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KARLSRUHE

Mai 1973

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Institut für Angewandte Kernphysik

Capabilities for the Study of Fast Neutron Interactions of the Isochronous Cyclotron Time-of-Flight Spectrometer

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KERNFORSCHUNG M.B.H.

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Gesellschaft für Kernforschung m.b.H., Karlsruhe

Invited Paper II. All-Union Conference on Neutron Physics, Kiev, Ukrainian SSR, May 28 - June 3, 1973

Abstract:

The capability of neutron time-of-flight spectrometry in conjunction with an isochronous cyclotron is discussed on the basis of the Karlsruhe facility. Present specifications of this spectrometer are given to demonstrate its ability for the study of all important neutron interactions in the energy range from several hundred keV to 30 MeV. The increasing importance of fast neutron data for several applied nuclear energy programs is pointed out. In the area of total and partial cross section measurements typical examples of new high resolution data are shown. Accompanying neutron physics work is briefly summarized.

Zusammenfassung:

In diesem Bericht werden die Möglichkeiten der Neutronen-Flugzeitspektrometrie unter Verwendung eines Isochronzyklotrons am Beispiel des Karlsruher Laufzeitspektrometers aufgezeigt. Um die Leistungsfähigkeit dieser Anlage für die Messung von totalen und partiellen Wirkungsquerschnitten zu demonstrieren, werden die heutigen Spezifikationen des Spektrometers diskutiert. Auf die wachsende Bedeutung der Daten Schneller Neutronen für verschiedene Anwendungsgebiete wird hingewiesen. Es folgt eine Beschreibung der Möglichkeiten zur Messung totaler und partieller Wirkungsquerschnitte anhand einiger typischer Beispiele von kürzlich durchgeführten Experimenten mit hoher Auflösung. Die wichtigsten neutronenphysikalischen Ergebnisse der bisherigen Untersuchungen werden in zusammengefaßter Form dargestellt.

CAPABILITIES FOR THE STUDY OF FAST NEUTRON INTERACTIONS OF THE ISOCHRONOUS CYCLOTRON TIME-OF-FLIGHT SPECTROMETER

S. Cierjacks

Institut für Angewandte Kernphysik
Kernforschungszentrum Karlsruhe
F.R. Germany

Abstract: The capability of neutron time-of-flight spectrometry in conjunction with an isochronous cyclotron is discussed on the basis of the Karlsruhe facility. Present specifications of this spectrometer are given to demonstrate its ability for the study of all important neutron interactions in the energy range from several hundred keV to 30 MeV. The increasing importance of fast neutron data for several applied nuclear energy programs is pointed out. In the area of total and partial cross section measurements typical examples of new high-resolution data are shown. Accompanying neutron physics work is briefly summarized.

I. Introduction

It is a well known fact that the highest instantaneous neutron intensities are provided by acceleration of charged particles to high energies. Of the existing high-energy accelerators the isochronous cyclotron is currently best able to take advantage of this capability in high-resolution fast neutron experiments. This machine combines both, high beam intensity and narrow pulse-width of a few nanoseconds. For proper use of this machine, however, additional equipment is necessary, because isochronous cyclotrons run continuously with a microstructure pulse-recurrence frequency of 10-30 MHz. This repetition rate is far too high in view of neutron overlap problems. It is obvious that for long flight paths the time interval of 30-100 nsec between two microstructure pulses is so short, that slow neutrons from preceeding bursts can be overtaken by fast neutrons from the following bursts. A reduction of the repetition rate by suppression of most of the microstructure pulses would entail a tremendous sacrifice in intensity. It is, however, possible to reduce the recurrence frequency, while largely preserving the high average beam intensity of an isochronous cyclotron. This condition has been met with the Karlsruhe concept of a new "deflection-bunching" system[1], which was developped in its specific form for use with our 50 MeV machine, but is believed to be unique for isochronous cyclotrons.

With our particular system the repetition rate can be reduced from 33 MHz to 200 kHz, while the average beam intensity is decreased only by a factor of 3. The principle of operation of the "deflection-bunching system" will not be discussed here, since the present interest is more in the application of the spectrometer. To develop this aspect, I propose to proceed as follows: The specification of the Karlsruhe facility will be given and briefly discussed in the first section. In the following two sections the capability of the isochronous cyclotron spectrometer for total and partial neutron cross section measurement will be demonstrated by a few characteristic results.

II. Performance and Specifications of the Karlsruhe Spectrometer

A top view of the spectrometer arrangement is shown in fig. 1. Neutrons are produced by bombardment of a thick natural uranium target with 50 MeV deuterons from the internal cyclotron beam. Collimators are positioned in the flight path to define a narrow neutron beam with a solid angle of $\sim 2 \times 10^{-6}$ sr. The neutrons are detected at the end of the evacuated flight path, usually by proton recoil detectors. A typical unmoderated time-of-flight spectrum is shown in fig. 2. The broad pronounced peak near 18 MeV is due to neutrons from deuteron break-up reactions. The neutron distribution below 6 MeV with the high peak near 1 MeV originates mainly from evaporation and fission processes. It can be seen that the useful energy range for neutron experiments is between several hundred keV and 30 MeV. In its present stage of developement the spectrometer has the following performance data: pulse width: 1.5 nsec, repetition rate: 20-200 kHz variable, time average neutron intensity at 200 kHz: 2×10^{13} n/sterad sec in the forward direction, resolution: 0.01 ns/m, this corresponds to an energy resolution of 30 ev at 300 keV.

The particular role of the isochronous cyclotron time-of-flight spectrometer for fast neutron investigations might be demonstrated by a comparison with other advanced neutron facilities. The basis for such a comparison has been worked out some years ago by E. Rae from the United Kingdom[2]. As a measure of the quality of a neutron spectrometer, he adopted for a given effective energy resolution the useful flux available at the detector. Since this flux depends strongly on the energy spectrum produced by the particular accelerator, the energy dependence of this value must be taken into account.

Fig. 3 shows such a comparison for the four main types of accelerator-based neutron facilities. In particular, the diagram shows the Harwell Booster, the Oak Ridge linac, the Harwell synchrocyclotron, and the Karlsruhe sector-focussed cyclotron. The numbers in brackets behind the symbols are the machine pulse-lengths in nsec. The data given below and above each curve are the pulse-repetition rates and the length of flight paths, needed to preserve the constant value of a given effective resolution. Comparing the available useful fluxes at the detector, it is obvious that the isochronous cyclotron has the highest neutron intensity and is without competition in the energy range from a few hundred keV up to 30 MeV. In the region of overlap with other accelerator types the isochronous cyclotron has introduced a new order of magnitude in neutron intensity. Furthermore, this machine is the only existing facility, suitable for continuous measurements in the many MeV range. However, it is not very useful, to employ this type of machine at energies below about 100 keV. The high beam intensity and the small pulse width can only be preserved for high repetition rates and unmoderated neutron spectra.

In this context I wish to stress the technological importance of fast neutron data. Neutron data in the MeV-range are presently gaining in importance as can be seen from the increasing number of data requests from the several applied nuclear programs. A majority of present requests in this range belong to needs for the development of fast breeder reactors. A number of data requests have also been formulated for the development of safeguards' purposes. Furthermore, the neutron data requirements for the study of technological problems of fusion reactors should be mentioned. Since the first prototype will presumably be a DTreactor, the neutron data between 1-15 MeV will be of prime interest. Finally, there is a need of data for material research problems. In this field especially the [n,α] reactions are of importance, since these reactions give rise to the appearance of He-voids and high temperature defects in fuel element cladding and structural materials used in fast breeder reactors.

III. Measurements of Total Neutron Cross Sections

During the last years the Karlsruhe fast neutron spectrometer has extensively been used for high-resolution total neutron cross section measurements. Since 1966 the Karlsruhe cyclotron has been used for a series of transmission measurements on a large number of elements and separated isotopes[3] using the 60 m flight path. Beginning in 1968, additional measurements were performed with very high resolution of 0.01 ns/m employing the new 195 m flight path[4].

Measurements of total neutron cross sections are quite simple in principle. The method is to determine the total neutron interaction by means of a transmission experiment. In very high-resolution experiments with long flight paths, data acquisition and accumulation requires quite sophisticated systems. For the 195 m flight path the neutron spectrum between 0.3 and 30 MeV is distributed over more than 25 μsec in time. To take advantage of the high resolution of the spectrometer, timing has to be accomplished in 2 x 28000 channels with 1 nsec channel width. For these measurements we use a special digital time-sorter [LABEN UC-KB] and an improved version of CDC-3100 on-line computer. This combined system allows measurement with rates up to 10^5 counts/sec, so that a complete transmission experiment with 1 % statistical accuracy can be performed within 15-20 h.

