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Projekt Schneller Brüter

Measurement of High Resolution γ-Ray Production Cross Sections in Inelastic Neutron Scattering on Al and Fe between 0.8 and 13 MeV

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ABSTRACT

Differential cross sections for the production of γ-rays by [n,n' γ] reactions in aluminum and iron have been measured at 125° as a function of the incident neutron energy from 0.8 - 13 MeV. The Karlsruhe isochronous cyclotron was used to produce a pulsed beam of neutrons having a continuous energy spectrum from $\sim$0.5 - 30 MeV. The γ-ray energies were measured using a Ge[Li] detector. The incident neutron energies were determined by the time-of-flight technique. The energy resolution obtained in this measurement was $\leqslant$ 1.7 keV at 0.8 MeV and $\leqslant$ 110 keV at 13 MeV, respectively. Neutron flux determination was accomplished by use of a calibrated proton recoil detector. Below approximately 3 MeV our results can be used to determine inelastic scattering cross sections for the excitation of six levels in aluminum and five levels in iron. A comparison of the presented results with other available data is shown and discussed.

ZUSAMMENFASSUNG

Es wurden γ-Produktionswirkungsquerschnitte für verschiedene γ-Linien aus [n,n'γ]-Reaktionen an Aluminium und Eisen im Energiebereich zwischen 0.8 und 13 MeV gemessen. Ein gepulster Neutronenstrahl mit einem kontinuierlichen Energiespektrum zwischen $\sim$ 0.5 und 30 MeV wurde im Karlsruher Isochron-Zyklotron erzeugt. Der Nachweis der γ-Strahlung erfolgte mit einem Ge[Li]-Detektor. Die Neutronenenergie wurde aus der Flugzeit ermittelt. Die Energieauflösung lag zwischen $\leqslant$ 1.7 keV bei 0.8 MeV und $\leqslant$ 110 keV bei 13 MeV. Zur Bestimmung des Neutronenflusses diente ein Protonenrückstoßzähler. Es werden Wirkungsquerschnitte für den 843 keV- und 1013 keV-Übergang in ^{27}Al sowie den 846 keV-Übergang in ^{56}Fe gezeigt und mit den Ergebnissen anderer Autoren verglichen.

INTRODUCTION

The measurement of γ -ray production cross sections for neutron interactions in medium weight and heavy nuclei, mainly in the MeV region, is of current interest in several areas of applied physics. Such cross sections are, in particular, required for the design of fast fission reactor assemblies and for the study of hypothetical fusion reactor blanket systems. More generally, this need is being exemplified by the large number of high priority requests. The cross section measurements should have as high accuracy as possible to be useful for application purposes. In addition, the resolution should be high enough to allow reproduction of the actual cross section in satisfactory detail.

In this paper, a new technique for the measurement of high resolution γ -ray production cross sections over a wide energy range is described. At the Karlsruhe isochronous cyclotron high resolution differential cross sections of aluminum and iron have been measured at an angle of 125^{o}. Total cross sections for the emission of the γ -rays of 843, 1013, 1719, 2209, 2980 + 3001 keV [Al] and of 846, 1238, 1808, 2093 + 2111 keV [Fe] were obtained by multiplying the differential cross sections at 125^{o} by 4π. As an example of these measurements results are presented for the production of 843 keV and 1013 keV γ-rays in aluminum and of 846 keV γ -rays in iron, in the region from 0.8 - 4.5 MeV.

EXPERIMENTAL METHOD

The experimental equipment consisted of a lithium drifted germanium high resolution γ -ray spectrometer used in conjunction with the Karlsruhe fast neutron time-of-flight spectrometer, which has been described previously.[1]

For operation of the time-of-flight spectrometer the Karlsruhe isochronous cyclotron was used to provide a pulsed beam of neutrons having a continuous spectrum of energies in the range $\sim$ 0.5 to 30 MeV, a pulse width $\leqslant$ 2 nsec and a pulse recurrence frequency of 200 KHz. Neutron production was accomplished by bombarding a thick natural uranium target with approximately 45 MeV deuterons from the internal beam of the cyclotron.

