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FINAL REPORT

THE FAST NEUTRON EMISSION SPECTRUM OF ^{252}Cf

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Atominstitut der Oesterreichischen Universitaeten, Vienna, Austria

December 1979

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1. SCIENTIFIC BACKGROUND AND SCOPE OF PROJECT

The radionuclide ^{252}Cf emits neutrons which arise in the spontaneous fission process. Several years ago, the International Atomic Energy Agency Consultants' Meeting on Prompt Fission Neutron Spectra recommended that the fission neutron spectrum of ^{252}Cf be defined as a standard neutron field. In recent years, ^{252}Cf has often been investigated by means of different experimental methods with a view to obtaining reliable knowledge of the spectrum.

The spectrum can be well approximated analytically by a Maxwellian distribution

$$N(E) \propto \sqrt{E} \cdot \exp(-E/T),$$

where T is the nuclear temperature. Of interest is mainly the value of the temperature parameter, which is given in MeV. Thus, the most important task in any investigation of the neutron emission spectrum is to determine the nuclear temperature and measure the characteristic deviations of the actual spectrum from a Maxwellian shape.

Surprisingly, though a considerable number of different measurements have been carried out, no unique spectral distribution has been determined. This may be due, firstly, to different source preparations and different source-to-detector arrangements and secondly (and probably to a larger extent), to different efficiency determinations of the neutron detector. The latest review [1] shows that more recent measurements support a value of 1.42 ± 0.01 MeV for the nuclear temperature. But further confirmation is desirable. No overall consensus has been achieved, especially as regards the detailed shape of the spectrum and the magnitude of a deviation from the Maxwellian shape. For example, for the region above 8 MeV there exist discrepancies[a]. Kotel'nikova et al. [2] report experimental values above a Maxwellian shape, whereas Green et al. [3] have measured a negative deviation. Other authors, e.g. Knitter et al. [4], have found no deviation from a Maxwellian shape. Most investigators use time-of-flight (TOF)

methods, where the neutron detectors are either liquid or plastic scintillators. The proton-recoil spectra measured by these types of detectors show a strong increase at small pulse heights. A high sensitivity of the detection efficiency therefore exists for small changes in the discriminator level. Though great efforts were made in most experiments to correct for amplification changes, some uncertainties came in owing to these corrections.

There are essentially two other methods which can be applied in measuring neutron energy spectra in the energy region of interest: nuclear reactions induced by neutrons and proton-recoil methods. The main disadvantages of the first method are small cross-sections and concurrence processes in the region 1 – 10 MeV, and complicated detector set-ups. The second method is a real alternative to the TOF experiments, though a considerable computer effort is necessary for analysing the measured recoil spectra. The advantages of proton-recoil methods are mainly that the total neutron energy can be transferred to the proton, that the elastic scattering of neutrons on protons is isotropic below 10 MeV and that the cross-section for this process is the best known of all.

The detectors can be of several kinds. One group consists of liquid or solid scintillators. The efficiency is very high. However, there is no linear dependence between proton energy and luminous efficiency; moreover, a certain probability of double scattering exists due to the high total efficiency. One, therefore, has complicated proton-recoil distributions, especially at higher neutron energies. On the other hand, scintillators have good γ-discrimination properties, except at energies below 1 MeV. The measured recoil distributions must be unfolded to the neutron spectrum by numerical methods. Encouraging applications have been reported, including applications with ^{252}Cf, by Capgras et al. [5].

Another possibility is the use of nuclear emulsions. Their outstanding properties are very good energy resolution (about 3 %) and good discrimination to background radiation. Their low

sensitivity and the laborious analysis of the recoil tracks are disadvantageous. The lower energy limit of this method is near 500 keV.

Particle telescopes are another method involving recoil techniques. These arrangements consist of a "radiator foil" containing hydrogenous substances and one or more proton detectors, which are connected in coincidence and record the proton energy in a small angular region. By means of the coincidence circuit, good discrimination against background is possible. However, the efficiency of these telescopes is very low - firstly, because the neutron beam must be collimated, secondly, because the radiator must be thin in order to avoid large losses of energy and, thirdly, because the proton detectors can "see" protons only in a small angle.

The best developed proton-recoil method is the application of gas-filled spectrometers. Benjamin et al. [6] introduced this method in 1964 for measuring neutron spectra, and Bennett [7] proposed an efficient method for discriminating against the accompanying γ-background over the different pulse rise-time. The main advantage is the relatively high efficiency, which depends on the size and filling pressure of the counting tube. The energy resolution is fairly good, about 4 % to 10 %, which is sufficient for most spectrum measurements. There are no concurrence reactions to distort the measured spectrum. The energy for creating one ion pair is constant between 200 keV and 10 MeV. A disadvantage is the need to unfold the recorded proton-recoil distribution, which is often distorted by wall and end effects.

The aim of this work was a new measurement of the neutron emission spectrum of ^{252}Cf neutron standard sources as the IAEA is offering them to users. The main feature was the application of gas-filled proton-recoil spectrometers and no TOF technique. The IAEA ^{252}Cf neutron sources consist of a cylindrical capsule with an outer length of 22.0 mm and an external diameter of 2.80 mm. The capsule material is an alloy of 90 % Pt and 10 % Ir; the wall thickness varies between

0.20 mm and 0.50 mm. This type of source has been calibrated by comparing its strength with that of a ^{252}Cf source standardized by the National Bureau of Standards. Consequently, we did not measure the source strength. We were especially interested in the temperature parameter of the Maxwellian distribution and in its relative deviations. In this connection, special measurements with high energy resolution were carried out in a search for fine-structure neutron groups, which have been observed in some TOF measurements (see e.g., V.Y. Averchenkov et al. [8], P. Guenther et al. [9].

2. EXPERIMENTAL METHOD

For our measurements we chose two different proportional counter spectrometers, a large tube of about 900 mm total length with an energy resolution of 8 % to observe the total energy range of around 0.9 MeV to 10 MeV, and a small tube with high energy resolving power of 4 % to examine the energy interval from 1 to 3 MeV in a search for fine-structure groups.

The proportional counters are of conventional type as successfully used for fast reactor and subcritical assembly spectrum measurements (Bennett [7]). The counter tubes were provided by Berthold Corp., Wildbad/Schwarzwald, Federal Republic of Germany.

