KERNFORSCHUNGSZENTRUM

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Institut für Angewandte Kernphysik

New Total Neutron Cross Section Measurement
of Uranium between 0.5 - 4.35 MeV

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New Total Neutron Cross Section Measurement of Uranium between 0.5 - 4.35 MeV

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Abstract

The total neutron cross section of natural uranium was measured with the neutron time-of-flight facility at the Karlsruhe Isochronous Cyclotron (KIC). The measurement covers the energy range between 0.5 and 4.35 MeV with a resolution of 0.03 ns/m; this corresponds to an energy resolution between 290 eV at 0.5 MeV and 7.4 keV at 4.35 MeV. In the energy region 1.1 - 4.35 MeV the statistical error was between 1 % and 0.5 %, below 1.1 MeV the error increases up to 2.7 % at 0.5 MeV. An extensive comparison with new available data is given. The existence of fluctuations in the cross section in the lower energy range is investigated.

Zusammenfassung

Der totale Neutronenwirkungsquerschnitt von natürlichem Uran wurde mit dem Flugzeitspektrometer am Karlsruher Isochron-Zyklotron gemessen. Die Messung wurde im Energiebereich zwischen 0.5 und 4.35 MeV mit einer Auflösung von 0.03 ns/m durchgeführt. Dies entspricht einer Energieauflösung von 290 eV bei 0.5 MeV und von 7.4 keV bei 4.35 MeV. Im Energiebereich von 1.1 bis 4.35 MeV liegt der statistische Fehler der Messung zwischen 1 % und 0.5 %; unterhalb von 1.1 MeV steigt dieser Wert bis auf 2.7 % bei 0.5 MeV an. Es wird ein ausführlicher Vergleich mit anderen Daten durchgeführt. Das Auftreten von Fluktuationen im Wirkungsquerschnittsverlauf bei niedrigen Energien wird diskutiert.

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NEW TOTAL NEUTRON CROSS SECTION MEASUREMENT OF URANIUM BETWEEN 0.5 - 4.35 MeV

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1. INTRODUCTION

For the design of fast reactor assemblies, high resolution total cross sections of medium weight and heavy nuclei, mainly in the keV and MeV region, are needed. These cross section measurements should have considerably less than 5 % uncertainty in order to be useful for reactor calculations. In addition, the resolution should be high enough to allow reproduction of the actual cross section in satisfactory detail.

The knowledge of the fast neutron total cross section for uranium has been improved by extensive experimental work during the last years [1 - 8]. Nevertheless, there remain some discrepancies in the absolute values, mainly in the energy region below 650 keV, and in the question of the existence of significant cross section fluctuations.

Because of these discrepancies, the evaluated accuracy of the recommended σ_T values has been rather low; i.e. ± 10 % between 100 - 700 keV, ± 6 % between .7 and 2 MeV and ± 4 - 5 % from 2 - 10 MeV [9].

The purpose of this work was to perform a high resolution total cross section measurement on natural uranium with good statistics. In section 2 of this paper a brief review of the experimental setup is given. In section 3 our results and comparisons with other available data are shown and discussed. Finally the question of fluctuations in the cross section is considered.

2. EXPERIMENTAL DESCRIPTION

The measurement was performed with the neutron time-of-flight facility at the Karlsruhe isochronous cyclotron using a flight path of 187.5 m /10/. The neutron beam was collimated at 1 m, 10 m and 37 m from the source to about 2 x 10^{-6} sr. The sample, natural uranium with thickness 0.09542 at/barn, was positioned 1.50 m from the source. Normalization difficulties for sample-in and sample-out measurements were eliminated by alternating the sample in and out of the beam on a 250 sec cycle. The effects of sample impurities were ascertained to contribute less than 3 ‰ uncertainty to the cross section. Neutrons were detected by a 25 cm dia., 1 cm thick proton recoil scintillator, NE 102A, viewed simultaneously by two XP-1040 phototubes. The average counting rate for the detector was ~0.4 neutrons per machine burst when the sample was out of the beam. The measurement spans the energy region 0.5 to 4.35 MeV in a total time-of-flight interval of ~16 μsec with 1 ns channel width. Up to three counts per machine burst could be accepted by the time analyzer and data acquisition system. Corrections for dead-time losses were performed in the data reduction computer code.