The scatterer-detector arrangement used for the measurement of γ -ray production cross sections is shown in Fig. 1. A ring-shaped scattering sample of aluminum or iron having 12 cm inner diameter, 24 cm outer diameter and a thickness of 1 cm [Al] and 0.6 cm [Fe] was placed at 57.92 m from the source with its axis collinear to the flight path axis. The energy of the γ-rays produced in the scatterer was measured with a 40 cm^3 Ge[Li] detector positioned on the neutron beam axis at a distance of 6 cm from the scattering sample. The detector and the crystal were shielded from source neutrons and γ-rays by a suitably shaped collimator [shown in section A-B of Fig. 1] with a total length of 1 m. The corresponding neutron energies were determined by the time-of-flight method, i.e. by recording the time between the production of neutrons and the detection of a corresponding γ -ray event in the Ge[Li] detector. In this experiment an average observation angle for the gamma rays of 125^o to the incident neutrons was chosen. The actual geometry, however, allowed the observation of γ-ray events in the range from 105 to 145^o. An average angle of 125^o was used because the P_2 term of a Legendre distribution is zero at 125^o and the P_4 and higher terms are generally quite small. The differential cross section at 125^o may then be multiplied by 4π to obtain the total cross section for the excitation of an individual level. The absolute neutron flux at the position of the ring scatterer was measured using a calibrated proton recoil detector. Flux measurement was carried out during the "sample out" period on a 600 sec cycle. For every γ-ray event in the Ge[Li] detector two signals were derived: the energy information via a slow analog signal and the time information via a fast timing signal provided by a conventional ORTEC constant fraction timing discriminator. The analog signal was digitized in a VICTOREEN 2048 channel pulse-height analyzer. For time recording a digital time analyzer [LABEN UC-KB] was used. The measurements were carried out over a total time-of-flight interval of $\sim 4\ \mu$sec with 2 nsec channel width.

The two parameter data were processed with a CDC-3100 on-line computer. Only the information needed to extract the peak areas of those γ-lines which were produced in neutron inelastic scattering were accumulated, and sequentially stored on the magnetic disc. With the present storage capacity the 2K time-of-flight spectra from 32 γ-lines could simultaneously be accumulated.

The overall time resolution obtained with the experimental equipment was $\leqslant$ 5 nsec. This resolution of 0.08 ns/m corresponds to an energy resolution of $\leqslant$ 1.7 keV at 0.8 MeV and $\leqslant$ 110 keV at 13 MeV.

RESULTS AND COMPARISON

Figs. 2a, 2b show typical γ-ray spectra [background subtracted] for aluminum and iron, integrated over the incident neutron energy range from 0.8 - 13 MeV. Only γ-lines produced by inelastic neutron scattering have been assigned. The origin of the assigned γ-rays can be seen with reference to the level schemes of ^{27}Al and ^{56}Fe as shown in the inserts of Figs. 2a, 2b. The information given in these diagrams have been obtained from Refs. 2,3 and 4. γ-ray energy determinations were only made for peak identification purposes. For the determination of the γ-ray production cross section, the accurate knowledge of the neutron flux, the γ-ray detector efficiency, and of the effects of flux attenuation, multiple scattering and the γ-ray attenuation in the sample is necessary.

The incident neutron flux was calculated from the measurement with the proton recoil detector. Its efficiency was calculated by a Monte Carlo method, using the well known scattering cross sections of hydrogen and the light response curves of R. L. Craun and D. L. Smith [5]. It is estimated that the efficiency was determined to a precision of 8% in the energy region between 0.8 and 4.5 MeV.

The γ-ray detector efficiency was determined with an IAEA calibration set of 8 γ-sources [$\sim$1% accuracy]. By use of an additional ^{24}Na source the detector efficiency was also determined at 2.7 MeV relative to the cascading γ-ray at 1.37 MeV. Full peak efficiencies for each γ-energy were measured at 25 positions in the scattering plane. This allows a numerical integration over the total area of the scatterer. Hence, the detector efficiency should be known to about $\leqslant$ 3%. The attenuation of the γ-rays in the sample was less than 15% in the total region of interest. This was calculated with a Monte Carlo program applying the attenuation coefficients of White-Grodstein.[6] The error introduced by this source is quite small, $\leqslant$ 2%.

The neutron flux attenuation and multiple scattering correction applied to our data is still preliminary. These calculations were made at only five energies in steps of 1 MeV. The presently available results from a Monte Carlo calculation give a maximum correction of about 15%. Since the two effects, the flux attenuation and the multiple scattering, are of the same order of magnitude and in opposite directions [i.e. tend to cancel each other], the estimated error, also with the preliminary correction, should be $\leqslant$ 8%. Considering the above sources of error, the overall uncertainty of our data, apart from counting statistics, is about 12 %.