An example of a recent total cross section measurement is given in fig. 4. Here the data obtained for iron is plotted over only a small part of the total investigated energy range. This measurement was carried out with a thick sample, in order to enhance the deep windows in the cross section. The high resolution is important here, since otherwise the full extent of the dips tend to be obscured. A comparison of these results with our previous measurement carried out with lower resolution on the 60m flight path showed that a completely new generation of small resonances has appeared. It is believed that the deep s-wave minima are now fully explored.

Neutron total cross section, when available over a wide energy range and for a number of nuclei, make it possible to study the details of the optical model potential. Such studies provide additional information not available from charged-particle interactions alone. Thus, for example, the isovector component of the potential can be distinguished by comparison of the neutron and proton optical potentials. The high resolution measurements, in addition, make it possible to study neutron strengths functions, intermediate structure phenomena and compound-nucleus level densities and widths. In this talk I will only summarize this work briefly:

The high resolution of this spectrometer gave the opportunity to extend strength function measurements to higher energies and include light nuclei. Analysis of our results shows[5] that the p-wave strength function of $^{40}Ca + n$ is quite small supporting the suggestion that the p-wave minima are anomalous[6]. This in turn has led to the supposition that the absorptive potential strength fluctuates with the quasi-particle level density[7]. Autocorrelation analysis of the high resolution cross sections has given some evidence for the existence of intermediate structure in the several MeV energy range[8]. Average compound-nucleus level widths and densities derived from the total neutron cross sections have been found to be in reasonable agreement with those, determined from the analysis of charged-particle excitation functions[8].

IV. Measurements of Partial Neutron Cross Sections

A. Elastic Neutron Scattering

The investigation of elastic neutron scattering with the continuous neutron source of the cyclotron requires a more sophisticated method than that, normally employed in mono-energetic measurements. In order to measure elastic scattering cross sections in general, a two-parameter set-up is necessary at least if elastic scattering is to be measured above the inealstic scattering threshold. A feasable method in these cases is to determine the incoming neutron energy by time-of-flight, and to accomplish the separation between elastic and inelastic scattering events by measurement of the pulse-height from a proton recoil detector. With the presently existing set-up at the Karlsruhe cyclotron, elastic scattering events are selected on-line from the highest portion of the proton recoil spectrum, which is not obscured by inelastic processes. The measurement of the cross sections by means of this method require a careful energy calibration of the detectors before starting an experimental run. The present method can be used for those cases, where the energy resolution of the proton recoil detector is smaller than the energy difference between elastically and inelastically scattered neutrons. This condition is fulfilled for a large number of light and medium weight nuclei up to several MeV incoming neutron energy.

A typical result of an elastic scattering measurement is shown in fig. 5. In the three upper curves of this figure the high-resolution differential elastic scattering cross section of ^{40}Ca+n is plotted as a function of energy in the range from 0.75 to 1.15 MeV for three different scattering angles[5]. From a comparison with the total neutron cross section, given in the bottom curve, it can be seen that elastic scattering measurements can be carried out with the cyclotron with quality and resolution equivalent to transmission measurements.

Experiments of this type provide a good possibility to unambiguously assign compound-nucleus level spins and parities. It has been shown from previous work in our institute[9] that the resonance shapes of compound-nucleus levels are quite sensitive to spin and parity as a function of the scattering angle. The differences are most apparent at the three selected angles of 140^o, 90^o and 54^o, since here the Legendre polynomials for s, p and d-waves cross the zero axis, i.e. the interference terms in the cross sections change sign.
Along with the neutron widths determined from the analysis of the total cross sections, these spin and parity assignments permit the determination of accurate s, p and d-wave strength functions.

The angular distribution measurements of elastic scattering also are useful in checking microscopic theories of nuclear reactions. Thus, the total and differential elastic cross sections for the scattering of neutrons from ^{15}N have been used to identify the resonances of the $[d_{3/2}\, p_{1/2}^{-1}]_{1^-2^-}$ coupling type at 2.3 and 2.9 MeV[10]. It could be shown, in addition, that coupled-channel calculation in a lp-lh configuration space can satisfactory reproduce the broad structure in the measured cross sections, when allowance is made for the effect of inelastic channels[11]. This approach has proved to be quite a useful way of studying simple classes of excited states in light nuclei such as ^{12}B and ^{16}N.

B. Fast Neutron Induced Fission

These experiments involve very thin samples of a few hundred $\mu gr/cm^2$ fissile material with typically a few cm diameter, if absolute counting of the fission products is intended. To deal with this situation, it is advantageous to use particular detectors systems, which allow to simultaneously expose a number of samples to the incident neutron beam. The presently used detector-system at Karlsruhe, which is shown in fig. 6, consists of 9 gas scintillation chambers. Fission events are identified through the energy spectra of the fission products and coincidences between the two fission fragments from adjucent chambers. For fission cross section ratio measurements identical foils of both nuclei can easily be arranged in such a chamber in a suitable order. Since fission foils are exposed at different distances from the source, the time-of-flight spectra for each foil are accumulated separately, and events for the same incoming neutron energy are combined off-line after the measurement. Fig. 7 shows some results from a measurement of the fission cross section ratio of $^{238}U/^{235}U$ between 1-30 MeV. The Karlsruhe data symbolized by the open circles have been normalized to the well established 14 MeV value. Also included for comparison in this figure are new result from other laboratories[13-17]. Our data are in general in agreement with the previous results.

Apart from the applicational point of view, the results of high-resolution measurement also are of interest for the study of isomeric fission and the properties of the double-humped fission barrier. Furthermore previous measurements for fissile nuclei are very scare in the high energy range, and thus the considerable data which now becomes available will be of importance in furthering our understanding of second and third chance fission.

C. [n,x]-Reactions

Neutron induced charged-particle reactions such as [n,p]-, [n,d]- and [n,α]-reactions from threshold up to more than 15 MeV have not been studied extensively in the past. Direct counting of reaction products for these processes could be made previously only in a few favorable cases, since these investigations, in general, require high-intensity neutron sources. The isochronous cyclotron gives reasonable intensity to measure differential cross sections of [n,x]-processes with good resolution. Measurements of this type with the isochronous cyclotron require a three parameter set-up. From the time-of-flight information the incoming neutron energy can be determined, while the particle identification has to be accomplished by a measurement of the specific energy loss in a thin dE/dx detector. To define the transition channel for the decay to a specific level of the residual nucleus, the total energy of the emitted charged particle is needed from a pulse height measurement. Results obtained from a first exploratory experiment[18] with a short flight path and moderate energy resolution for the reaction products are illustrated in fig. 8. Here, the angular distributions for the $^{9}Be[n,\alpha_0]$ and $^{9}Be[n,\alpha_1]$ reaction are given for 18 energies between 11 and 30 MeV. The right hand side of the figure gives the data for α-decay to the ground state, while the left hand side illustrates α-decay to the first exited state in ^{6}He.

D. Inelastic Neutron Scattering

Inealstic neutron scattering proceeds through the emission of associated prompt γ-rays. Investigation of specific γ-lines by means of a Ge[Li] detector, therefore, in addition to direct neutron counting is a good method to study inelastic processes. The facility[19] which has been set up at the Karlsruhe cyclotron for this type of measurements is shown in fig. 9. Since the efficiency also of very large Ge[Li] crystals is rather low, it is of advantage to employ a ring geometry for the scatterer. Typical dimensions of scattering sample are 25 cm for the outer ring diameter and 10 mm thickness. The Ge[Li] detector is set at a backward angle of 125^{o} and suitably shielded against neutrons and gamma-rays coming directly from the cyclotron source.

Observation of a specific γ-lines leads in turn to γ-ray production cross sections. Assuming that the decay scheme of the residual nucleus and the multi-polarity of the transition is known, the γ-ray production cross sections can be related to inelastic scattering cross sections proceeding through specific reaction channels. Fig. 10 shows a partial result from a high resolution measurement on iron[20]. Here, the cross section for the production of the 846 keV γ-line from inelastic scattering is plotted in the energy range from 0.8-1.5 MeV. Our data are symbolized by the small circles with the small vertical bars. The results from other laboratories included here are mainly characterized by the large horizontal bars. It can be seen that the spectrometer allows the resolution of the complicated resonance structure, typical for nuclei in this mass region and for energies of a few MeV.