The overall time resolution obtained in this measurement was 5.48 nsec. This resolution of 0.029 ns/m corresponds to an energy resolution of ~ 290 eV at 0.5 MeV and 7.44 keV at 4.35 MeV. Since the measurement was performed with 1 ns channel width, a 4 channel compression could be applied after the measurement to improve the counting statistics, keeping a high resolution. The resolution width in the final reduced data corresponds to 1.37 times the point spacing. The statistical uncertainty lies between 0.45 % at 4.35 MeV and 2.58 % at 0.5 MeV.

3. RESULTS AND COMPARISON

Since more than 3000 data points were obtained in this measurement, a partition into several subintervals has been chosen for clearness of presentation. In Figs. 1 - 5 our data are presented together with the data from other authors [1 - 8] available from CCDN, Saclay. As an insert in each drawing the symbols used for the different authors are given.

In Fig. 1 and Fig. 2, in the energy range 0.5 to 0.6 MeV and 0.6 to 0.7 MeV, respectively the data are illustrated on an elongated energy scale. In these two figures our data points are connected by straight lines. In this region the energy resolution was ~ 0.29 keV at 0.5 MeV and ~ 0.48 keV at 0.7 MeV, respectively. The lines between the data points are definitely not intended to represent meaningful physical structure in all cases. They have been drawn to allow the viewer to appreciate the existence of some real structure. To give an impression of the statistical accuracy, the error bars are shown every 10 keV. The existence of real structure is discussed in detail in the next section. In the energy range 0.5 - 0.55 MeV, our data are compared with the results from Henkel et al. [2], Seth et al. [4], Uttley et al. [6] and the more recent and very extensive work performed by Whalen et al. [8]. Only one data point from Henkel et al. was available. These authors performed their measurement in 1954 with the Electrostatic Accelerator at Los Alamos using the $T(p,n)He^3$ reaction as a neutron source in the energy range 160 keV to 3.8 MeV. The energy resolution obtained in this region was within 20 - 40 keV; the statistical error ~ 200 mb. The agreement of this data point at 0.545 MeV with our measurement is satisfying. Also Uttley et al. measured only at one energy in this region. These authors performed a time-of-flight measurement at the Harwell booster pulsed neutron source in 1966 with an energy resolution of ~ 50 keV for energies higher than 0.5 MeV. This data point also agrees with our measurement within the statistical error. The cross section data from Seth et al. do not agree with our results; these data are ~ 15 % lower than ours. The measurement was performed in 1964 in the energy range 30 to 650 keV with a resolution of 5 to 10 keV and a statistical error of ~ 200 mb. As previously shown by Schmidt [9], these data also do not agree with the earlier recommended cross sections. In addition the p-wave strength function deduced from this measurement is much lower than that derived by Uttley et al.. The recent results from Whalen et al. performed at ANL in 1969 with a statistical error of 140 mb agree quite well with our results within the quoted errors. Also the suggestion of meaningful physical structure is present. We could not find any specific reference to this data but we assume that this measurement had been performed under conditions similar to the other total cross section measurements carried out at ANL, i.e. with an energy resolution of 1.5 - 2.5 keV. In the energy range 0.55 - 0.6 MeV only data from Seth and Whalen were available. Here the situation is similar to the energy region 0.50 - 0.55 MeV.

In the upper part of Fig. 2, one value from Uttley, 11 values from Seth and 25 values from Whalen were available for comparison. There is still disagreement between Seth's values and ours while the agreement with the other values is excellent. In the region 0.65 - 0.70 MeV only a comparison between the Whalen data and the present results is possible because Seth's values run out at 0.65 MeV and only one value is given by Henkel.