The γ-ray production cross sections obtained for the 846 keV γ-ray of iron are compared in Fig. 3 with other measurements. In general there is good agreement between the present results and those from Harwell.[7] The Harwell measurements cover the energy region from 0.9 - 3.5 MeV. Good agreement is also found with the measurements of Nishimura et al.[8] [JAERI 65] between 2.5 and 2.6 MeV. The data points from Japan [9] in the range from 1.6 to 1.9 MeV and from TNC[3] above 3 MeV are generally higher than the present values, which is what would be expected for the latter results, since multiple scattering effects have been neglected. The n,n′ cross sections which have partially been included in the figures can be directly compared with our measurements up to 2.1 MeV. Above this energy the γ-ray production cross sections also contain contributions from inelastic scattering to higher levels. In the region 1.6 to 2.1 MeV our data are in excellent agreement with the measurements of Gilboy and Towle [10] [Aldermaston]. Above 2.1 MeV their data are systematically lower as expected. With a few exceptions the present measurements between 1 and 1.5 MeV agree with the n,n′ data obtained at Argonne.[11] Figs. 4 and 5 show the results for the 843 keV and the 1013 keV γ-ray measurements of aluminum. Up to 3.6 MeV there is no cascading from higher levels to the 843 keV level. In the upper part of Fig. 4, 14 values from Argonne[12] were available for comparison. The agreement with most values is excellent; there is a large discrepancy for only two data points, at 1.175 and 1.275 MeV. Between 1.4 and 3.5 MeV our data are in good agreement with measurements from the Aldermaston and the Studsvik group.[14] Disagreement is found with the result obtained at NRD.[15] Though the TNC-data[16] between 3.6 and 4.5 MeV coincide with the present results within the quoted uncertainty, there is again the already mentioned systematic deviation toward higher cross section values.

Fig. 5 compares our results with the measurements from Argonne[12], Aldermaston[13], Studsvik[14] and TNC.[16] All data points of Argonne and 2 points of the Aldermaston measurement are considerably higher than our average curve. It can be supposed that a large part of the discrepancy might be due to a shift in the absolute energy scales. Excellent agreement is found with the recent measurements by the Studsvik group. The TNC data and the result of the Kentucky[17] group are, in general, higher than our data for the reasons which have already been mentioned.

In summary, the present results are in good agreement with other data. For the discrepancies possible explanations were discussed. Our ~3000 data points provide good definition for the aluminum and iron γ-ray production cross section in the range from 0.8 - 4.5 MeV. It could be demonstrated that the γ-ray production cross sections for these elements show rapid fluctuations with energy, which are still present at 4.5 MeV.

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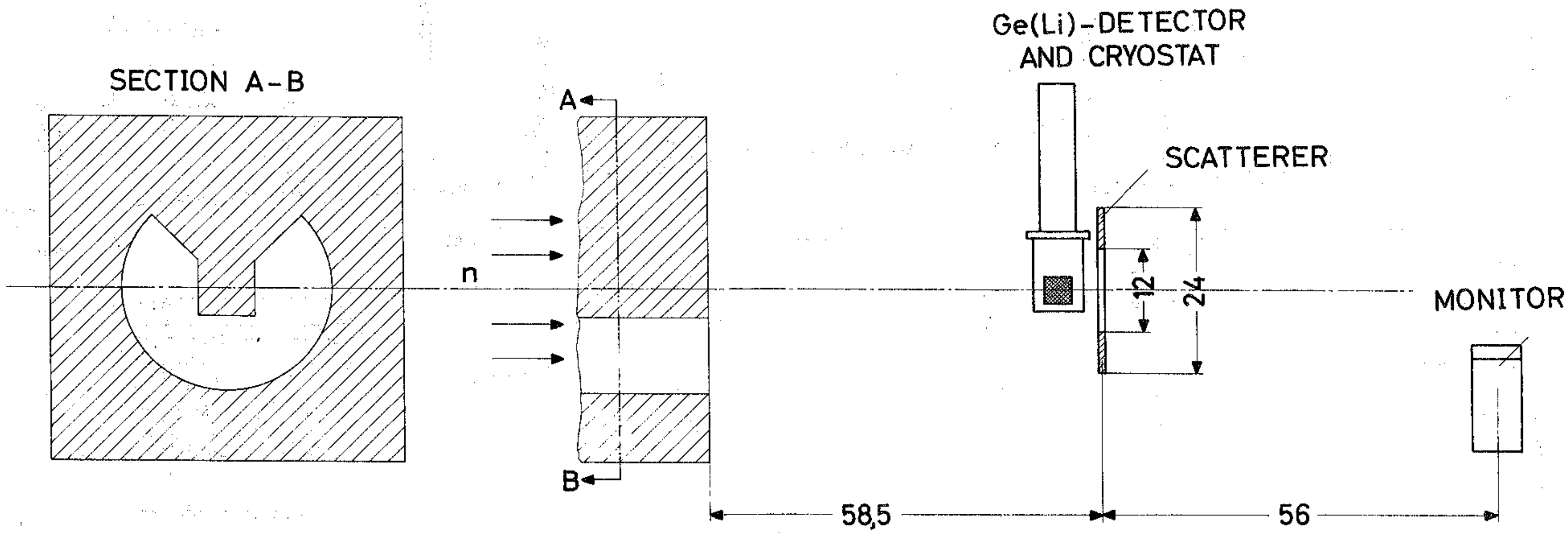

