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PROMPT FISSION NEUTRON SPECTRA

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ABSTRACT

Some of the main features of the present theoretical understanding of the fission neutron spectra are discussed. The effect of a possible center-of-mass anisotropy and the validity of Terrells $\bar{T}(\bar{\nu})$ relation are discussed. Results of some calculations on the prompt fission neutron spectra are given.

РЕЗЮМЕ

Излагаются некоторые основные аспекты теоретического описания энергетических спектров нейтронов деления. Рассматривается воздействие анизотропии, могущей возникнуть в системе центра масс осколков, а также область действительности зависимости Террелла $\bar{T}(\bar{\nu})$. Приводятся результаты нескольких расчетов по спектрам нейтронов деления.

KIVONAT

A hasadási neutron energia-spektrumok elméleti leírásának néhány főbb vonását tárgyaljuk. Vizsgáljuk a fragmentek tömegközépponti rendszerében fellépő esetleges anizotropia hatását, továbbá a Terrell-féle $\bar{T}(\bar{\nu})$ összefüggés érvényességi körét. Megadjuk néhány hasadási neutronspektrum-számolás eredményét.

I. INTRODUCTION

The main purpose of this paper is to give a short survey of the present state of the theory of the emission of prompt-fission neutrons. The topic is a very large one and is of great importance both for "pure" nuclear physics and for reactor physics and design. The large amount of experimental data and observations of the pre-1965 period and also most "macroscopic" measurements of the ensuing period were surprisingly well interpreted by Terrell's considerations [1] /The terms microscopic and macroscopic are used in a similar sense as in nuclear physics, that is the first term is used in connection with the individual fragment nuclei, while the second refers to the totality of fission reactions./

But understanding of such new observation as the saw-tooth dependence of the average number of prompt neutrons on the fragment mass, or the interpretation of the more sophisticated "microscopic" measurements, including those with higher excitation energies, have revealed the need for an extension and detailing of the earlier theoretical interpretations. /It is a pity that not much has happened in this field./

The need seems to be twofold; the interpretations of the microscopic spectra, the possible existence of more detailed characteristics of scission neutrons and the understanding of emmission processes at higher excitation energies on the one hand, the deviations and some new observations on the characteristics of the measured spectra on the other, require new considerations to solve the possible contradictions and new attempts to clarify the situation in a unified manner. I should like to make a small contribution in this direction by reviewing the present status of understanding.

Remarks on the experimental situation.

There seems to be no significant progress in the microscopic measurement of neutron spectra from low-energy fission, not even in the interesting but rather difficult problem of the scission neutrons, since the important measurement of Bowman et al., Ramanna et al., Skarsvag et al., Sargent et al. [2-6]. This is not the situation for fission induced by particles of higher energy, e.g. [7-11]. To only enumerate the results would be beyond the scope of this review. The practical need for better nuclear data has stimulated a number of authors to carry out neutron energy-spectra measurements, partly with new techniques, partly over an extended energy range, or just to confirm earlier data or such newly observed phenomenon as the detection of peaks or some excess in the low-energy part of the fission neutron spectra [12-24].

II. BASIC CONCEPTS ON EMISSION SPECTRA

The contradictory deviations in the conclusion drawn from experiment and the attempt to understand the best way of extracting information from measured spectra make it necessary to develop or revize Terrell's conclusions by tracing all approximations made, whether consciously or not, in evaluations of the experimental data. The energy and angular distributions of prompt-fission neutrons measured in the laboratory frame of reference are described partly as a sum of contributions of neutrons emitted from flying fragments and, as an assumed possibility for the case of low-energy fission, partly by the contributions of "central" or "scission" neutrons, that is of neutrons emitted before or just at the instant of scission of the fissioning nucleus. The investigation of neutrons of the later kind is being carried out by studying the deviations between experimentally determined and calculated spectra, assuming only neutrons from the fully accelerated fragments in the calculations. In the course of such calculations one tries to determine the spectrum form in the frame of reference of the fully accelerated fragments and then one transforms them into the laboratory system for possible comparision with the experimental data.