Starting with the energy region 0.7 - 0.9 MeV in Fig. 3, the present results are no longer connected by straight lines but are given as open circles. In the higher energy regions, the evidence of fluctuations is not as significant as in the low energy part. Furthermore, the density of data points is higher due to a compression of the energy scale. In this energy range, an extensive comparison between Whalen's results and the present results is possible. In addition, two values from Henkel and two from Uttley are shown. Again the agreement between these measurements and the present work is good. Furthermore, some earlier results measured by Whalen et al. /5/ in 1965 are shown. The agreement between this measurement and the recent results from Whalen is good. In the energy region 0.9 - 1.2 MeV the most extensive results available are again those from Whalen /8/. In addition, some other results are presented /2, 5, 6/. In the the region 0.7 - 1.2 MeV the statistical error of our data lies between 140 mb and 60 mb, respectively.

Fig. 4 shows the energy range 1.2 - 2.0 MeV. From 1.2 - 1.5 MeV approximately 70 data points from Whalen [8] are presented for comparison. The measurement extends to an energy of 1.5 MeV. Due to an error on the CCDN data tape, data are not shown between 1.46 and 1.5 MeV. The agreement between Whalen's data and ours again is excellent. The error bars of our measurement in this energy range are equal to or less than the point size. Also the data from Henkel (3 points) and the earlier data from Whalen (15 points) agree quite well with our results. Between 1.5 and 2 MeV only values reported by Henkel and by Leroy et al. [3] were available. In 1963, Leroy et al. measured the cross section of natural uranium in the energy range 1.61 - 9.92 MeV using a 600 keV accelerator and the time-of-flight technique. In order to obtain a broad neutron spectrum the T-target was surrounded by an uranium sphere. The energy resolution between 2 and 4 MeV was ~ 60 to ~ 160 keV. The statistical error was ~ 250 mb for this region. The agreement between these results and ours is adequate up to 1.8 MeV. From 1.8 to 2 MeV their data are ~ 400 mb higher than our results while the agreement between Henkel's results and ours remains good.

In the last figure, data are presented in the energy range 2 - 4.5 MeV. In the upper part of this figure, our results are shown together with those from Henkel, Leroy and Foster et al. [7]. In 1967, Foster et al. performed their pulsed beam time-of-flight measurement on ^{238}U using a 2 MeV Van de Graaff. Their measurement spans an energy range 2.25 - 15 MeV with a resolution of 50 keV at 2.25 MeV and 115 keV at 4.5 MeV, respectively. The statistical precision quoted is between 200 mb and 80 mb in this region. The agreement between this measurement and the present results is good. The consistency between our data and the data from Leroy is not a severe test because of the large scatter of the latter data. Again the agreement between Henkel's data and ours is very good.

In the lower part of Fig. 5 data are shown from 3 MeV to 4.35 MeV. A comparison is given with the data from Henkel, Leroy, Nereson et al. [1] and Foster. The Foster data are the most extensive and recent data available for this comparison; only seven data points measured by Nereson et al. can be presented. The measurement performed by

Nereson et al. in 1953 at the Los Alamos Fast Reactor has an overall accuracy of better or equal than $\pm$ 10 % and was carried out with an energy resolution of ~ 300 keV. The consistency between the Foster data and our results is excellent. The data from Leroy agree well with our data with the exception of the last three points between 4.20 and 4.50 MeV. The data from Nereson are lower by about ~ 150 mb while the agreement between our data and those of Henkel is within the statistical accuracy.

4. DISCUSSION

The question of resolvable structure in the total cross section of uranium below 1 MeV is of considerable interest and has been approached with caution in this work. In order to address this problem quantitatively we have calculated the actual variance of the total cross section, i.e. the mean square deviation of single data points in reference to an average cross section. The averaging interval was such that the residual statistical error is vanishing but gross structure (~ 100 keV) remains. The average cross section was represented by a value obtained by smoothing the original data over an interval containing 100, 200, 300 or 400 data points. The average values obtained in this manner did not differ significantly for the four intervals.

The variance in four separate regions (0.50 - 0.55, 0.55 - 0.60, 0.60 - 0.65 and 0.65 - 0.70 MeV) was then compared to the variance based only on counting statistics, and the significance level of the ratio was investigated (F-test).

The statistical counting uncertainty used for this comparison properly includes the counting statistics of sample-in, sample-out and background measurements. We found that the variance is 2.7 times larger than that based on the statistical error for the energy range 0.50 to 0.55 MeV. This factor decreases smoothly to 1.6 for energies between 0.65 to 0.70 MeV. If, as we assume, the additional component of the actual variance is caused by significant cross section fluctuations of very narrow width, then the variation of the ratio quoted above is in accordance with our decreasing resolution with increasing energy.