Fig. 1 Experimental arrangement

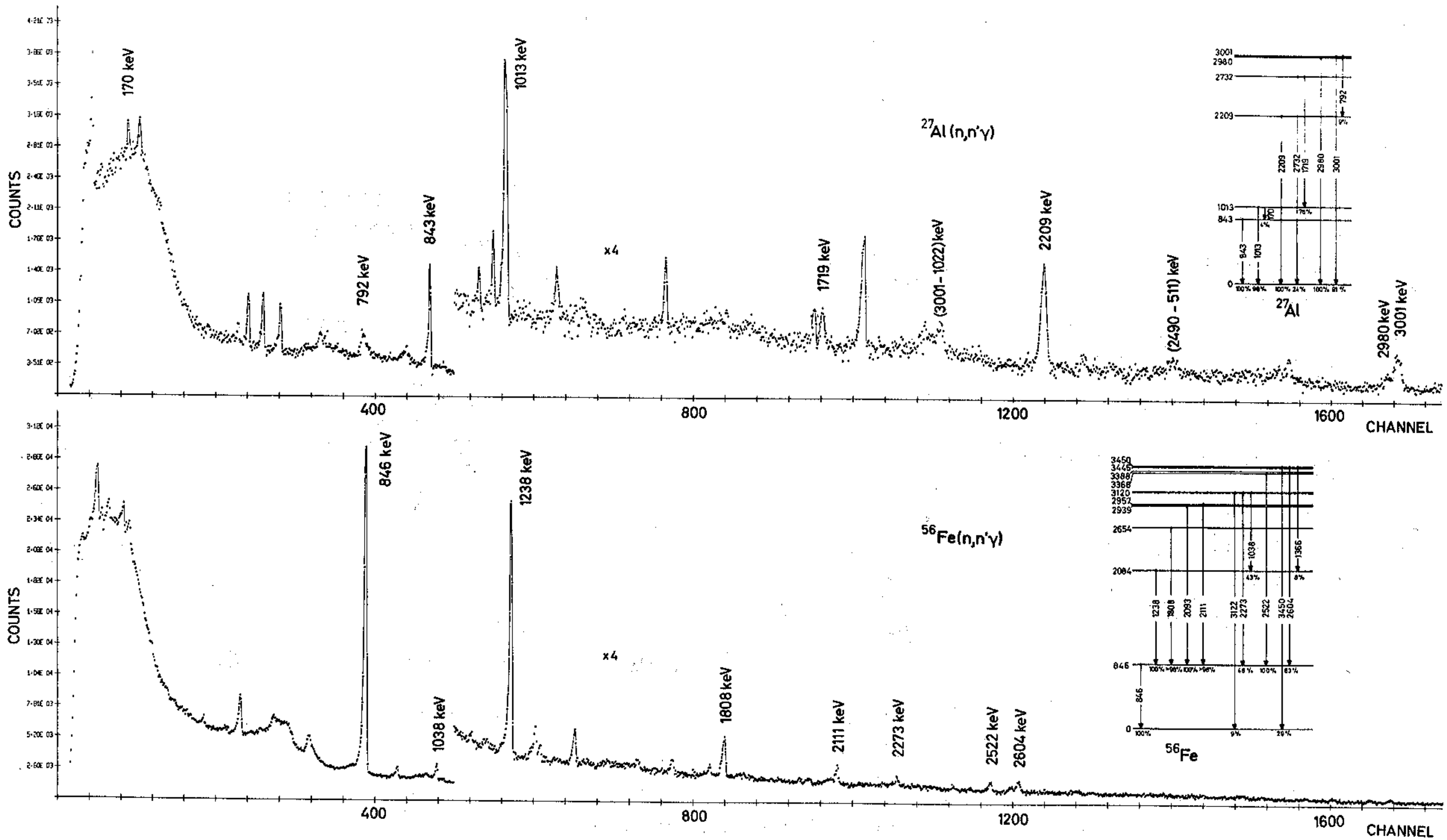

Fig. 2a Gamma ray spectrum for the ^{27}Al [n,n'γ] reaction for neutrons in the energy range from 0.8-13 MeV.
Insert: Energy level and decay scheme for ^{27}Al.

b Gamma ray spectrum for the ^{56}Fe [n,n'γ] reaction for neutrons in the energy range from 0.8-13 MeV.
Insert: Energy level and decay scheme for ^{56}Fe.