It has to be emphasized that the determination of the center-of-mass spectra is physically of basic importance and at the same time a most difficult task. There may be a lot of different spectra, depending on such characteristics of the individual fragments as the initial excitation energy /E^*/, number of neutrons and protons, /N,Z/, spins and so on. Only those spectra $\varphi_{c.m.}(\varepsilon,\vartheta,E^*,N,Z,E_k)$ retaining parameters which are thought to be the most important will be considered. /First approximation/ Here, ε and ϑ are the energy and the angle characterizing the direction of the emission of the neutrons in the c.m system. E_k , the kinetic energy of the fragment, seems to be included only formally, but it connects the total and excitation energies of the fragments through the relation $E_{total} = E_k + E^*$. The total spectra of neutrons in the c.m. system could be described by

$$n(\varepsilon,\vartheta)d\varepsilon\, d\vartheta = \sum_{N,Z} \int_{E^*} \rho(E^*,E_k,N,Z)\varphi_{c.m.}(\varepsilon,\vartheta,E^*,N,Z,E_k)dE\, d\varepsilon\, d\vartheta$$

The ρ-function gives the frequency of occurence of the fragment with the given characteristics.

These spectra must be transformed individually into the laboratory system according to the kinetic energy of the given fragment. The connection between the center-of-mass neutron energy, ε , and that in the laboratory system, is the well-known relation

$$E = E_f + \varepsilon + 2\sqrt{E_f \varepsilon}\cos\vartheta$$

where E_f is the fragment kinetic energy per nucleon (E_k/A), or more precisely the energy of a neutron moving with the velocity of the fragment.

Even if the c.m. spectrum forms for different fragments show strong similarity, in the laboratory system rather large differences have been observed in at least some characteristic spectrum parameters. Let the transformed spectra be $\phi(E,\Theta,E^*,N,Z,E_f)$. Then the total spectrum of neutrons can be given as

$$N(E,\Theta)dE\,d\Theta = \sum_{N,Z} \int_{E^*} \rho(E^*,E_k,N,Z)\ \phi(E,\Theta,E^*,N,Z,E_f)dE^*\,dE\,d\Theta$$

The next approximation is the replacement of the N,Z pair by A, which implies an imaginary averaging over the different N,Z on the condition that $A = N + Z$.

Then

$$N(E,\Theta)dE\,d\Theta = \sum_{A} \int_{E^*} \rho(E^*,E_k,A)\ \phi(E,\Theta,E^*,A,E_f)dE^*\,dE\,d\Theta$$

In Terrell's "classical" consideration the sum over A is ignored by using one or several representative fragments, and so the weighting function is reduced to the distribution probability of the different excitation energies, or in other words to the probability distribution of the fragment temperatures.

$$N(E,\Theta)dE\,d\Theta = \int_{T} p(T)\ \phi(E,\Theta,T)dT\,dE\,d\Theta\ .$$

As the transformation from c.m. to laboratory system is independent of T, formulas in the c.m. and laboratory system are similar.

The further approximation used to be to neglect the $p(T)$ distribution by using only one of their T values.

In our work [25] we have investigated another possible approximation, namely replacement of the initial energy distributions of the individual fragments by an average value, again in principle by an averaging

$$N(E,\Theta)\,dE\,d\Theta = \sum_{A} \rho\left(\bar{E}^*,\bar{E}_k,A\right)\,\phi\left(E,\Theta,\bar{E}^*,A,E_f\right)\,dE\,d\Theta \;.$$

In this case $\rho(E^*,E_k,A)$ becomes an expression proportional to the product of number of neutrons and the mass yield

$$\nu(A)\;.\;y(A).$$

Beyond the problems of averaging and of transforming from c.m. to laboratory system, the basic problem is the adequate description of the neutron cascades emitted from the individual fragments, that is the calculation of the function $\varphi_{c.m.}(\varepsilon,\vartheta,E^*,N,Z)$ or $\varphi_{c.m.}(\varepsilon,\vartheta,E^*,A)$. These functions ought to be determined in a detailed Hauser-Feshbach calculation, but the enormous quantity of calculations involved makes it necessary to find reasonable simplifications.