The present measurement has a resolution of ~ 1.4 times the point spacing. Thus, only the question of counting statistics remained. The F-values of 2.7 and 1.6 correspond to a probability of $>$ 99,95 % and 99 %, respectively, that the hypothesis of significant fluctuations is correct.

In summary, the present results are in good agreement with other data with the exception of some older measurements. Our $\sim$ 3000 data points provide good definition for the uranium total cross section from 0.5 - 4.35 MeV. The analysis of fluctuations indicates meaningful physical structure in the energy range 0.5 - 0.7 MeV though these fluctuations show only small amplitudes.

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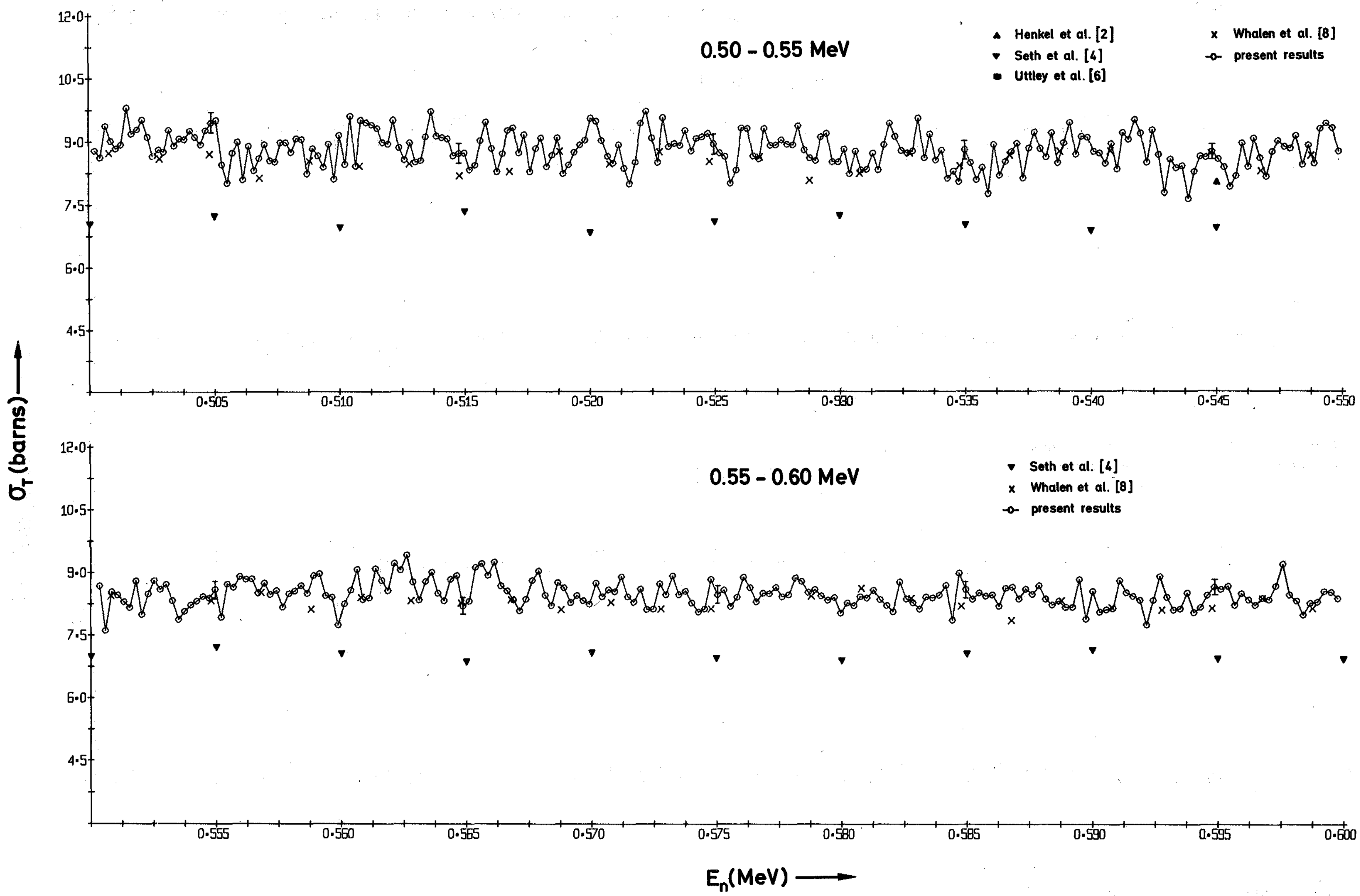