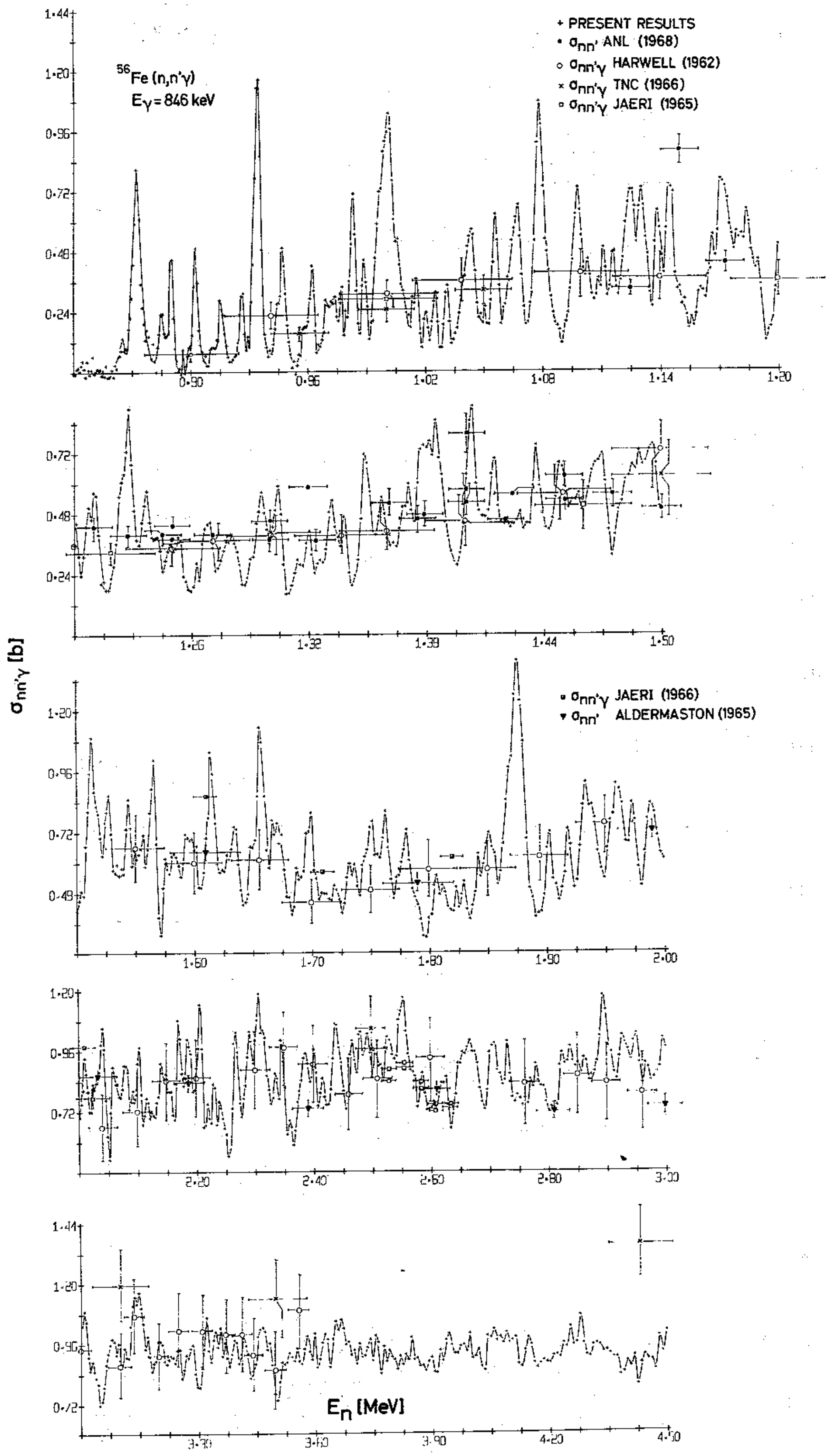

Fig. 3 Cross section for the production of the 846 keV γ-ray from inelastic neutron scattering in iron.