Information on inelastic excitation of a number of levels makes it possible, to study channel dependent average level widths and level densities as well as correlated intermediate structure phenomena. Sophisticated statistical calculations suggest that level widths and densities are channel dependent. This has not been conclusively demonstrated so far, although our recent investigations on Al do show a significant effect of this nature, which is qualitatively in agreement with the predictions[21]. One of the problems associated with the interpretation of the phenomenologically observed intermediate structure is the differentiation of spurious intermediate resonances from those caused by doorway states. It has been shown that channel correlations are most improbable for spurious intermediate resonances, and thus this technique holds considerable promise for identification of doorways.

E. Neutron Flux Measurements

The determination of absolute partial cross sections depends strongly on accurate measurements of the fast neutron flux. Since above ~100 keV the H[n,p] cross section is the only standard, which is presently known with an overall accuracy of better than 2 %, any flux measurement for the energy range of the cyclotron spectrometer must rely on the use of this quantity as a reference cross section. The flux detector system developped for the Karlsruhe spectrometer consists of a gas scintillation device, similar to that used in fission experiments. Because of the wide energy range to be covered, the flux is determined in two detector systems, seperately for low neutron energies and high neutron energies with a short range of overlap. The detector shown in fig. 11 was developed for flux measurements in the energy range between 5-30 MeV. The assembly consists of three optically separated scintillations chambers filled with xenon gas at atmospheric pressure. High energy protons from the radiator foil at the entrance of the detector are identified by coincident events in all three chambers and by their specific energy loss in the scintillators. In the energy range above ~20 MeV charged particles from neutron reactions in carbon can enter the third chamber. These events can be eliminated by means of pulse-height selection.

Since the range of 5 MeV protons is approximately equal to the length of the two first sections of the detector, application of this telescope is restricted to flux measurements of neutrons with energies higher than this value. Neutrons with energies between 0.5-6 MeV are well below the thresholds of the C[n,x] reactions. Therefore, only the H[n,p] reaction produces charged particles by neutron reactions. In this range a modified type of the flux detector is used, which consists only of a single chamber viewed by three photomultipliers. The overall detector efficiency obtained with both flux detectors is in the range from $1-4 \times 10^{-4}$ for neutron energies between 0.5-30 MeV. With an accurate determination of the threshold an overall accuracy in the flux measurement of 3-4 % can be achieved. The chambers do not disturb the neutron spectrum during an experimental run, since the net transmission of both devices is higher than 99,99 % and they have a larger diameter than the neutron beam.

V. CONCLUDING REMARK

The principle conclusion I would like to draw from this paper is, that the isochronous cyclotron neutron spectrometer has proven to be a useful device for the study of total and partial fast neutron cross sections. An isochronous cyclotron with associated fast neutron time-of-flight spectrometer is currently under construction at the Kiev laboratory, details of this facility are given in other papers of this conference. It can be expected that facilities of this type will provide in the future a large amount of neutron data for the previously poorly explored energy range above several hundred keV.

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Figure Captions:

Fig. 1 Schematic drawing of the geometry for the Karlsruhe fast neutron time-of-flight spectrometer.

Fig. 2 Typical unmoderated neutron time-of-flight spectrum obtained from bombardment of a natural uranium target with 50 MeV deuterons.

Fig. 3 Comparison of the four main types of advanced neutron spectrometers based on continuous neutron spectra[2]. The quality of a neutron spectrometer is measured in terms of the useful flux available at the detector for an effective energy resolution of $\Delta E/E = 8.8 \times 10^{-4}$. HB = Harwell booster, ORL = Oak Ridge electron linac, HSC = Harwell synchrocyclotron, KSFC = Karlsruhe sector-focussed cyclotron.

Fig. 4 Total neutron cross section of iron from 0.63-0.80 MeV measured with a thick sample of 0,458 at/b and a resolution of 0.015 ns/m.

Fig. 5 a] Differential elastic scattering cross section of calcium between 0.75-1.15 MeV determined at 54^{o}, 90^{o} and 140^{o}.

b] Total neutron cross section of calcium. The solid line represents an R-matrix multilevel least squares fit.

Fig. 6 Gas scintillation detector-arrangement used in fission cross section and fission cross section ratio measurements.

Fig. 7 Result of the fission cross section ratio determination of $^{238}U/^{235}U$.

Fig. 8 Angular distribution measurements for a] the $^{9}Be[n,\alpha_{o}]^{6}He$ reaction and b] the $^{9}Be[n,\alpha_{1}]^{6}He$ reaction at 18 energies between 11 and 30 MeV. Dotted lines are eye-guide curves only.

Fig. 9 Scheme of the Karlsruhe experimental set-up used for the study of neutron inelastic scattering.

Fig. 10 Cross section for inealstic scattering to the 846 keV level in ^{56}Fe between 0.8-1.5 MeV.

Fig. 11 Scheme of the gas-scintillation proton recoil telescope used for absolute flux measurements in the energy range from a few MeV to 30 MeV.

