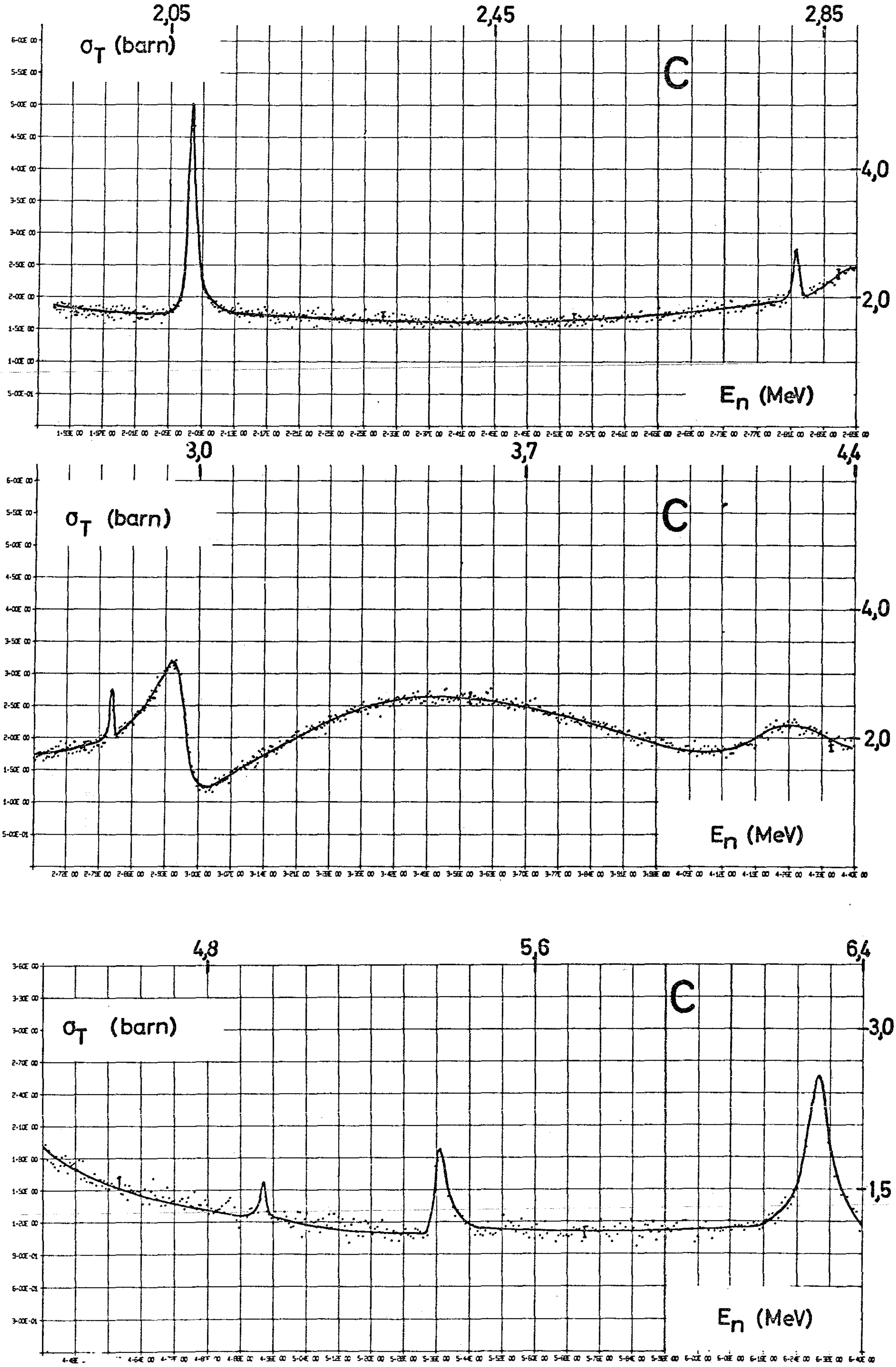

Fig.1 Total neutron cross-section of carbon