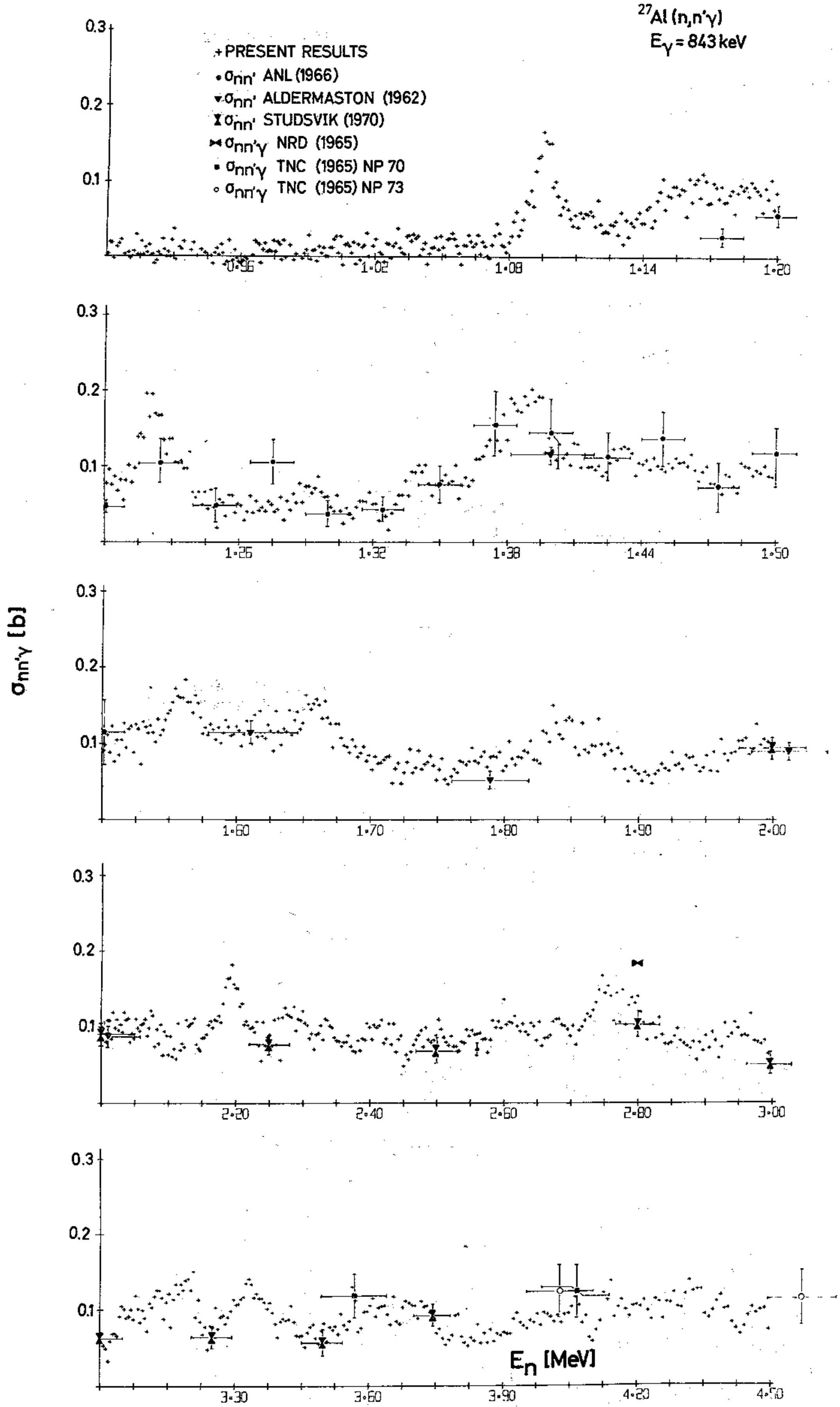

Fig. 4 Cross section for the production of the 843 keV γ-ray from inelastic neutron scattering in aluminum.