Counter tube data:

		counter tube I		counter tube II	
inner diameter		8.8	cm	4.8	cm
active length		83.3	cm	40.0	cm
total length of inactive volume at the ends		3.1	cm	3.1	cm
wall thickness		0.25	cm	0.20	cm
high voltage		3600	V	3200	V
gas mixture	CH_4	200	kPa	300	kPa
	Kr	200	kPa	---	
	^3He	0.1	%	0.1	%

Because it is necessary to keep the wall effects for high-energy protons as small as possible, one must use filling gases with large stopping power and, for attaining high efficiency, gases with a large number of hydrogen atoms per molecule. Accordingly, only hydrocarbonates or mixtures of hydrocarbonates with heavy noble gases are suitable. Counters filled with pure hydrogen can be used only up to energies of about 200 keV. The advantage of the high stopping power of heavy noble gases is offset by the disadvantage of low efficiency. We use in our

large counter tube krypton as stopping medium. Though it has a lower stopping power, it has the merit of a very small reaction cross-section. Therefore, no distortions of the proton-recoil spectra due to reaction products of krypton appear. In our measurements we chose a neutron incidence parallel to the counter axis. If the length of the cylindrical counter tube is large compared with its diameter, a proton-recoil distribution up to a proton energy E_{max} can be evaluated where the proton range $R(E_{max})$ should be about twice the diameter. In our case, the large counter tube has a diameter of about 90 mm, i.e. the recoil-proton range may not exceed, say, 200 mm. According to the energy-range tables of Ward-Whaling [10], we can fill our counter either with 700 kPa ≈ 7 atm methane or with a mixture of krypton with methane, pressure 400 kPa ≈ 4 atm. For technical reasons we chose the latter possibility. The smaller counter tube is filled with pure methane to a pressure of 300 kPa ≈ 3 atm since we use it only for the narrower energy range between 1 MeV and 3 MeV, where stopping power considerations do not apply.

The counter designs are very simple. The cylindrical wall of the counter tube serves as cathode. The tube is made of stainless steel and is burnished. For good energy resolution the anode wire must be uniformly thick (50 μm) over the whole length and be precisely centered. For further details see the schematic cross-section of counter I in Fig. 1.

The energy resolution of a proton-recoil spectrometer is influenced by:

1. Geometric factors: The field distribution in a cylindrical counter is concentrated in the vicinity of the anode wire and depends strongly on its diameter. As mentioned earlier, the uniformity of the wire thickness over the whole length of the counter tube is an essential operating condition. The shape of the cathode has a slight influence on gas multiplication and, thus, on the energy resolution.

At the end of the anode wire some distortions of the electrical field occur if it is terminated only by insulator

seals. Bennett [7] proposed using "field tubes" to keep the distortions as small as possible. In our case we did not use special designs since the inactive end volumes are small compared with the active volume of the counter tubes. Calibration measurements have shown that no significant worsening of the energy resolution occurred.

2. Gas-dependent factors: Ion recombination and the creation of negative ions during charge collection worsen the energy resolution. However, if the counter diameter is small (a few cm) and the gas pressure is only a few atmospheres, then this recombination effect can be neglected. Admixtures of electronegative gases such as O_2, F_2, Cl_2, etc. cause an enlargement of the recombination by some orders of magnitude, i.e. the negative ion is lost for the process of charge collection and the gas multiplication factor becomes about 1. Therefore, the filling of these types of spectrometers must be done with great care. No carbon tetrachloride, no trichlorethylene and no acids may be used for cleaning. The filling gases must be ultrapure.

3. Time-dependent factors: Standard sources (source strength $\approx 10^6$ neutrons/sec) require long measuring times. High stability of the electronic arrangement is therefore necessary. The amplification must be checked from time to time with a pulser. The stability should be better than 10 % of the inherent energy resolution of the counter.

The energy calibration for this type of spectrometer is more complicated than for TOF techniques. There exists no neutron standard with discrete monoenergetic neutron groups up to 10 MeV. If no neutron generator with variable neutron energy is available, the only possibility is the application of stationary neutron sources with well-known neutron emission spectra. The best realization to this requirement seems to be the use of the photoneutron system ^{24}Na-Be with discrete neutron groups at 974 keV, 1780 keV and 2272 keV. Since the higher energetic contributions $E > 974$ keV are rather weak,

this source can only be used for calibrating purposes to large spectrometers with rather high efficiency. In our case this calibration method was readily applicable. We measured the ^{24}Na-Be source in the same geometry as the ^{252}Cf source, except that the direct beam from the γ-emitter to the spectrometer was shielded by a 15 cm thick lead layer. The actual neutron source is a Be-cylinder of 5 cm height and 6 cm diameter. We chose this geometry so as to reduce ~~the reduce~~ the disturbing γ-background, which releases electrons mainly by photoeffect in the counter wall. In our case the background was sufficiently low. Therefore, no electronic γ-discrimination techniques had to be applied. The relation between ionization in the counter and true energy values must be known for the energy calibration. Several authors have found a linear dependence of energy on ionization. For the energy interval of interest in our measurement, the best relation for methane-filled counters is given at Powell and Rogers [11]

$$E(\text{MeV}) = I(\text{MeV}) + 0.004\ \text{MeV}.$$

That means that the measured energy scale must be shifted by 4 keV if the ionization is known. Since no distortions of the scale occur, one can calibrate the multichannel analyzer directly. An additional energy calibration point was obtained by adding 0.1 % ^{3}He to the filling gases. Irradiation with thermal neutrons gives rise to 764 keV protons from the reaction ^{3}He(n,p)^{3}H. A paraffin layer 20 cm thick produces sufficient thermal neutrons. On account of the large absorption cross-section of ^{3}He for thermal neutrons (0.5327 pm^{2} = 5327 barn), the proton peak was visible in all spectrum measurements and served not only as calibration point but also as a check on the gain stability of the whole system. For this reason we restricted ourselves to a low energy limit of 0.9 MeV in all measurements, since lower energies are affected by the ^{3}He distributions.

Knowledge of the efficiency of the counter tube for monoenergetic protons is necessary in order to transform the measured pulse-height distribution to the true one. In the

ideal case, one should have available a set of monoenergetic proton sources in the energy region of interest. These proton sources should be distributed isotropically in the counter tube. Since such sources do not exist, Bennett [12] has proposed another way of obtaining efficiencies of gas-filled recoil counters. The reactions $^{14}N(n,p)^{14}C$ and $^{3}He(n,p)^{3}H$ (see above) induced by thermal neutrons provide monoenergetic protons of 615 keV and 764 keV, respectively. By lowering the gas pressure, the range of the protons can be increased. Apparently sources with higher energy are therefore simulated. The advantage of this technique is that all effects, not only geometrical ones but also physical ones, are taken into consideration. Experimentally, however, it is very complicated to vary the pressure of gases of extremely high purity. In the most cases, therefore, theoretically calculated "response functions" and efficiencies are used.