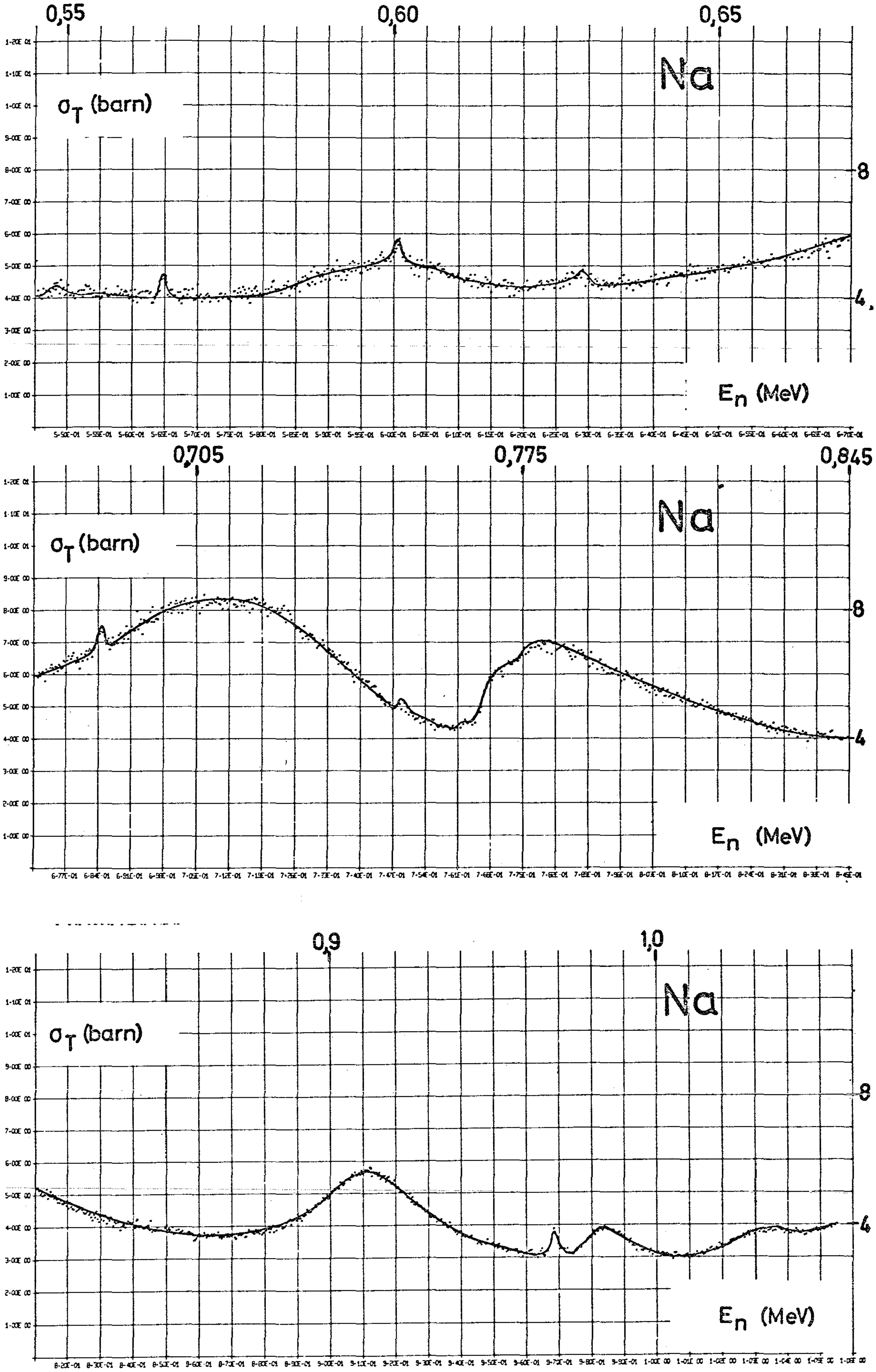

Fig.2 Total neutron cross-section of sodium