Fig.1 Neutron total cross section of uranium from 0.5 - 0.6 MeV

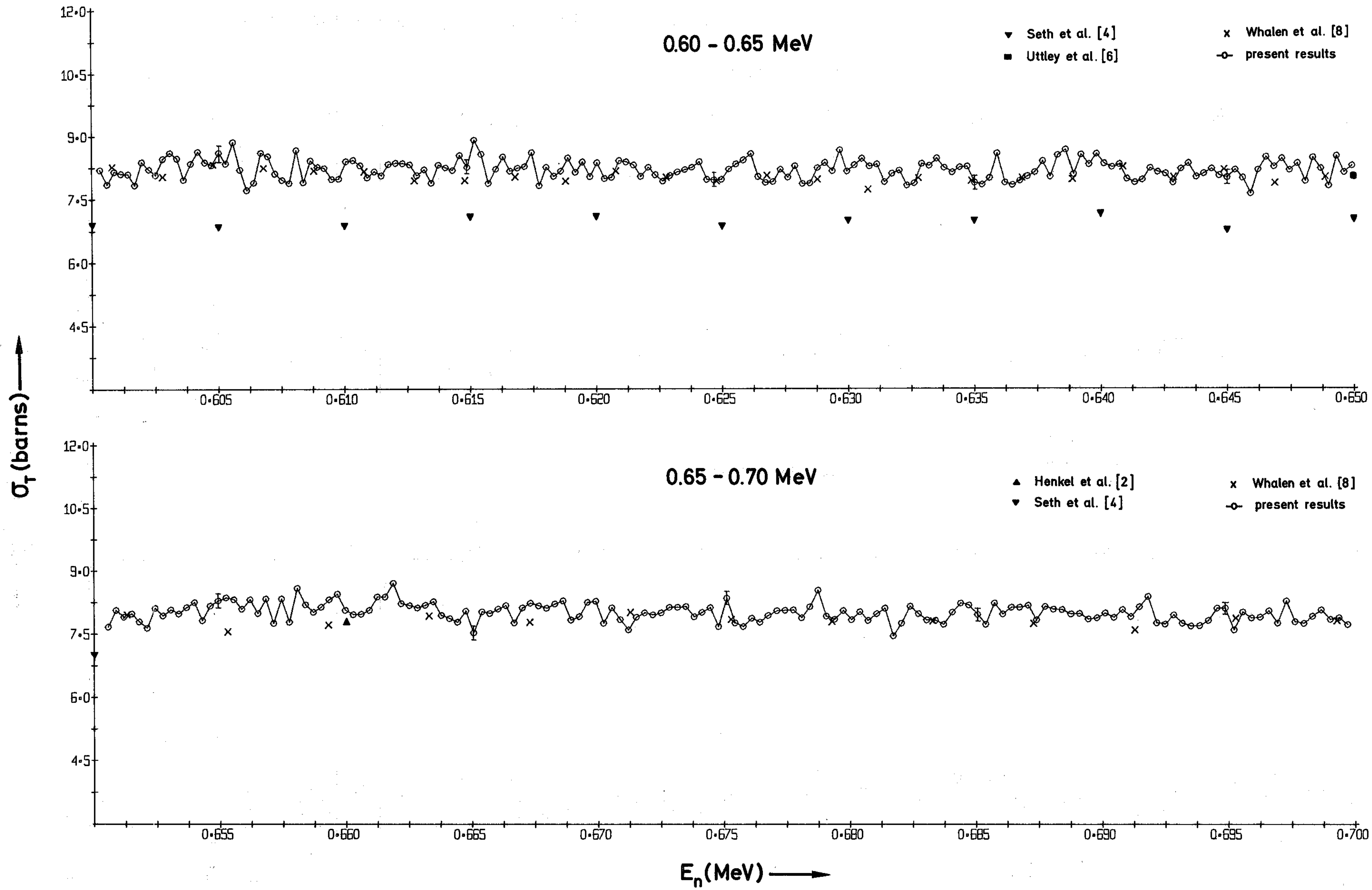