The following situations can influence the response of a cylindrical counter:

1. The proton trace is on the whole in the active volume
2. The proton trace is on the whole in the inactive volume at the end of the counter tube
3. The proton trace starts in the active volume and ends in the inactive volume
4. The opposite case: the proton starts near the ends and is moderated in the active volume
5. The proton trace is truncated in the counter wall ("wall effect")
6. The proton trace is partly in the active volume and partly in the inactive volume, and is truncated in the counter wall

For isotropic incidence to the counter, these different possibilities with different probabilities can be evaluated analytically; this has been done by Snidow and Warren [13].

In our case, as mentioned above, only neutron incidence parallel to the cylinder axis is allowed. In a similar geometry Werle [14] has measured neutron sources and used

a Monte-Carlo routine to calculate the response of the counter. Since this method proved to be suitable, we also utilized the main features of this type of analysis but we modified it in some aspects.

The measured proton-recoil pulse-height distribution P(y) can be written as follows

$$P(y) = \int_{X_2}^{X_1} R(y,X) \cdot A(X)\, dX \qquad (2)$$

where A(X) is the desired proton-recoil distribution and R(y,X) is the so-called "response function". X_1 and X_2 are the energy limits between which the spectrum is evaluated. Since the spectra are recorded in discrete steps ("channels") we can write equation (2) in vector representation as

$$\vec{P} = R \cdot \vec{A} \qquad (3)$$

where R is then called the "response matrix" of the detector system. The higher the order of the matrix the better is the approximation (3) in comparison with equation (2). It is necessary to invert the "response matrix" in order to obtain the true distribution $\vec{A}$:

$$\vec{A} = R^{-1} \cdot \vec{P}$$

The numerical capacity of computers used not to be sufficient for inverting large (> 100 x 100) matrices with appropriate accuracy. Iterative methods for solving this problem had therefore to be applied. By means of modern computers it is no problem to invert matrices like ours (256 x 256) with high precision. Consequently, we chose this way.

If the vector $\vec{A}$ is known, one gets the neutron distribution desired by the well-known relation

$$\varphi(E) = - \frac{E}{\sigma(E)} \cdot \frac{dA(E)}{dE} \qquad (4)$$

E is the energy obtained by the calibrated multichannel analyser and $\sigma(E)$ is the elastic scattering cross-section of neutrons on

protons. This cross-section is very well known and can be fitted with sufficient accuracy between 1 MeV and 40 MeV by an expression given by Gammel [15]:

$$\sigma(E) = 3\pi(1.206\ E + (-1.86 + 0.09415\ E + 0.0001306\ E^2)^2)^{-1} + \\ + \pi(1.206\ E + (0.4223 + 0.13\ E)^2)^{-1} \qquad (E \text{ in MeV})$$

In this investigation we applied a method, introduced by Baumann [16], which connects eq. (2) and eq. (4):

$$\vec{N} = R'^{-1} \cdot \vec{P} \qquad (5)$$

Now the measured proton-recoil distribution will be directly transformed into the desired neutron spectrum. In this case, the response matrix R' is a triangular matrix where the column vectors are the response functions characterizing how the counter tube records the proton-recoils of a monoenergetic neutron source. These values are multiplied with the corresponding elastic scattering cross-section. Here the response functions were calculated with the Monte-Carlo code MATRI [16], which is a modified version of Werle's code SPEC-4 [17]. In this program a neutron with initial energy E is assumed to hit a proton in the counter gas. The path of the proton is pursued and the length of the trace recorded. This procedure is repeated 50 000 times for each response function. Afterwards, the response functions for the desired channels are interpolated. The only input is a realistic energy-range table for the protons. We used the recent values of Northcliffe and Schilling [18].

The following fact emerged: if the measured proton spectrum is recorded with good statistical accuracy, then it is not necessary to use matrix inversion subroutines; it is sufficient to use the Gaussian elimination method for calculating the neutron distribution.

Although this method seems so far to be straightforward, there is a serious restriction if continuous spectra with a significant high-energy part are recorded. It is obvious that contributions of neutrons

(a) beyond the high-energy limit of the unfolding relation (2) ($E_n > X_2$) or

(b) higher than the highest energy channel in relation (5) give rise to proton-recoil distributions in the energy interval of interest. If this high-energy distribution is unknown but cannot be neglected for intensity reasons, it is impossible, in principle, to get reliable results. In many cases the upper limit of the spectral distribution is within the range of the multichannel analyser. In our case we chose the energy interval between 0.9 MeV and 10 MeV for analysis. We therefore had to correct for the high-energy part of the ^{252}Cf neutrons. We took a Maxwellian shape for this distribution with a temperature parameter T = 1.42 MeV derived in a recent review. The error of this assumption is much smaller than the error of the response functions calculated by the Monte-Carlo routine. We took into account the high-energy part of neutrons between 10 MeV and 15 MeV by summing all proton response functions for 100 keV broad energy bins. This proton-recoil distribution was normalized, so that it corresponds to the numbers of counts in the highest energy channel (channel number 256) of the measured proton-recoil distribution. Then we subtracted the corresponding part of the high-energy distribution in all channels considered. In this way we apparently got a proton-recoil distribution which has no contribution in the highest energy channel, as in the case when no high-energy tail contributes. This method has already been applied successfully by Werle [17].

Experimental set-up

A schematic view of the experimental set-up is shown in Fig. 2. A nearly free geometry was realized in a separate room with a distance of 1.5 m between detector and the floor of the room. A paraffin layer (thickness 5 cm) with a 0.5 cm thick boron carbide sheet on the surface covered the floor in a square 2 x 2 m between source and detector. This arrangement should suppress the neutron background backscattered from the floor. If single scattering occurs in the paraffin layer of this geometry, a neutron loses approximately 80 % of its initial energy. That means thata neutron up to 4.5 MeV will not be recorded in our measurements if it has undergone one single scattering process in the paraffin layer as the low-energy threshold was chosen at 0.9 MeV. The boron carbide layer should reduce the thermal neutron background as the counters used are sensitive to this radiation due to the ^{3}He admixture.