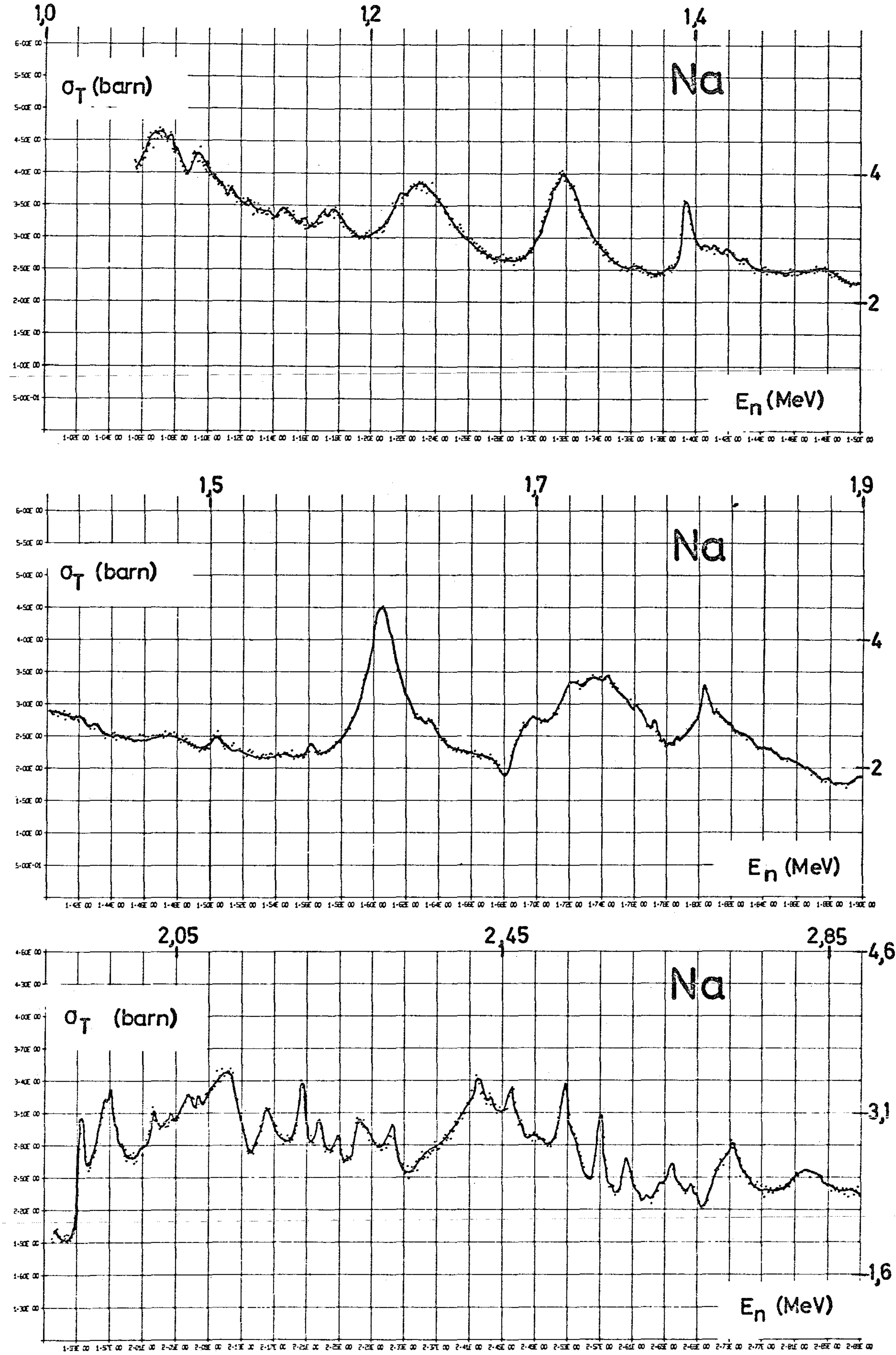

Fig.3 Total neutron cross-section of sodium