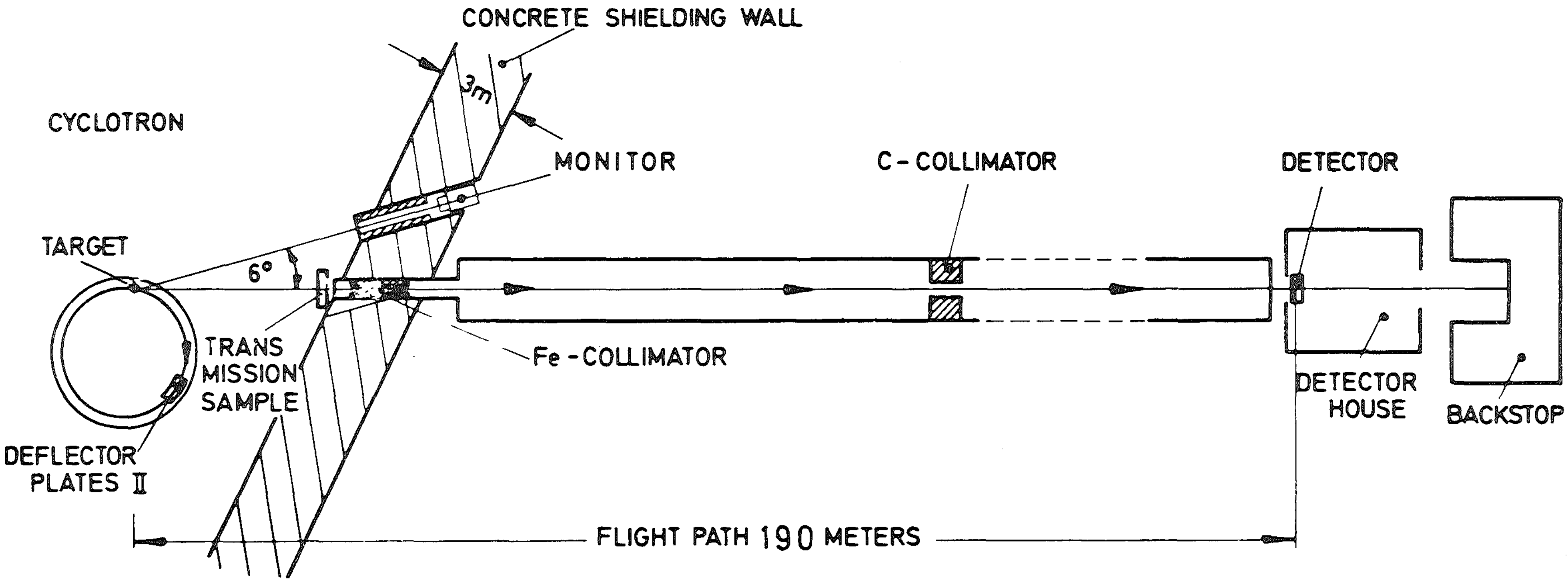
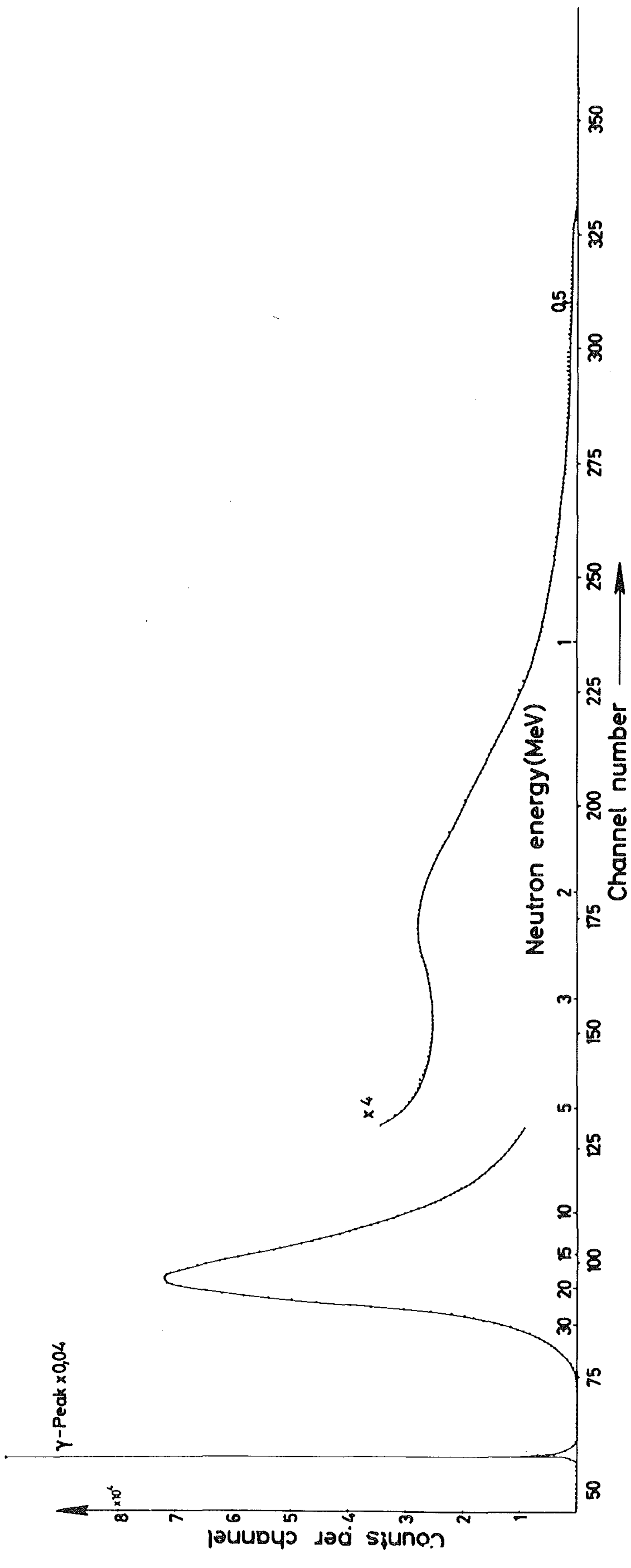
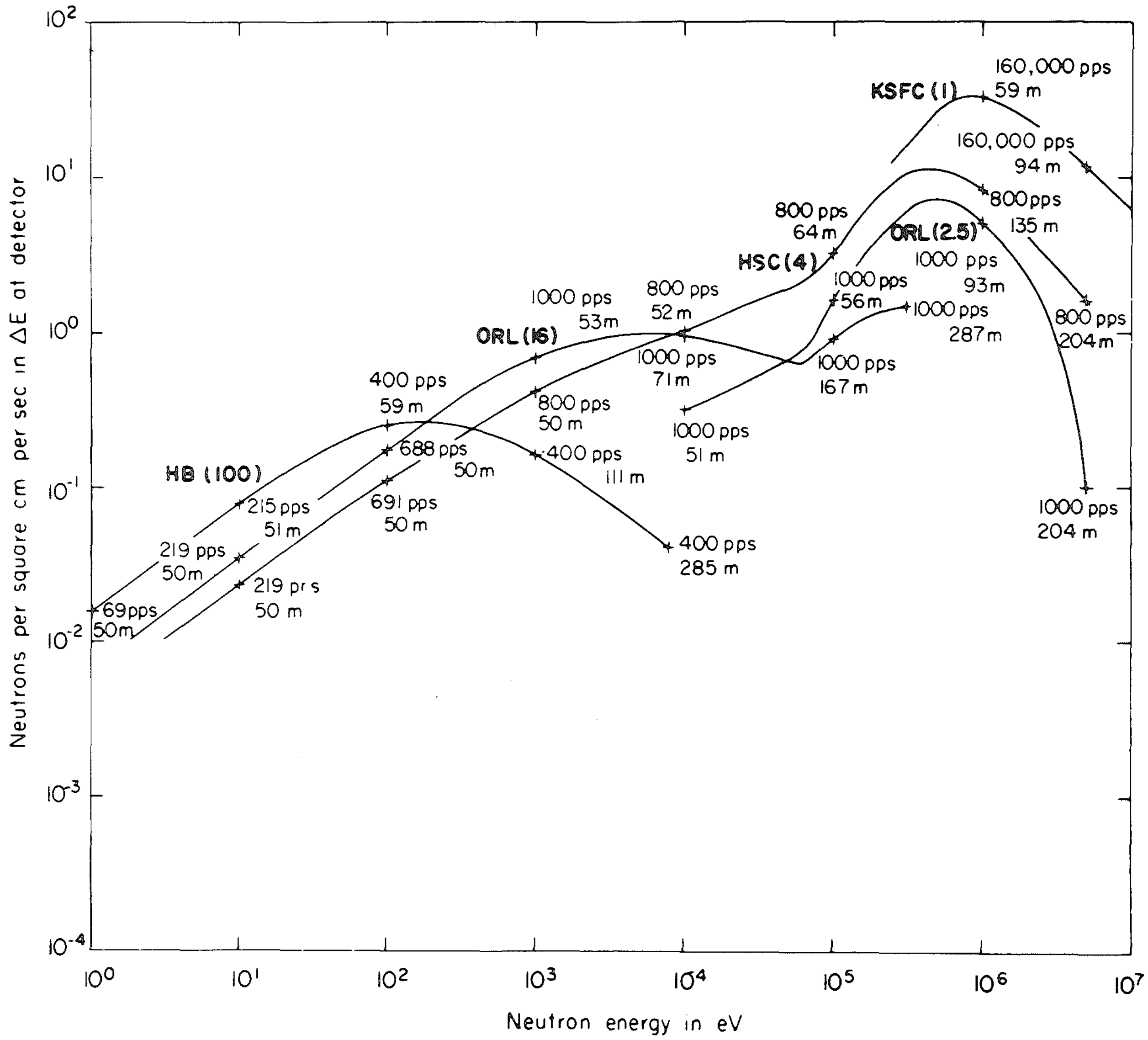

CONCRETE SHIELDING WALL
3m
CYCLOTRON
MONITOR
C-COLLIMATOR
DETECTOR
TARGET
6°
TRANS
MISSION
SAMPLE
Fe-COLLIMATOR
DETECTOR
HOUSE
BACKSTOP
DEFLECTOR
PLATES II
FLIGHT PATH 190 METERS

Fig. 1



Counts per channel
$\times 10^4$
γ-Peak x 0,04
x 4
Neutron energy (MeV)
Channel number