As mentioned earlier, we used both counters in axial geometry, i.e. the incident neutron beam must be parallel to the cylinder axis. For point sources like the ^{252}Cf sources, the condition holds that the distance to the source must be at least four times the diameter of the counter tube. Otherwise there may arise errors in the unfolding procedure of the proton-recoil spectra (Werle [17]). In our case the source strength of the ^{252}Cf neutron source is sufficiently high (about $10^{6}/(sec \cdot \mu g)$). Therefore, it was possible to choose a distance of 80 cm between the source and the end of the spectrometer.

The electronic equipment used was very simple. We first thoroughly investigated the γ-background of the ^{252}Cf source. For this purpose we designed an electronic circuit to distinguish between γ-quanta and neutrons. We differentiated the pre-amplifier output signal using a small time-constant (100 psec). Then a timing point at the beginning of the ascending pulse is set by means of a "constant fraction discriminator" (CFD). A "timing single channel analyser" (TSC) in cross-over operation sets a timing point where the pulse crosses the

baseline. These timing points are fed into a "time-to-amplitude converter" (TAC) as a start and stop signal. This time interval represents the rise-time of the original pulse in good approximation. On a multichannel analyser one can clearly distinguish between γ-quanta and neutrons if the pulse-rate is not too high (i.e. up to 10^4/sec). We gated the original output signals from the main amplifier with the "gamma signals" and saw that these few pulses contribute only at the lowest pulse heights and that almost no pulses exceed our experimental threshold of 0.9 MeV. We therefore renounced the γ-discrimination in the actual measurements. Thus, we used only a pre-amplifier (ORTEC PC 109), a main amplifier (ORTEC 450 Research Amplifier) and a multichannel analyser (NUCLEAR CHICAGO Model 25603). For calibration we used a precision pulser (BERKELEY NUCLEONICS PB-4) and a stabilized high-voltage supply (TENNELEC TC 942).

3. RESULTS OBTAINED AND CONCLUSIONS

As pointed out earlier, our intention was to measure a large part of the ^{252}Cf neutron spectrum, which is important mainly in standardization measurements. We were interested not only in the temperature parameter T but also in the significant deviations from a Maxwellian distribution in the energy range from 0.9 MeV to 10 MeV. With the small counter with good energy resolution (about 4 %) we looked for fine-structure neutron groups in the energy range between 1 MeV and 3 MeV.

Before the long-term measurements, both counter tubes were thoroughly tested, especially for the optimal value of gas multiplication. This value was found by varying the high-voltage and observing the energy resolution. With the large counter long-term measuring were carried out over two periods. One period lasted 9 days and the other one 4.5 days. Between the two periods 7 days of background measurements were inserted. The background was also recorded before and after the measurements. From time to time during the runs the position of the ^{3}He peak was checked to ensure that no shift in the amplification of the detector and amplification system had occurred. With the large counter we measured altogether approximately 2×10^{7} events. Since we could not find any change in the background distribution and in the amplification, we added the two proton-recoil distributions for final evaluation. The resulting neutron spectrum is shown in Fig. I. The error bars include not only statistical but also systematic errors due to the Monte-Carlo method used in obtaining the response functions. No significant deviations from a monotonically decreasing function were noted. As the next step we fitted a Maxwellian distribution to these data by means of the least-squares method. The resulting temperature parameter was $T = 1.409 \pm 0.015$ MeV. To show the significant deviations from the Maxwellian shape we divided all channel contents by the best fit Maxwellian value; we present the result in Fig. 2.

Although the scatter of the data is rather large, one can see significant deviations from the Maxwellian shape; especially in the region from 1 MeV to 5 MeV. The amount and location of these deviations are consistent with the results of Green et al. [3] and Werle [14]. This is a strong indication for the correct determination of the response matrix and a good estimate of the high-energy contribution (see section 2). Encouraged by this result we looked for a simple representation of this spectral deviation. Green et al. [3] proposed a model which is based on physical facts but has the disadvantage of depending on twenty (!) parameters. We therefore chose a simple polynomial of fourth degree which fits the deviations to ± 7 % between 0.9 MeV and 10 MeV.

The total spectral shape of the ^{252}Cf source measured in this research project can be written as follows:

$$N(E) = K \cdot (\sqrt{E} \cdot \exp(-E/T) \sum_{i=0}^{4} a_i E^i) \qquad (6)$$

The accuracy of this approximation is ± 4 % at 1 MeV, ± 7 % at 3 MeV, ± 20 % at 6 MeV and ± 50 % at 10 MeV. The coefficients of the polynomial fit and the temperature parameter values are listed in Table I. The normalization constant K depends on the source strength and is meaningless if only the relative neutron spectrum is considered.

A subordinate purpose of this work was the search for fine-structure neutron groups in the spectra of ^{252}Cf. In 1971 Averchenkov et al. [8] reported monoenergetic fine-structure peaks which were partly confirmed by Kotel'nikova et al. [2] and Guenther et al. [9]. The question was raised as to whether these neutron groups arise from delayed emission processes of stopped fragments or are dummy effects which originate from inelastic scattering of the source neutrons in air. It is clear that the complicated unfolding procedure which introduces a relatively large systematic error will probably obscure these fine-structure groups. We used another method already presented in the last progress report. The

basic idea is that the gross spectral shape is of no interest for the purpose considered. As shown in eq. (1), the neutron distribution depends strongly on the energy derivative of the proton-recoil distribution; i.e. any structures must become clearly apparent if the measured proton-recoil distribution is differentiated. Since no wall or end effects and no cross-sections are considered, the resulting distribution has no overall similarity with the neutron spectrum. To correct at least for the uniform and smooth main contribution, we subtract the same but sufficiently smoothed distribution. It proved sufficient to "differentiate " by subtracting neighbouring channels since the underlying neutron distribution is decreasing monotonically. We smoothed the derivative by applying three point averaging (i.e. between three neighbouring channels) thirty times. Almost no statistical fluctuation was noted in this distribution. We applied this procedure to the distributions measured with the large and with the small counter. The results obtained with the large counter were shown in the last progress report. Within the statistical error bars no fine-structure groups were observed. We have improved the method and applied it to data obtained by the small counter, which has much better energy resolution (about 4 %). The result is shown in Fig. 5. Although, depending on the energy resolution, the full width at half maximum should be more than twenty channels at 1.5 MeV, no significant deviations were observed. The irregularities at 0.95 MeV and 1.1 MeV do not coincide with the positions of fine-structures which have been reported by other authors. An estimate taking into account the counting statistics shows that fine-structure groups down to 1 % of the main contribution should have been visible with this method. Averchenkov et al. [8] report groups with 3 % intensity between 1 MeV and 2 MeV. The derivative procedure works well and can easily be checked by the appearence of the differentiated ^{3}He peak in lower energy channels. The additional oscillations in the neighbourhood of the ^{3}He peak originate from the subtraction of a smoothed and thus broadened ^{3}He peak. In short,