Fig. 2 Neutron total cross section of uranium from 0.6 – 0.7 MeV

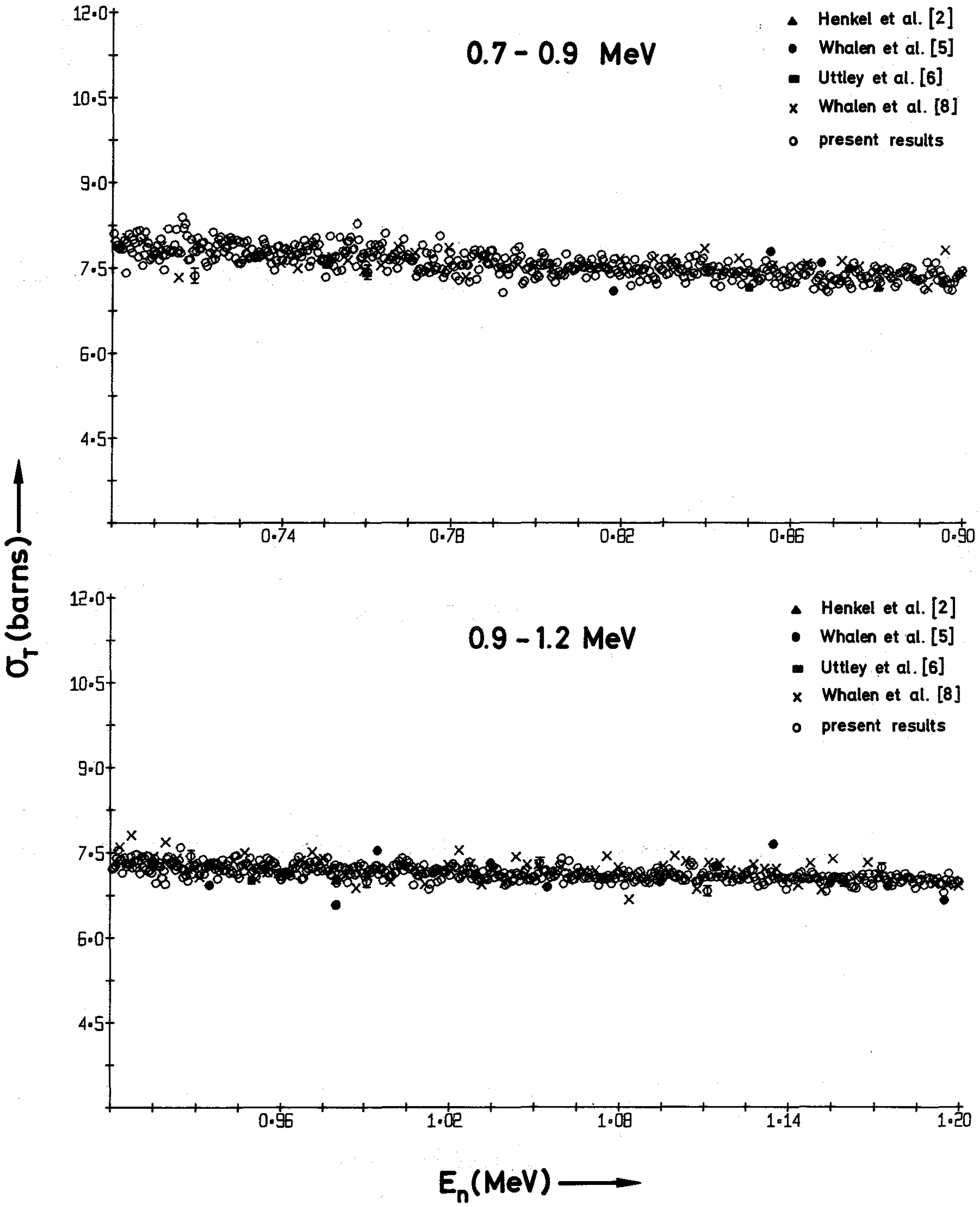

Fig.3 Neutron total cross section