Fig. 2


Neutrons per square cm per sec in ΔE at detector
Neutron energy in eV
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
KSFC (1)
160,000 pps
59 m
160,000 pps
94 m
800 pps
135 m
800 pps
204 m
ORL(2.5)
1000 pps
93 m
1000 pps
287 m
1000 pps
204 m
HSC(4)
800 pps
64 m
1000 pps
56 m
1000 pps
167 m
1000 pps
51 m
ORL (16)
1000 pps
53 m
800 pps
52 m
1000 pps
71 m
800 pps
50 m
400 pps
59 m
688 pps
50 m
691 pps
50 m
400 pps
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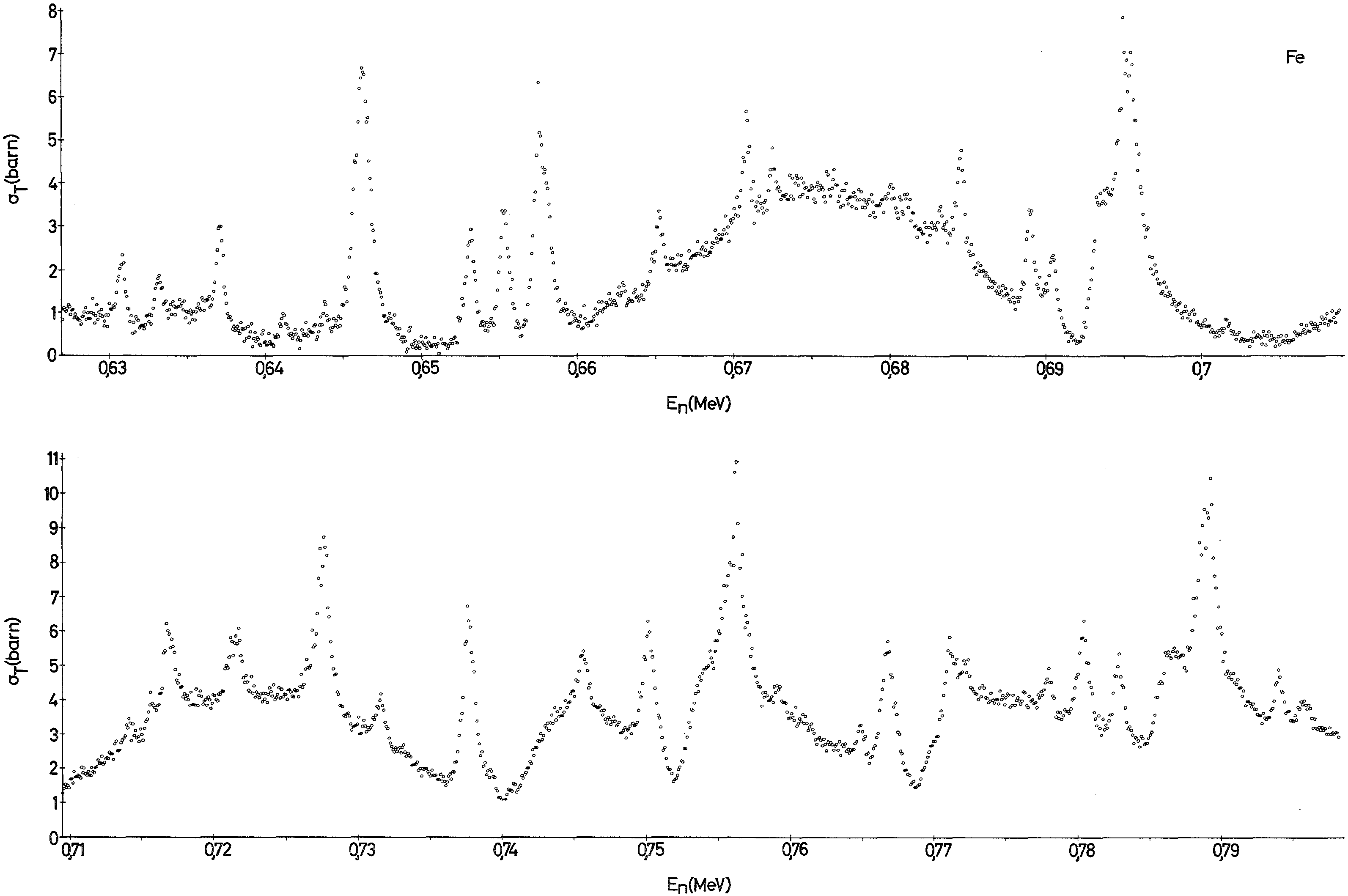
69 pps
50 m

Fig. 3


Fe
σ_T(barn)
0
1
2
3
4
5
6
7
8
0,63
0,64
0,65
0,66
0,67
0,68
0,69
0,7
E_n(MeV)
σ_T(barn)
0
1
2
3
4
5
6
7
8
9
10
11
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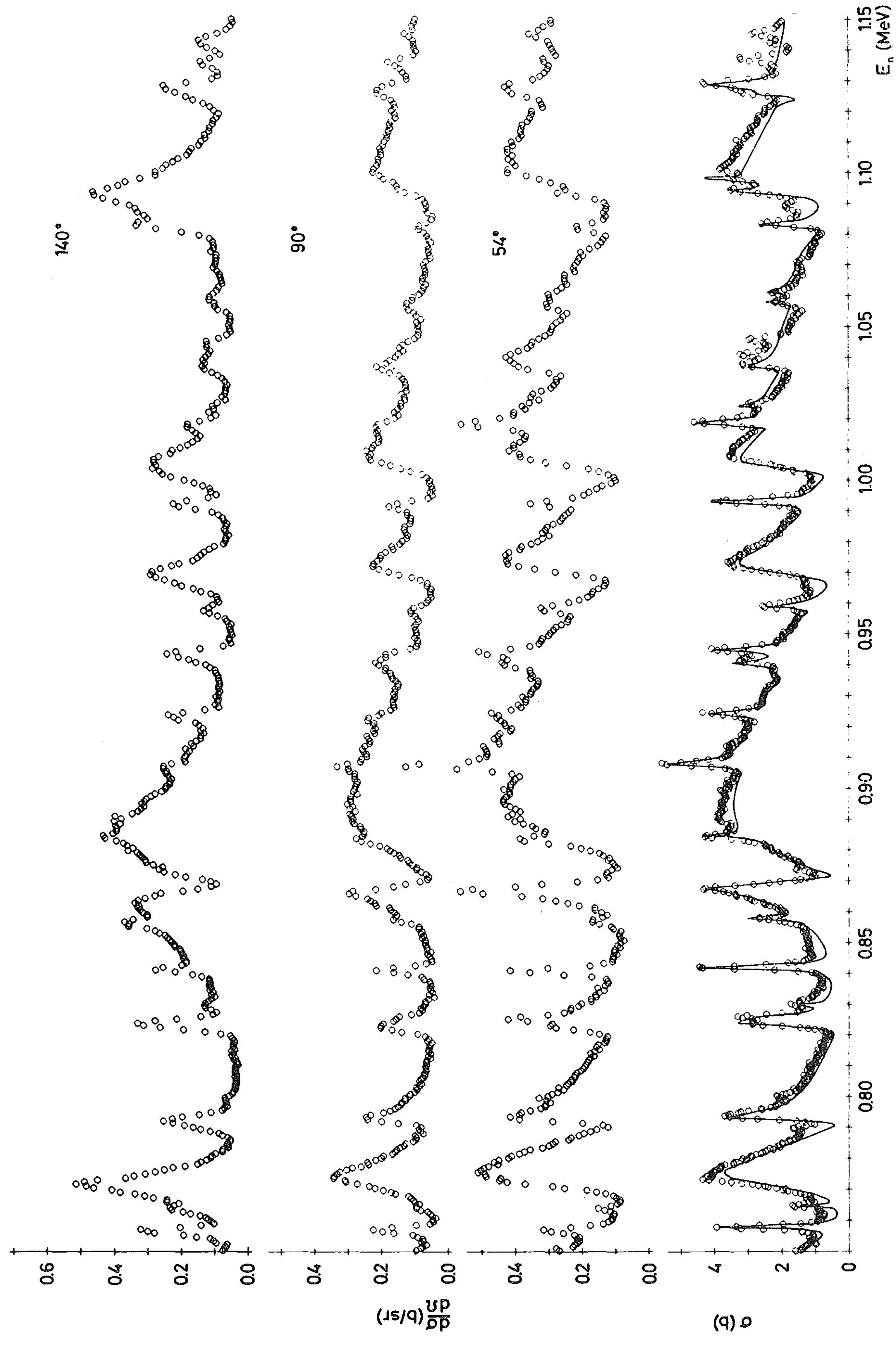
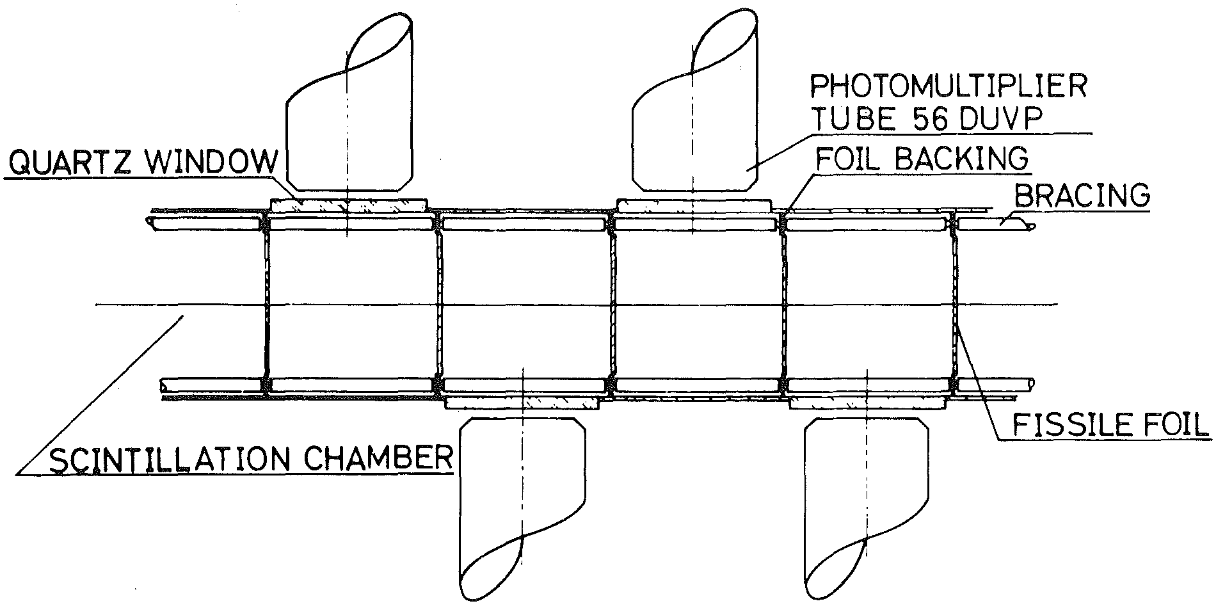
0,72
0,73
0,74
0,75
0,76
0,77
0,78
0,79
E_n(MeV)