even using the small counter provided with better energy resolution we were not able to observe any fine-structure neutron groups. The unfolded spectrum obtained with the large counter exhibits a temperature parameter T = 1.409 ± 0.015 MeV and significant deviations from a Maxwellian shape which are consistent with earlier results. Thus, the proton-recoil method using gas-filled counters is as suitable as time-of-flight techniques for measuring fast neutron spectra provided that the high-energy part of the distribution is known or negligible.

Remark: We intend to publish the essential contents of this Final Report in a scientific journal.

Acknowledgment: The authors would like to thank Mr. M. Davies of IAEA for his assistance with some points of English.

TABLE I. PARAMETERS OF THE APPROXIMATION TO THE ^{252}Cf NEUTRON SPECTRUM

$$N(E) = K \cdot (\sqrt{E} \cdot \exp(-E/T) \cdot \sum_{i=o}^{4} a_i E^1)$$

Parameter	Value
a_o	0.89250
a_1	-0.36978×10^{-3}
a_2	0.30352×10^{-2}
a_3	-0.59229×10^{-2}
a_4	0.29983×10^{-3}
T	1.409 MeV

PAPERS PUBLISHED ON WORK DONE UNDER THE CONTRACT

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Figure captions:

Figure 1

Cross section of the large counter tube (counter I).

Figure 2

Schematical view of the experimental arrangement.

Figure 3

Resulting neutron distribution after unfolding the measured proton-recoil distribution.

Figure 4

Ratio of the neutron distribution to a Maxwellian. Full line is a fit to the data by a fourth degree polynomial.

Figures 5 and 5a

Differentiated and renormalized proton-recoil distribution measured by the small counter tube (counter II).

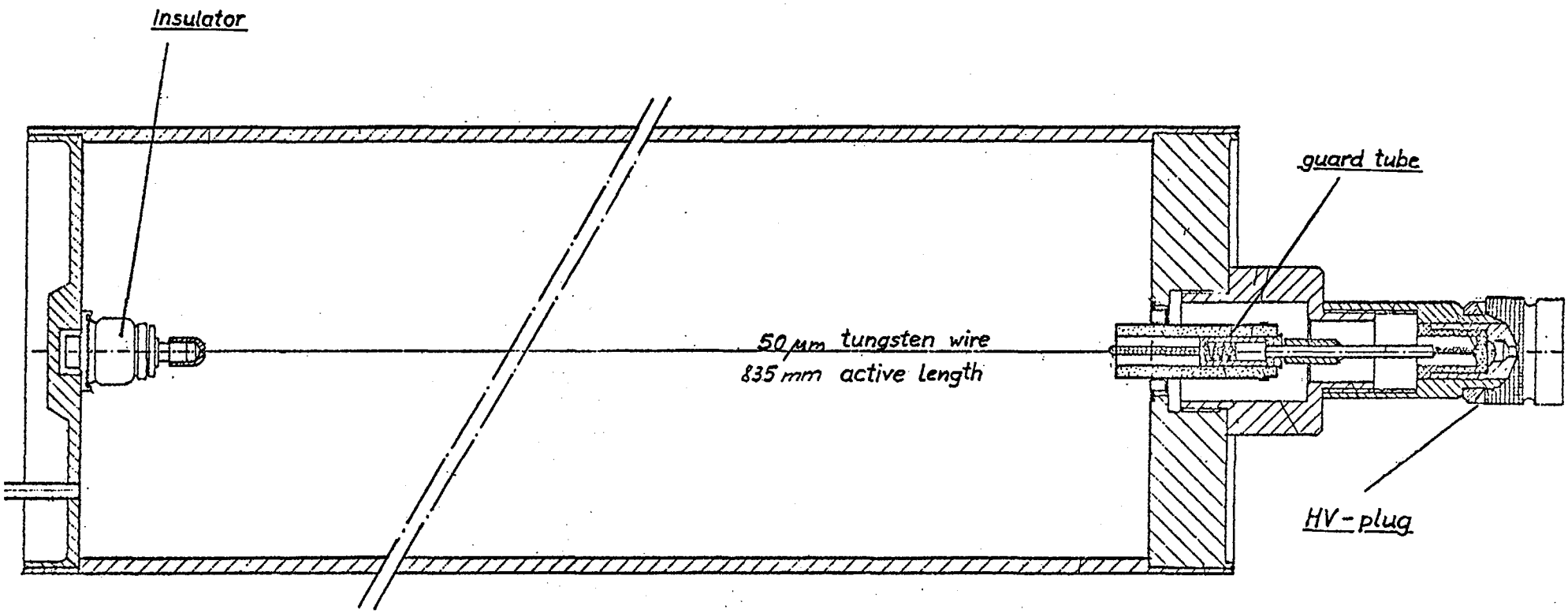
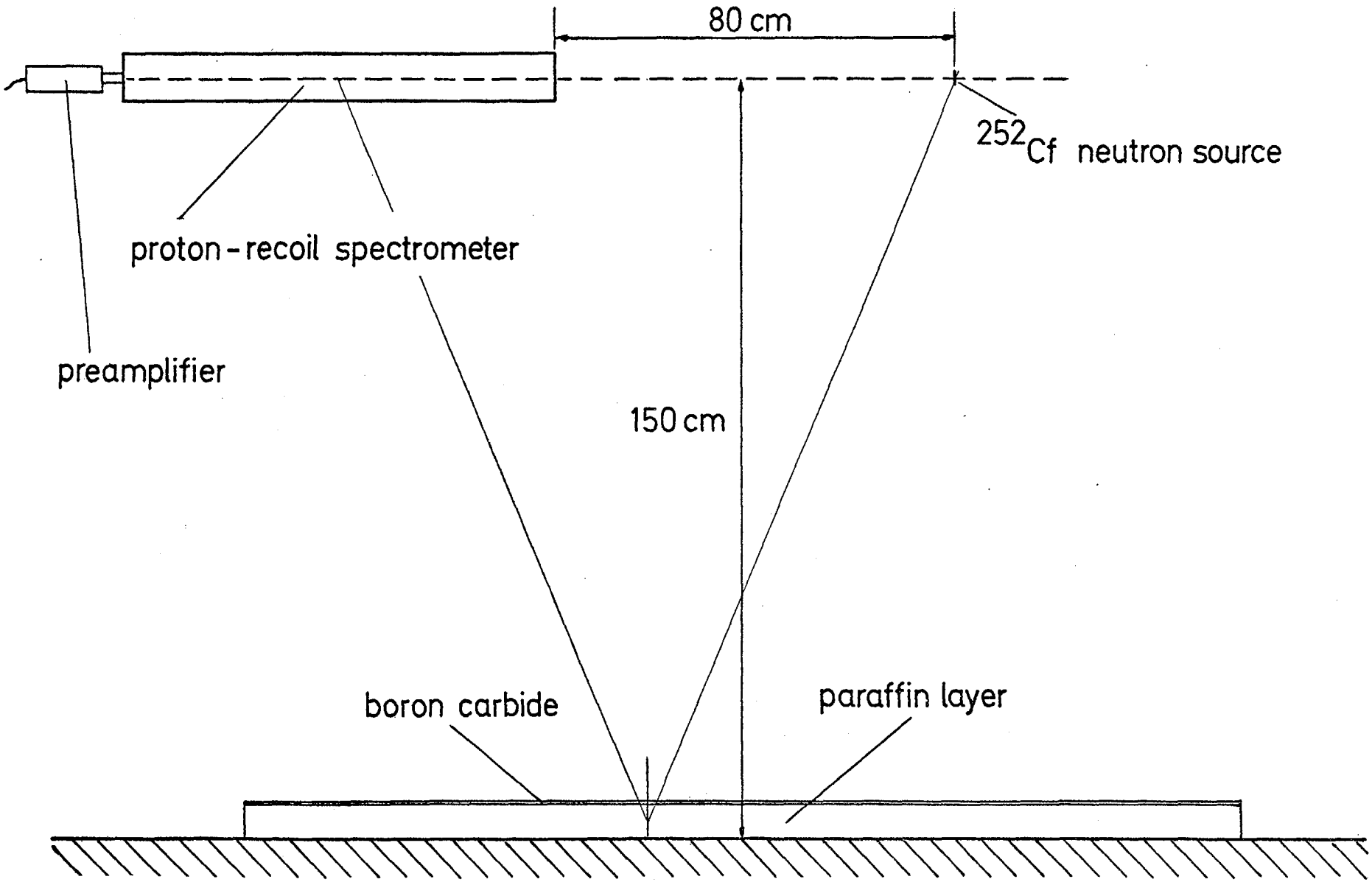