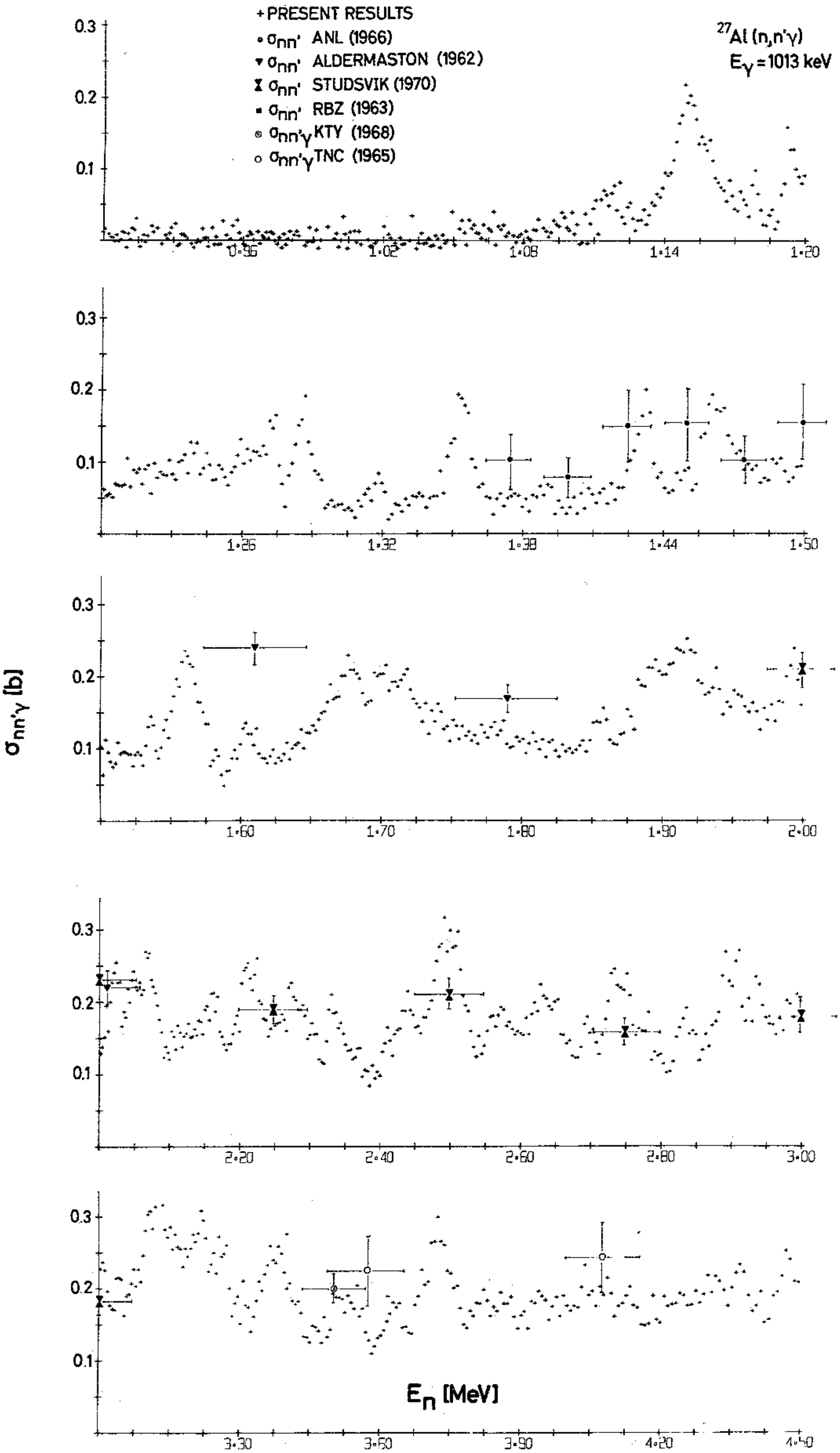

Fig. 5 Cross section for the production of the 1013 keV γ-ray from inelastic neutron scattering in aluminum.