Fig. 4

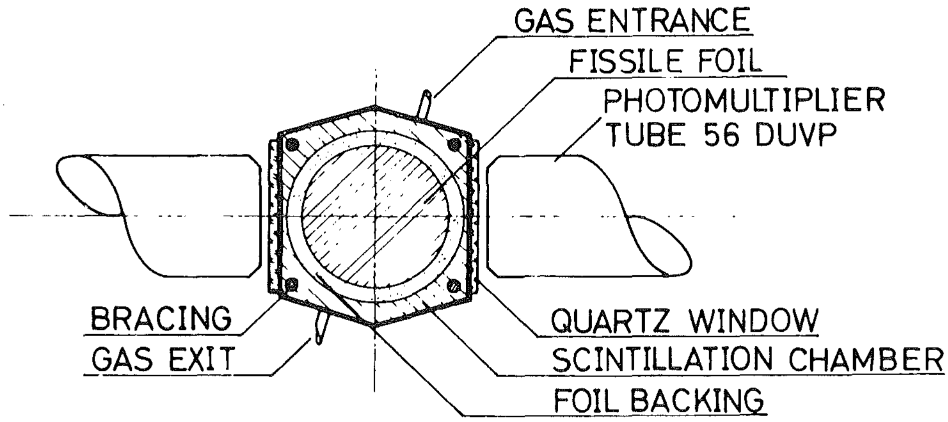


140°
90°
54°
dσ/dΩ (b/sr)
σ (b)
0.0
0.2
0.4
0.6
0
2
4
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
E_n (MeV)

Fig. 5



TOP VIEW



FRONT VIEW

Fig. 6

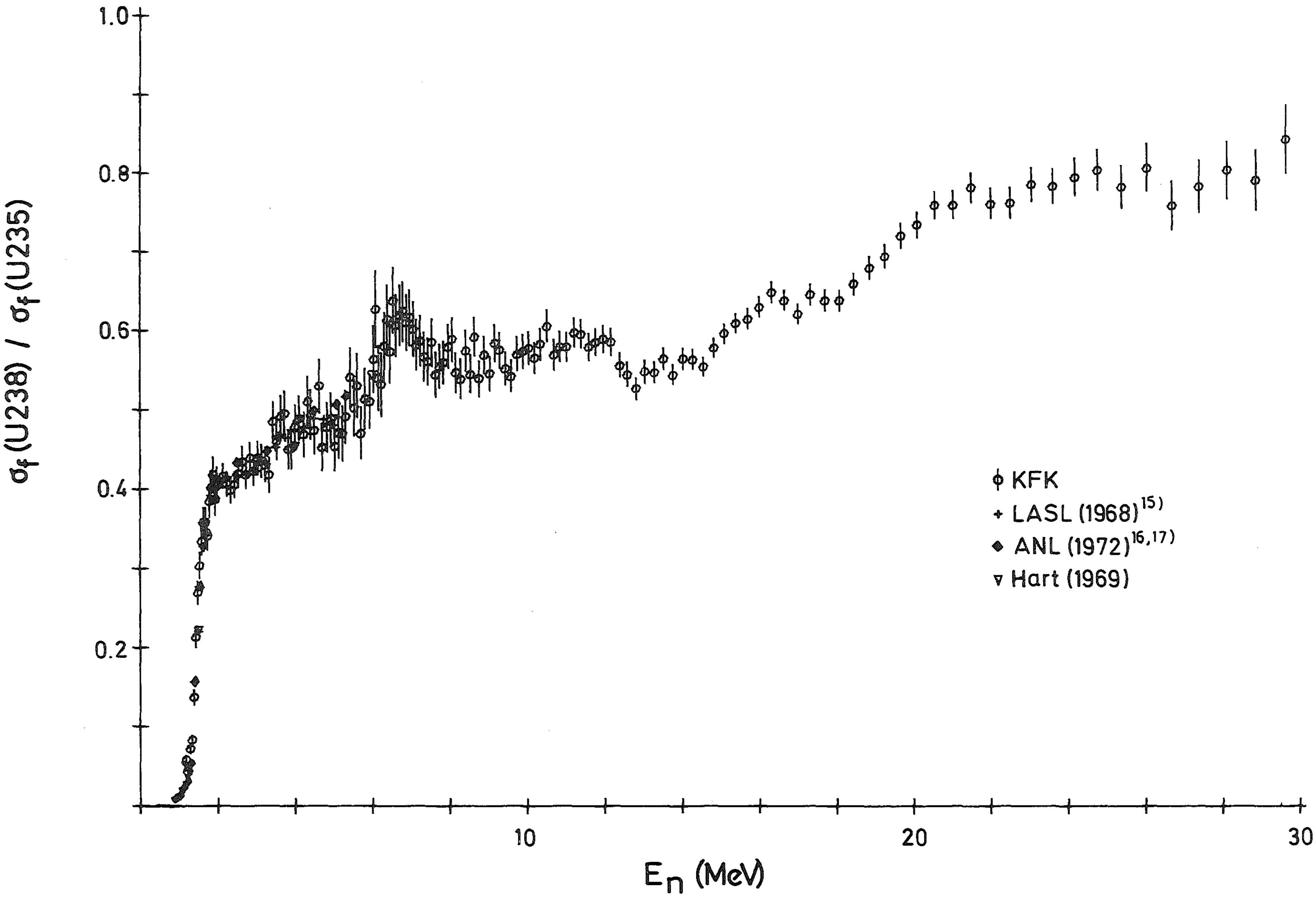

1.0
0.8
0.6
0.4
0.2
σ_f(U238) / σ_f(U235)
KFK
LASL (1968)[15)]
ANL (1972)[16,17)]
Hart (1969)
10
20
30
E_n (MeV)