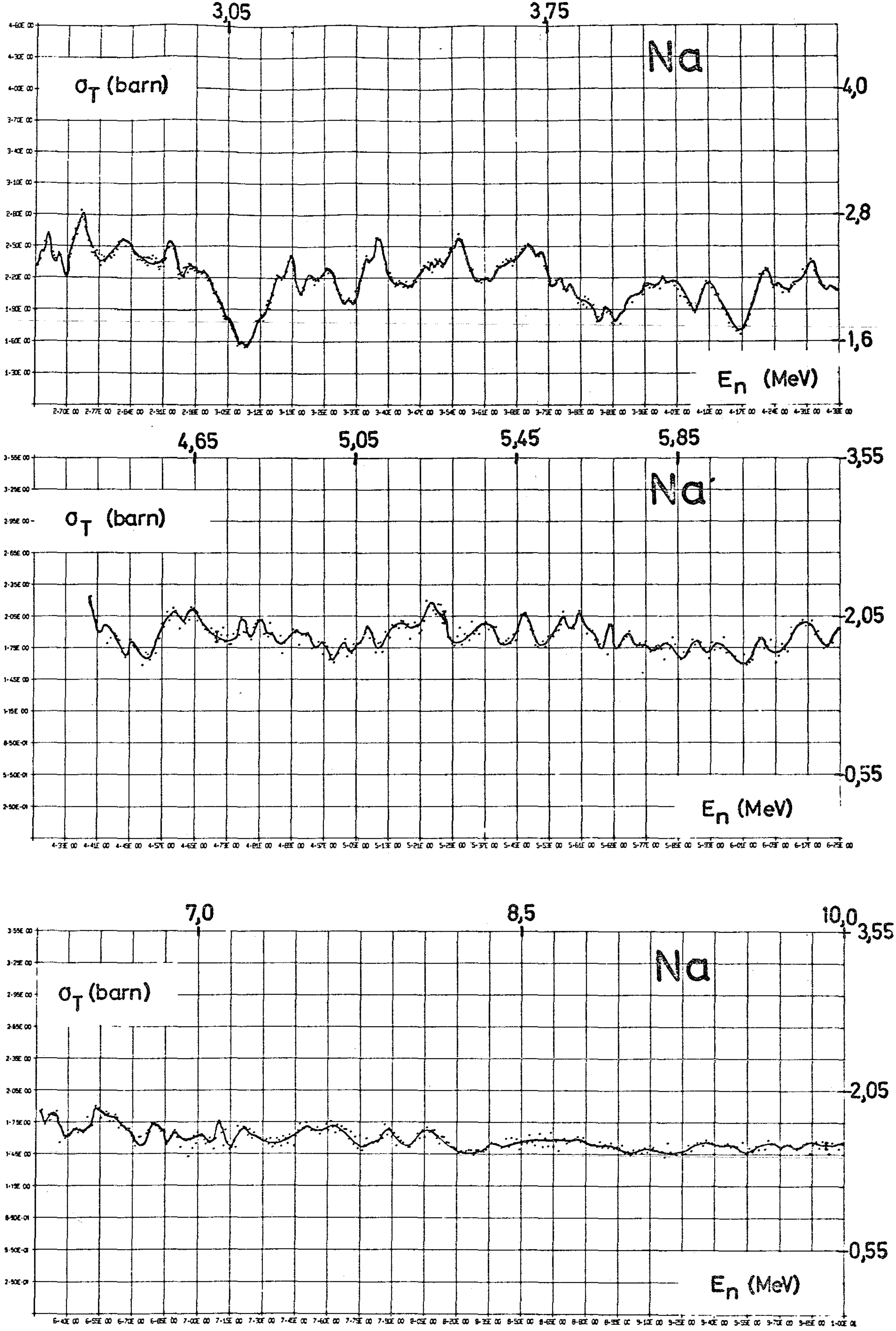

Fig.4 Total neutron cross-section of sodium