of uranium from 0.7 - 1.2 MeV

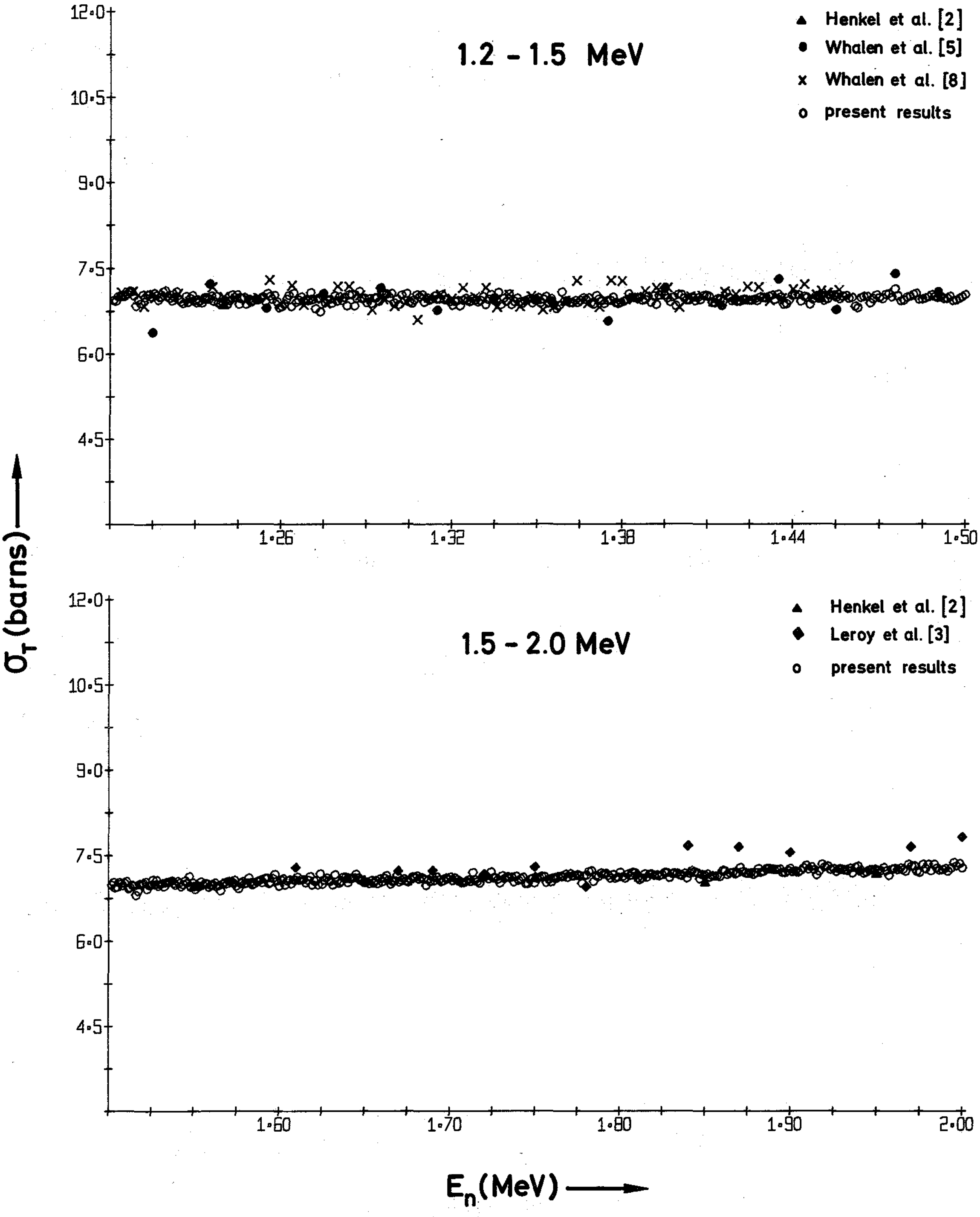

Fig.4 Neutron total cross section of uranium from 1.2 - 2.0 MeV