Fig. 7

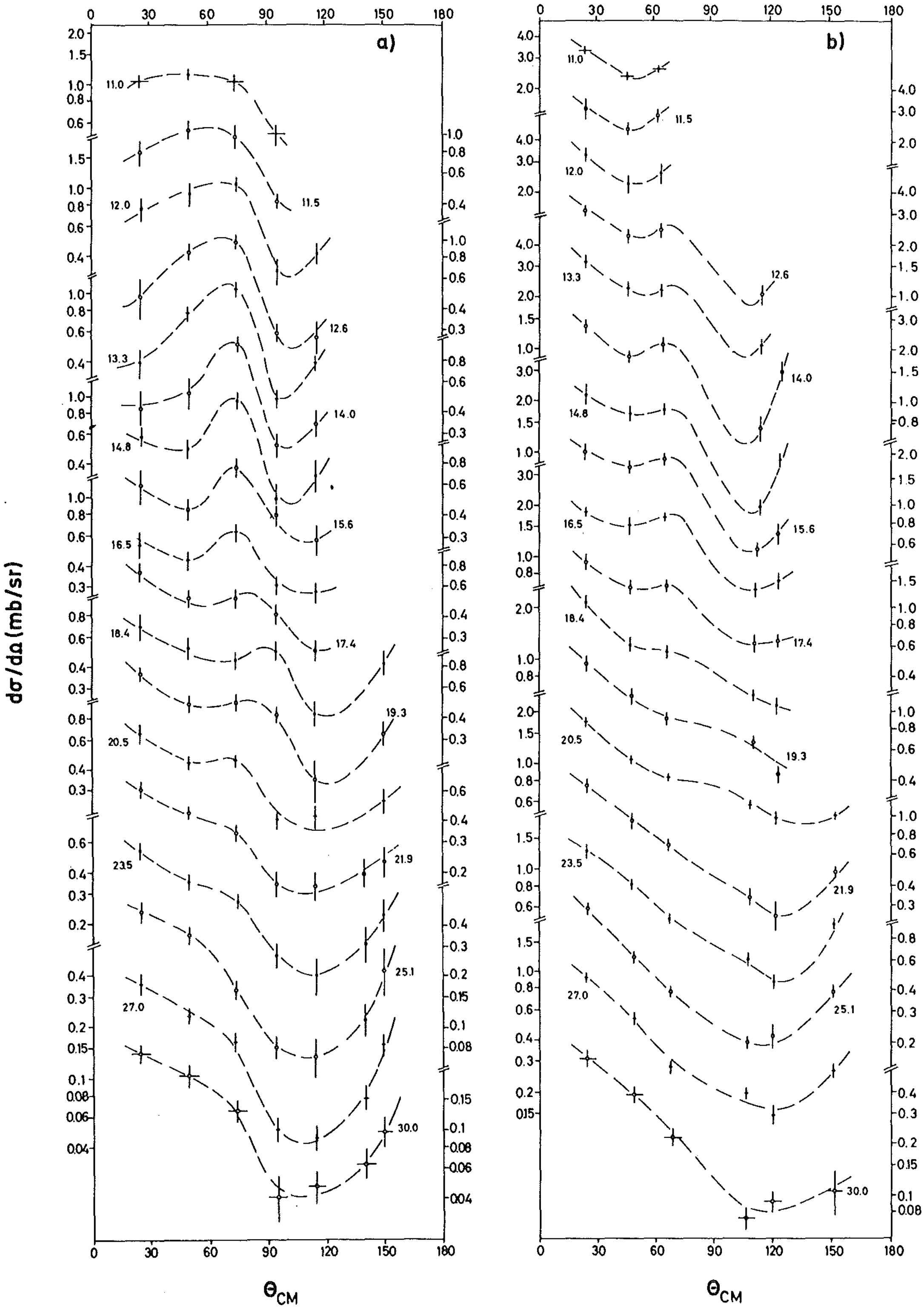

a)
b)
dσ/dΩ (mb/sr)
Θ_CM
11.0
11.5
12.0
12.6
13.3
14.0
14.8
15.6
16.5
17.4
18.4
19.3
20.5
21.9
23.5
25.1
27.0
30.0