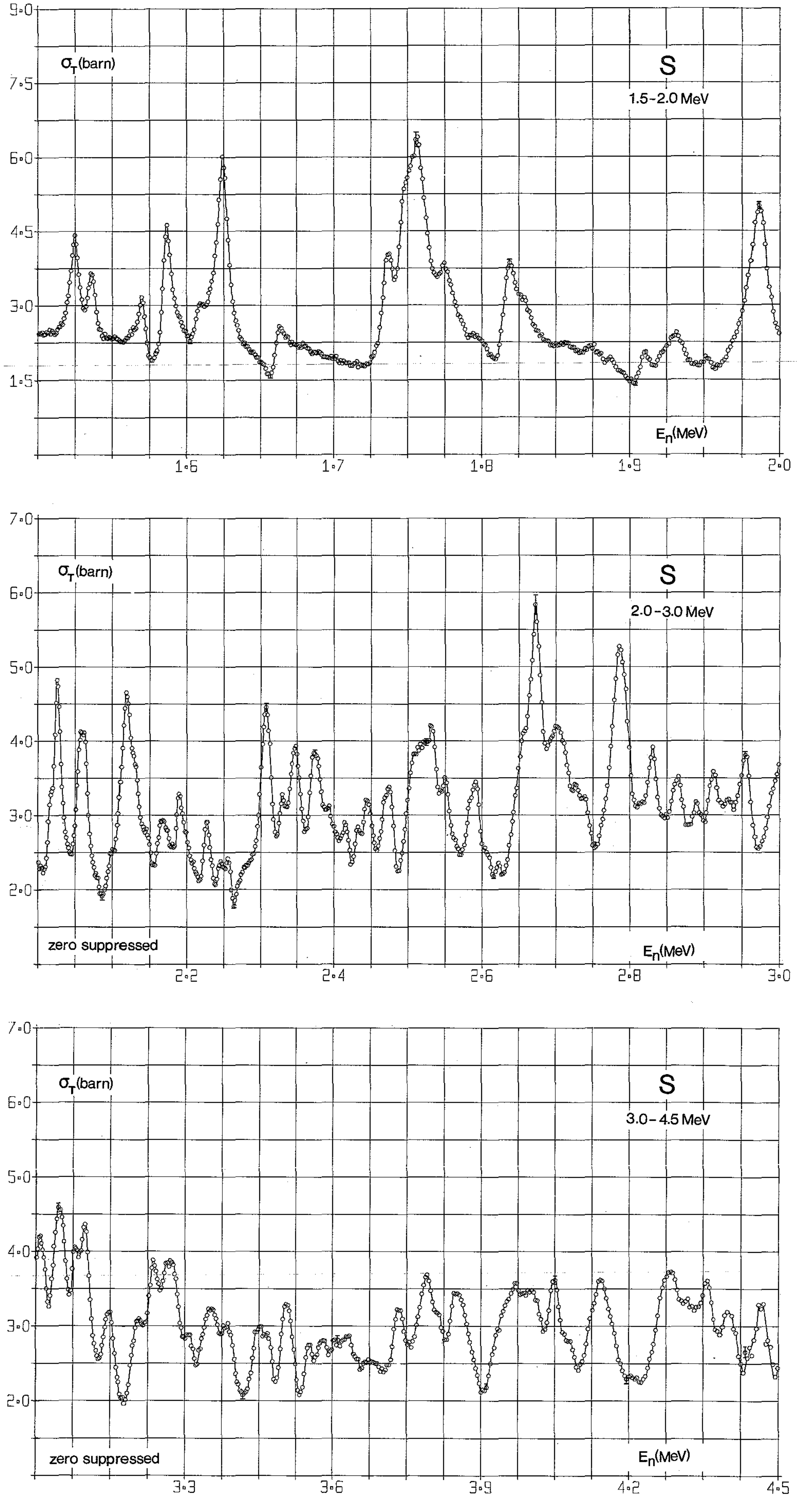

Fig.5 Total neutron cross-section of sulfur