Insulator
guard tube
50 µm tungsten wire
835 mm active length
HV-plug

Figure 1

Figure 2


80 cm
252Cf neutron source
proton-recoil spectrometer
preamplifier
150 cm
boron carbide
paraffin layer

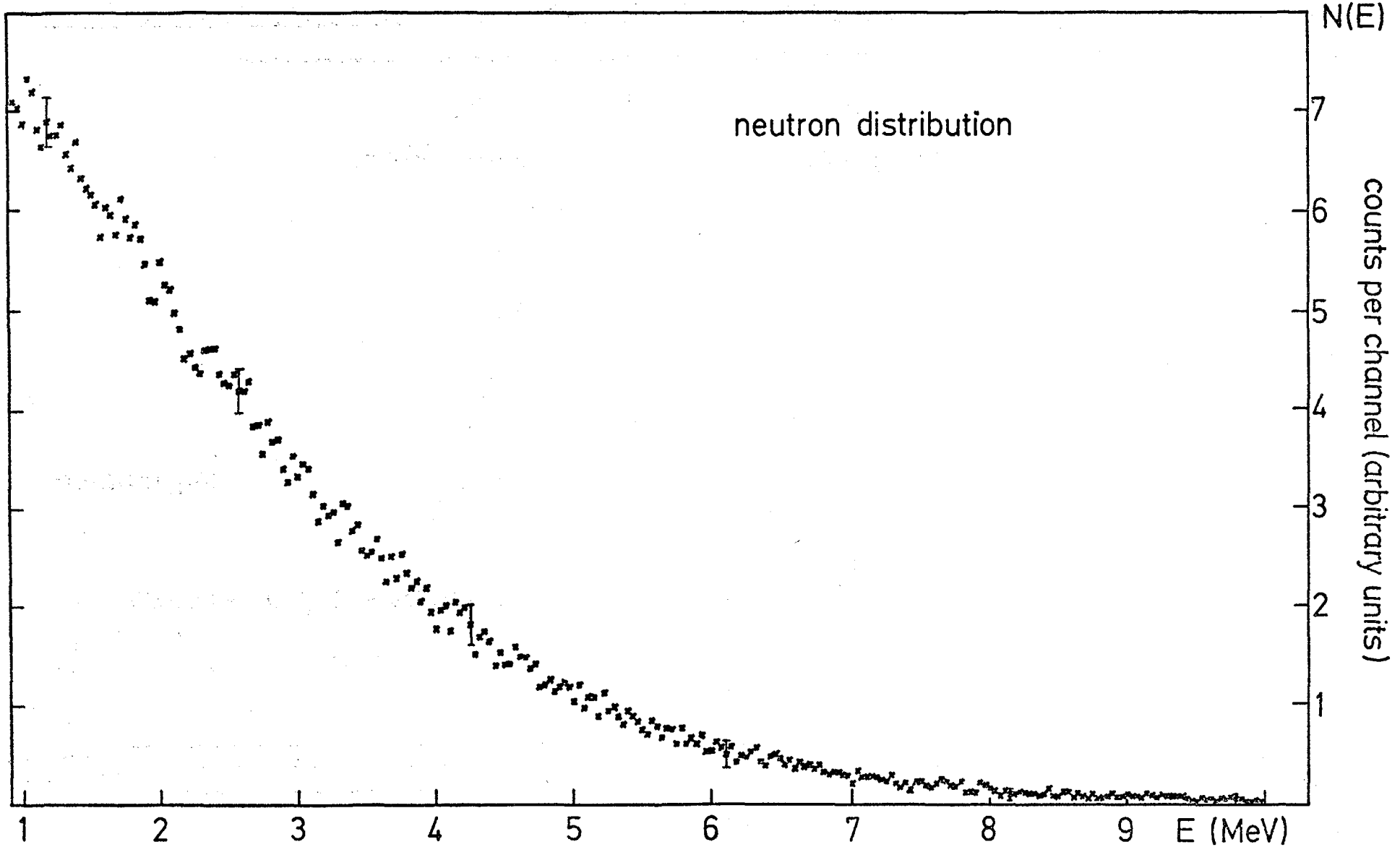

neutron distribution
N(E)
counts per channel (arbitrary units)
1
2
3
4
5
6
7
E (MeV)