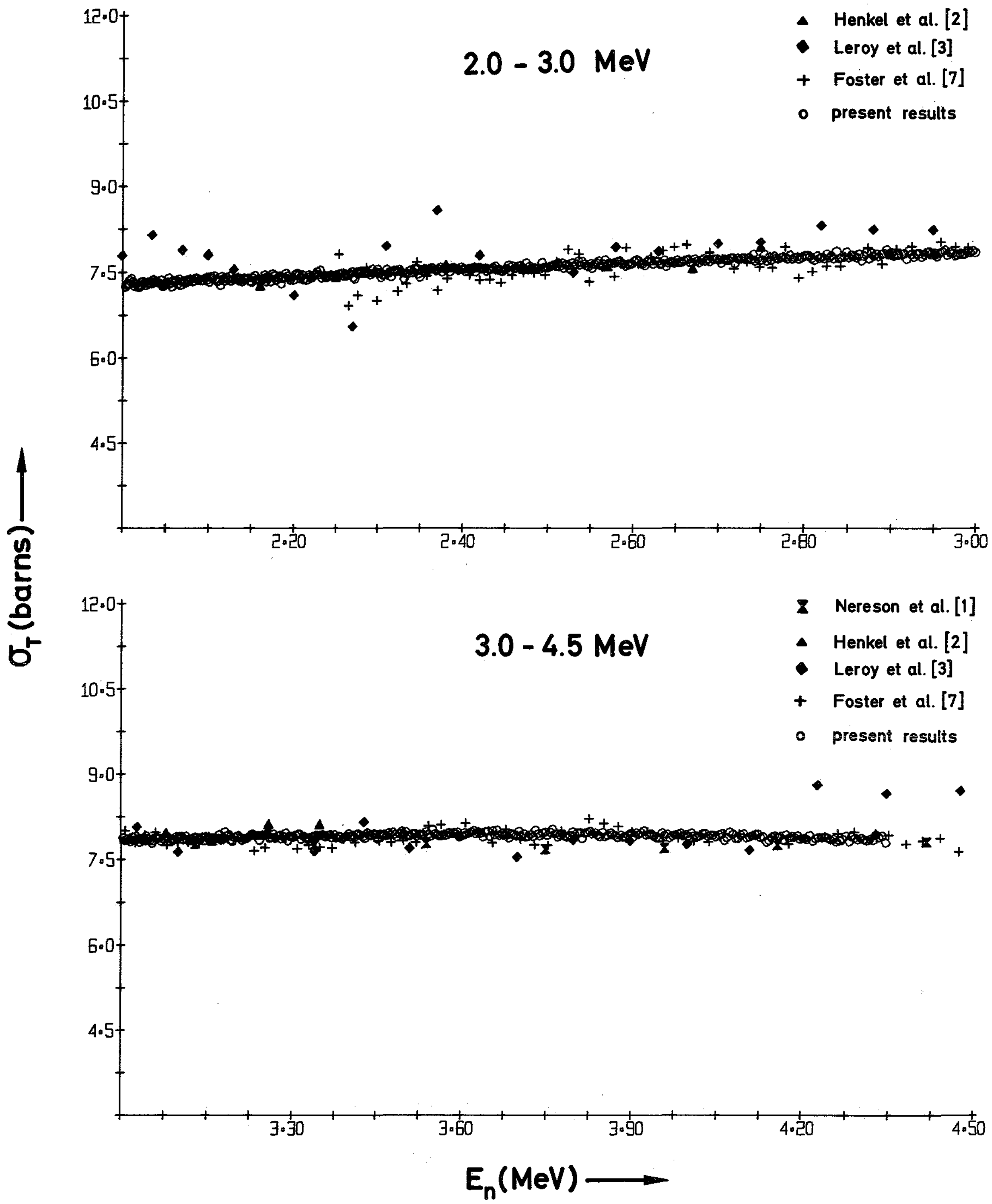

Fig.5 Neutron total cross section of uranium from 2.0 - 4.5 MeV