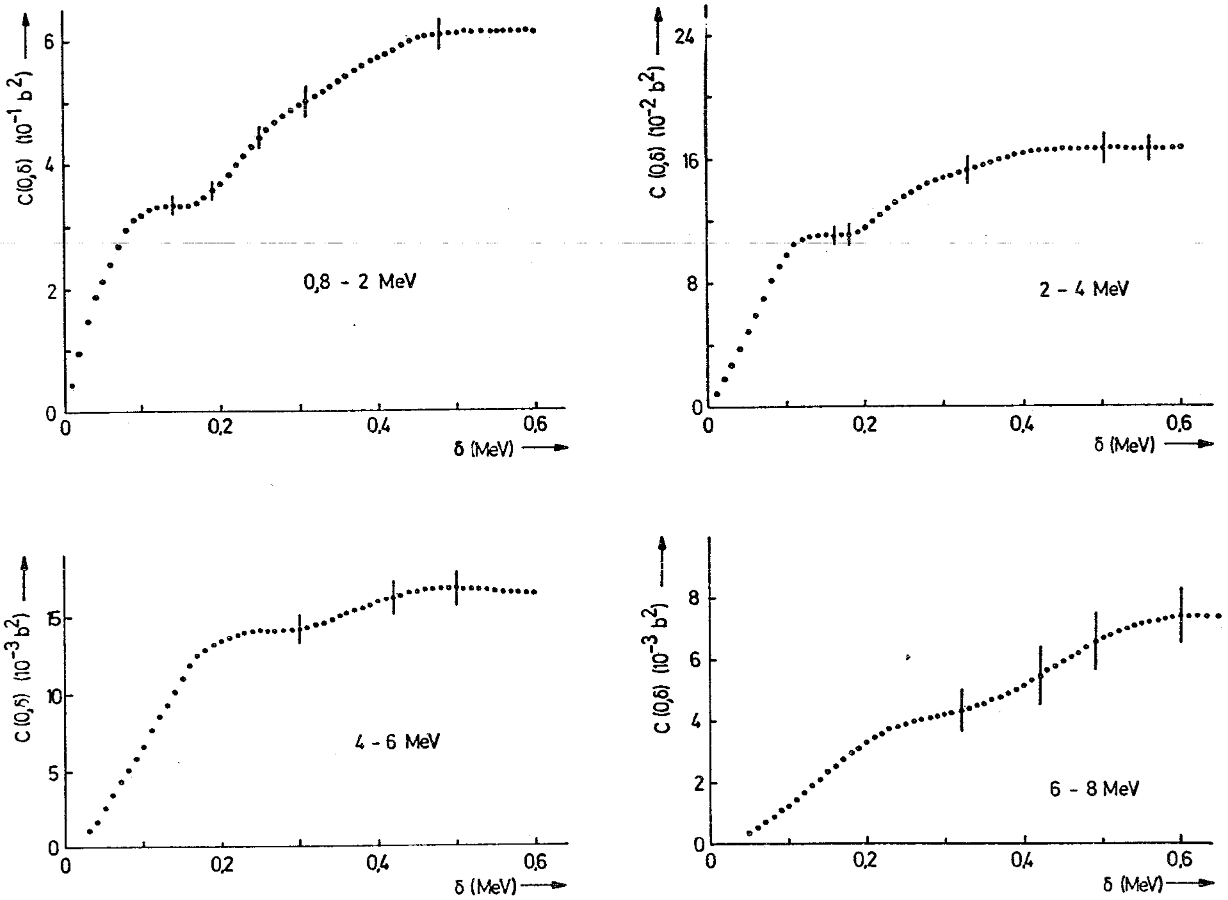

Fig.6 Self-correlation functions for the Al data