Figure 3

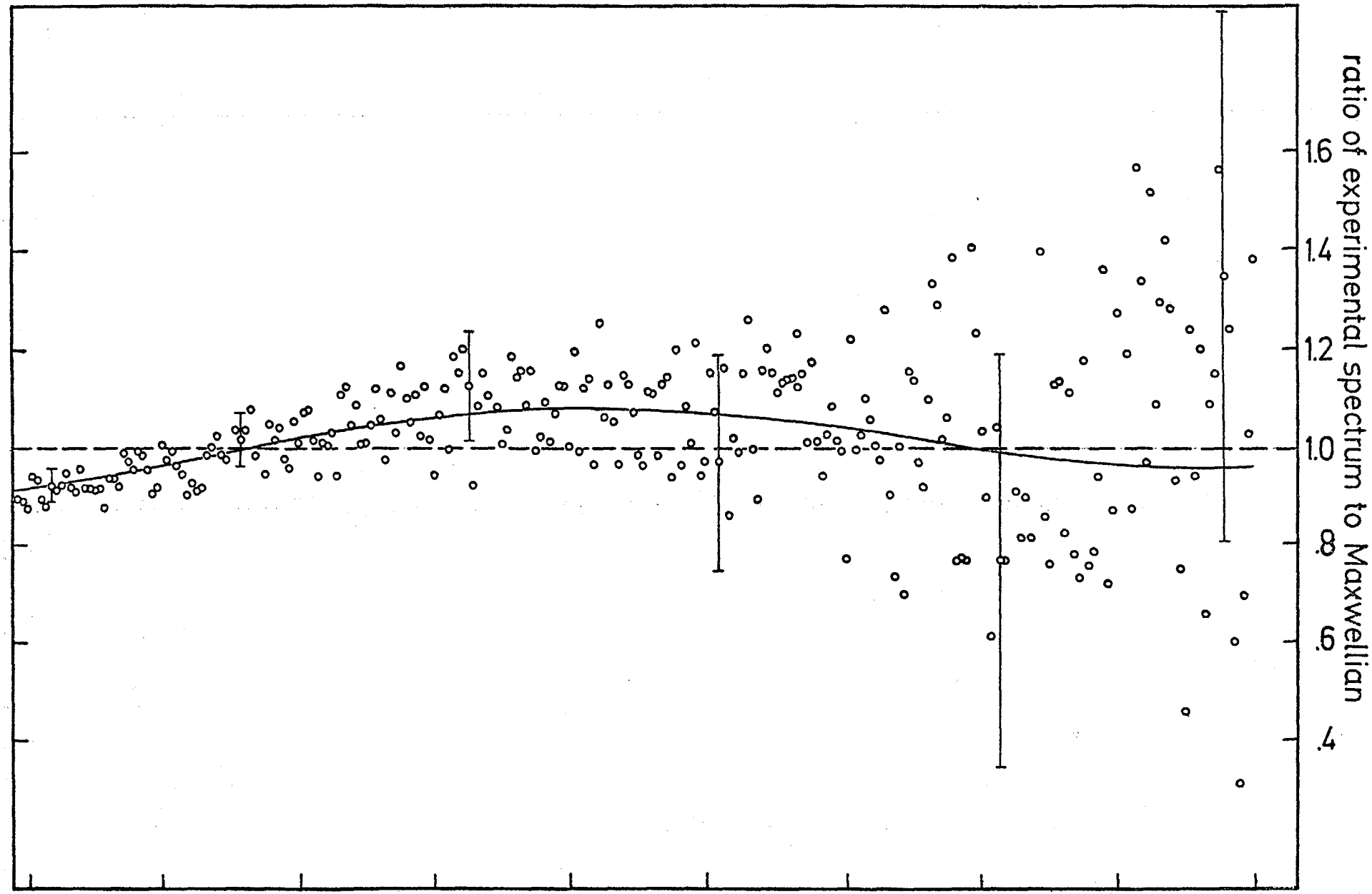

ratio of experimental spectrum to Maxwellian
1.6
1.4
1.2
1.0
.8
.6
.4
1
2
3
4
5
6
7
8
9
E (MeV)