Fig. 8

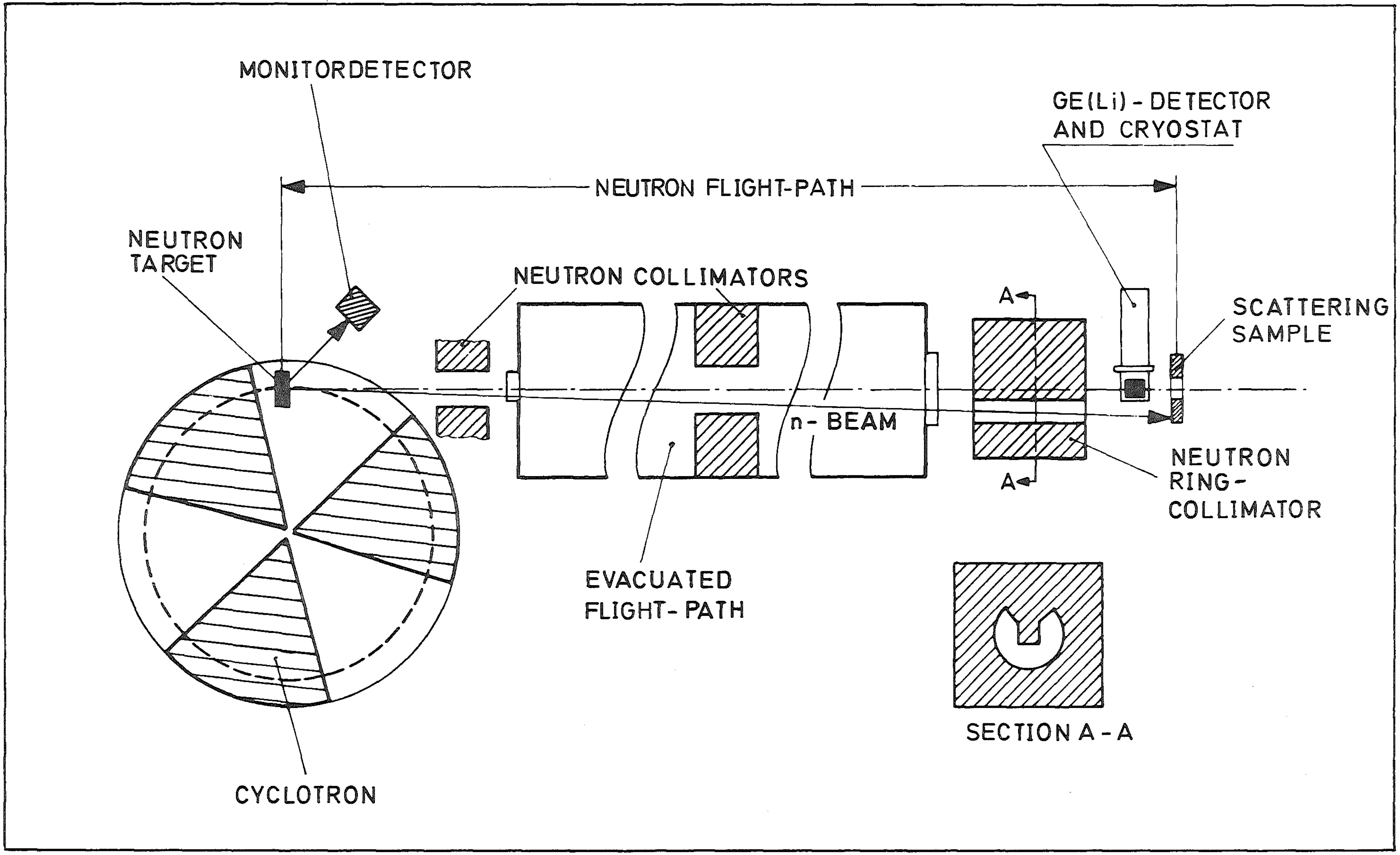
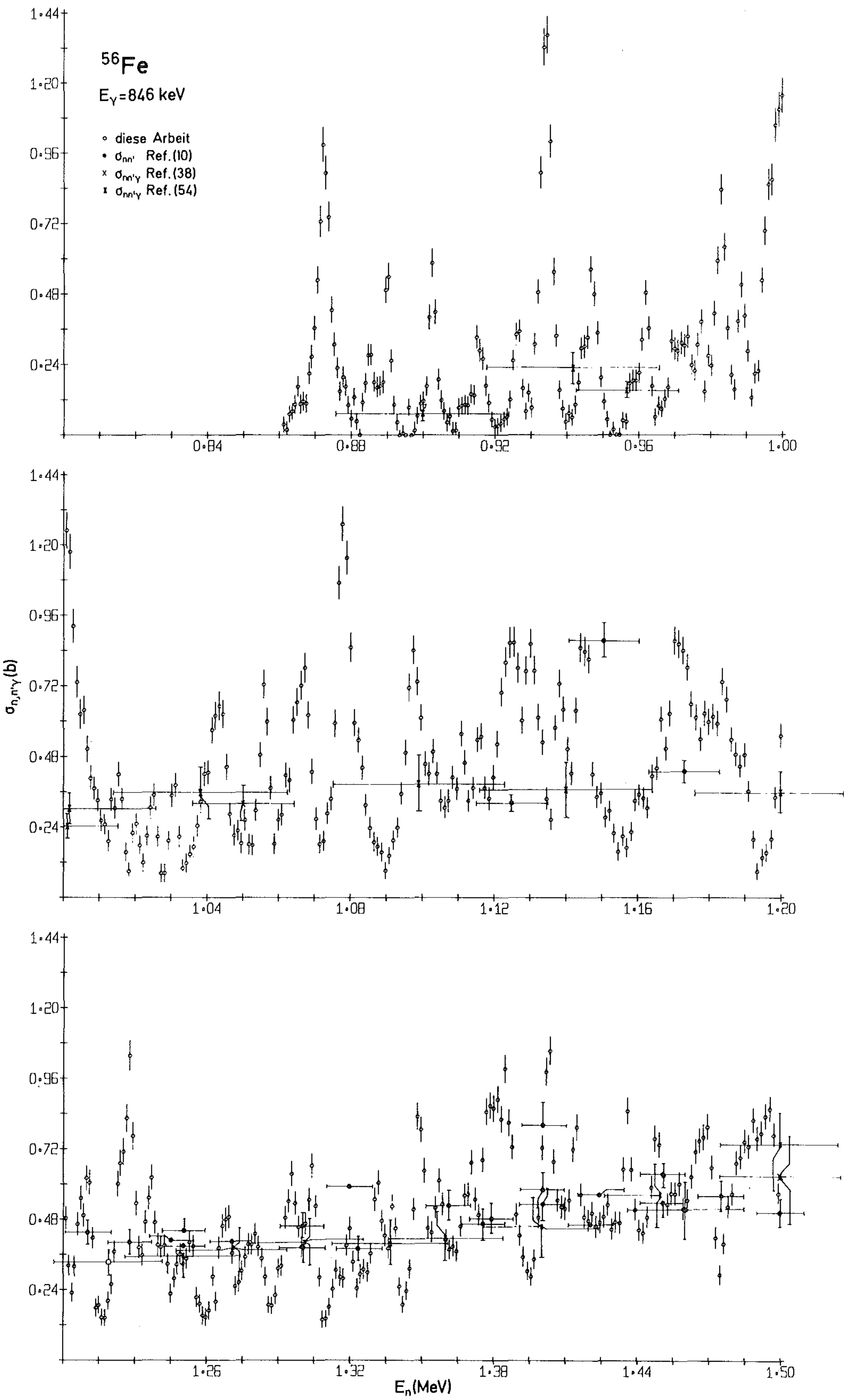
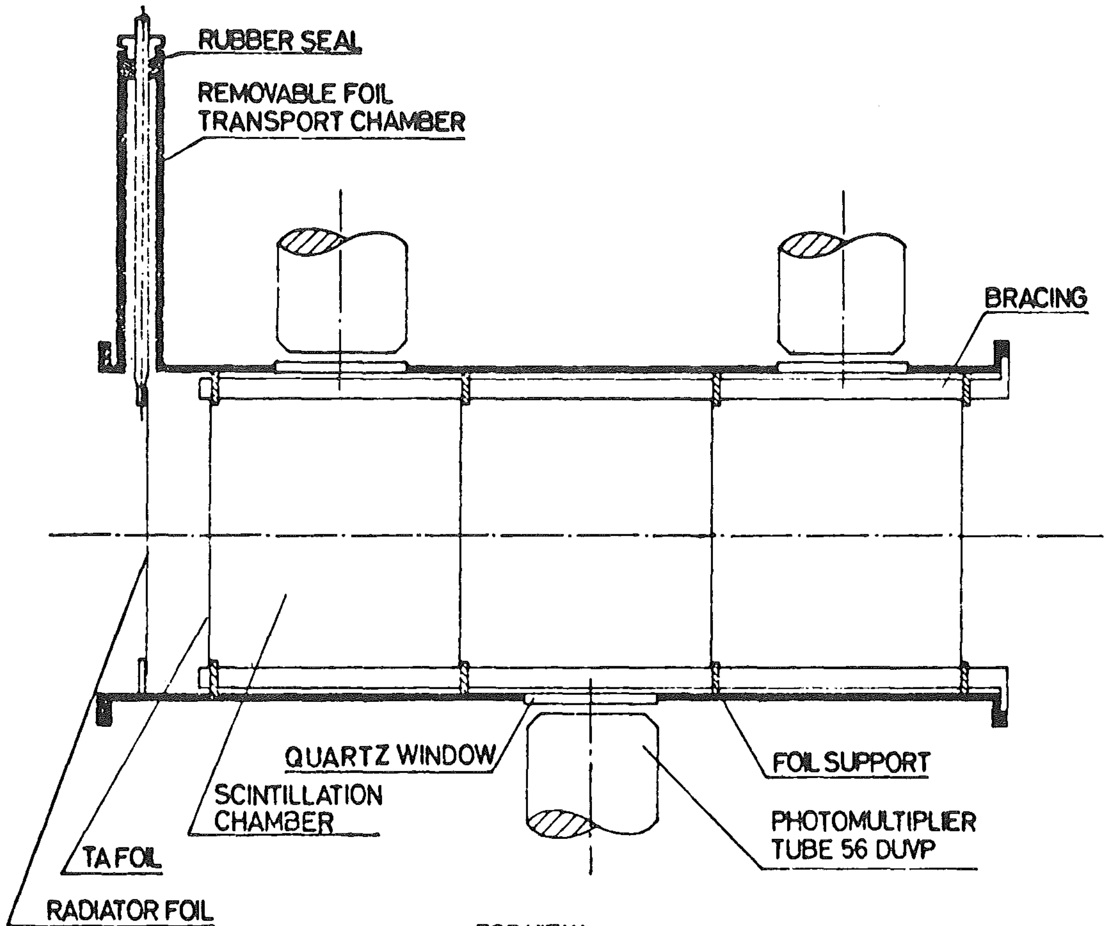

MONITORDETECTOR
GE(Li) - DETECTOR
AND CRYOSTAT
NEUTRON FLIGHT-PATH
NEUTRON
TARGET
NEUTRON COLLIMATORS
A
SCATTERING
SAMPLE
n- BEAM
NEUTRON
RING-
COLLIMATOR
A
EVACUATED
FLIGHT- PATH
SECTION A - A
CYCLOTRON

Fig. 9

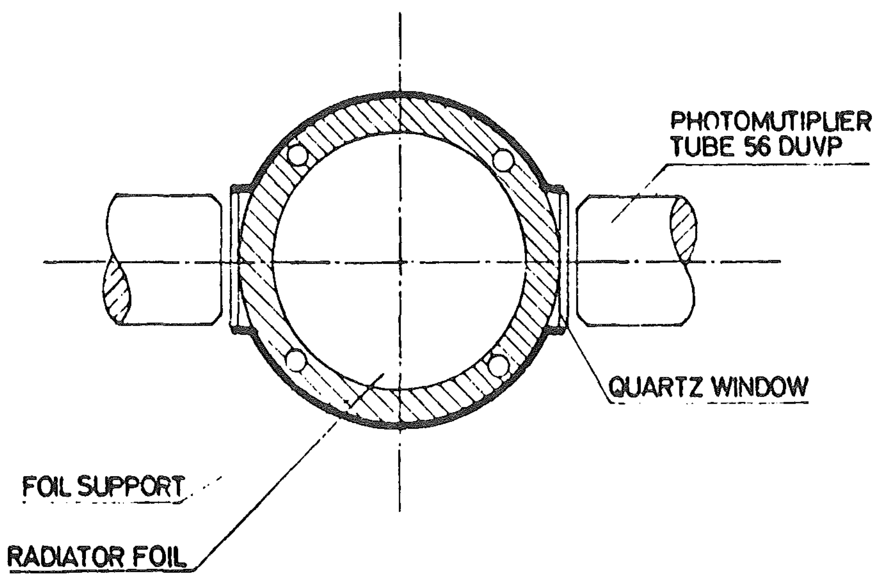


56Fe
Eγ=846 keV
diese Arbeit
σnn' Ref.(10)
σnn'γ Ref.(38)
σnn'γ Ref.(54)
1·44
1·20
0·96
0·72
0·48
0·24
0·84
0·88
0·92
0·96
1·00
σn,n'γ(b)
1·04
1·08
1·12
1·16
1·20
1·26
1·32
1·38
1·44
1·50
En(MeV)

Fig. 10



TOP VIEW



FRONT VIEW

Fig. 11