Figure 4

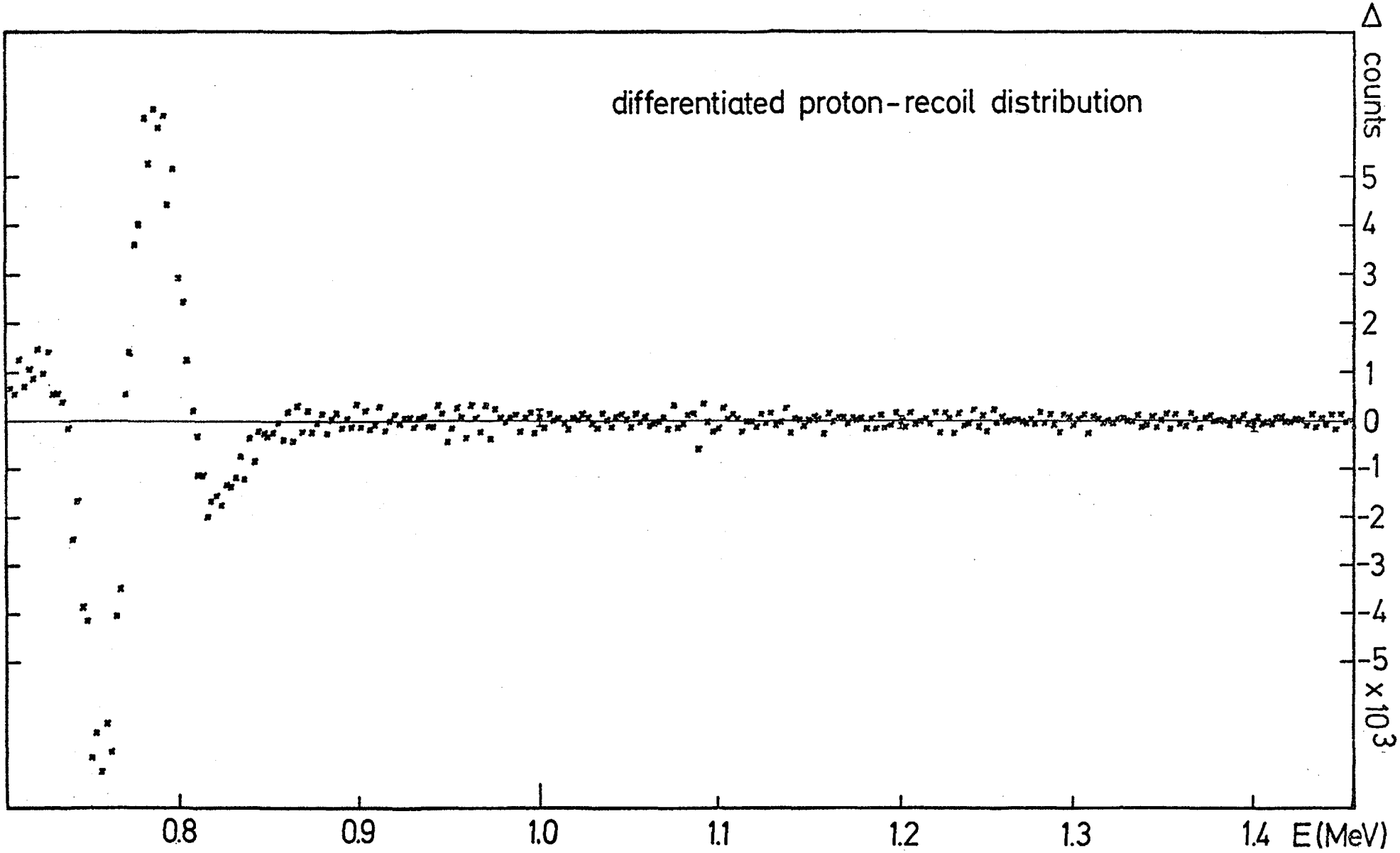

differentiated proton-recoil distribution
Δ counts
5
4
3
2
1
0
-1
-2
-3
-4
-5
x 10^3
0.8
0.9
1.0
1.1
1.2
1.3
1.4
E(MeV)

Figure 5

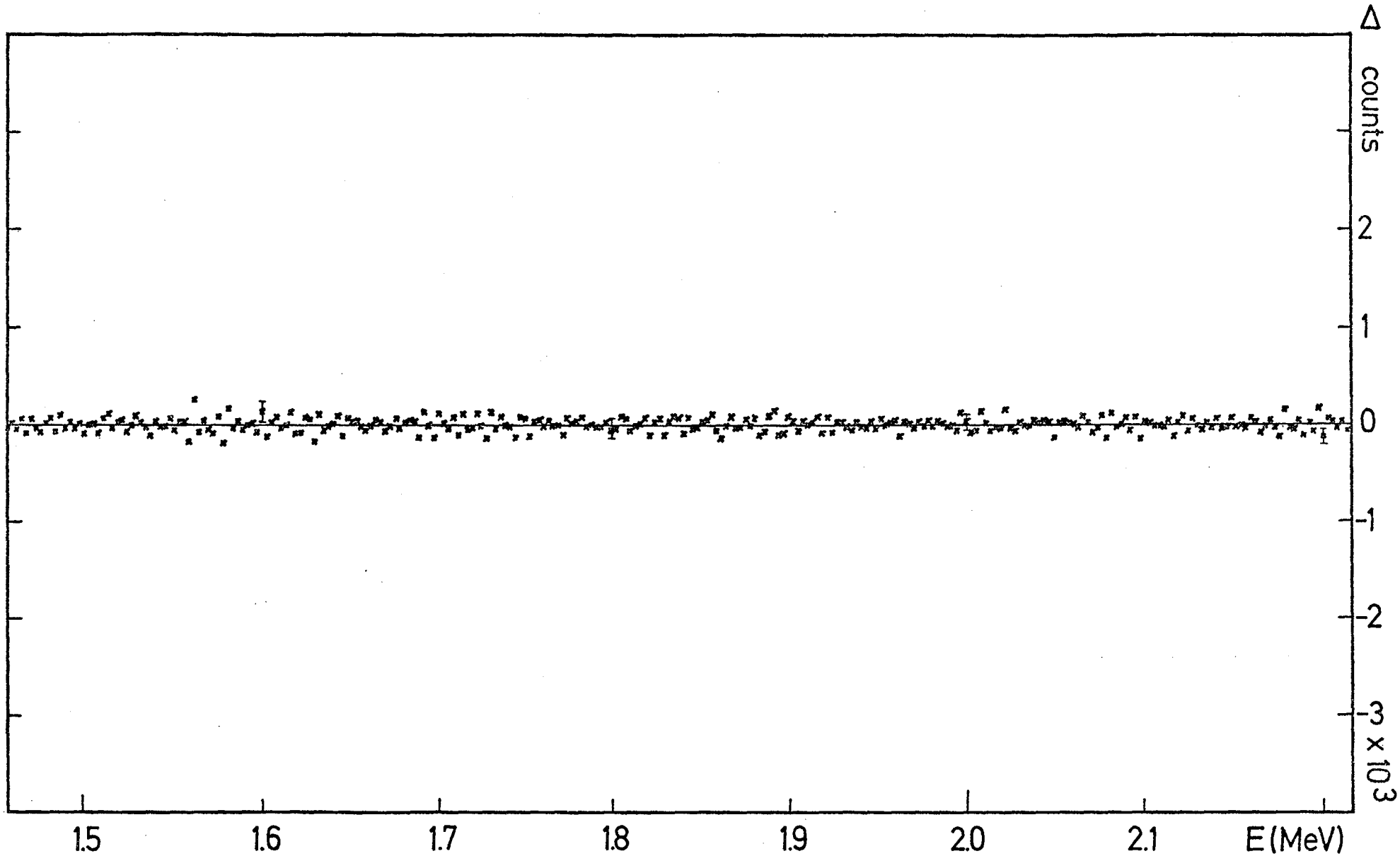


Figure 5a