One approximation, based on the compound reaction theory, is the assumption of isotrop, or at least symmetric angular distribution about 90°. This can be realized by a general function $\varphi(\varepsilon,E^*,A)\cdot(1 + b\cos^{2J}\vartheta)$. For $\varphi(\varepsilon,E^*,A)$ there exists a number of different assumptions and approximations. The most often used one are the following:

a/ $\varphi_{c.m.}(\varepsilon,E^*,A) \sim \varepsilon.\sigma^{c}_{A}(\varepsilon).\omega_{A-1}\,(E^*-B_n-\varepsilon)$

where $\sigma^{c}_{A}(\varepsilon)$ is the cross-section of formation of a compound nucleus A of excitation E_i by a neutron of energy ε; $\omega_{A-1}(E^*-B_n-\varepsilon)$ is the density of nuclear energy levels in the final nucleus with mass number $A-1$, and B_n is the binding energy of a neutron.

From this an evaporation spectra of the form $\varepsilon \exp(-\varepsilon/T)$ is derived in the case of one neutron emission with the assumption of a constant σ_A^c. In this case, and in this case only, does the T parameter have some real, immediate relation to the nuclear temperature, although on the other hand the validity of the derivation for neutron energies $\varepsilon \ll \bar{\varepsilon}$ or $\varepsilon \gg \bar{\varepsilon}$ is rather questionable. /However, in the latter case, at small residual excitation energies the exact level densities could show a similar functional form up to energies where the use of level-densities becomes meaningless./

b/ The Maxwellian approximation $\varphi_{c.m.}(\varepsilon,E^*,A) \sim \varepsilon^{1/2} \exp(-\varepsilon/T)$ is supported by two special reasons. One is the general $1/\sqrt{\varepsilon}$ behaviour of the inverse cross-sections at low energies, the other is the theoretical reasoning of Lang and Le Couteur's studies [26], according to which a spectrum of the neutron cascade emission from a nucleus having a distribution of the initial excitation energies can be approximated tolerably well by a Maxwellian spectrum and there is a simple relation between the T parameter of the spectrum and the average initial excitation energy.

c/ There are the numerical results of "exact" cascade calculation [25], which seem to reproduce rather well the experimentally observed spectra, too.

d/ Phenomenological spectrum forms such as that of Brown et al. [2].

In sum, we can draw the conclusion that until recently the best theoretical established spectrum form is the Maxwellian one. This form takes into account the spread in the initial excitation energies automatically, so giving a reasonable simplification in the very complicated calculations. For tests with experiment these spectrum forms have to be transformed into the laboratory system and averaged for the different fragments and excitation energies.

III. SCISSION NEUTRONS

Comparison of the measured and calculated total angular and energy spectra indicates that there are extra neutrons with isotropic angular distribution in the laboratory system [2-6]. It appears that about 10-15 % of all prompt neutrons belong to this "central group" of neutrons and their average energy is somewhat greater than that of the prompt neutrons generally. It assumed that they are emitted about the instant of the scission and they are therefore referred to as "scission" neutrons.

In 1965 Sargent et al. were unable to demonstrate the existence of scission neutrons in photofission of ^{232}Th. As an attempt to clarify the problem of the reality of the scission neutrons, or at least of some of their properties, it has been shown in Ref. 25 that one can not exclude the possibility that this central component of neutrons might arise as a consequence of insufficiently precise evaluation of the experimental data.

IV. ENERGY SPECTRA OF FISSION NEUTRONS

If the center-of-mass emission spectrum is isotropic, the laboratory energy spectrum for a given E_f is

$$N(E)dE = \int_{(\sqrt{E}-\sqrt{E_f})^2}^{(\sqrt{E}-\sqrt{E_f})^2} \varphi(\varepsilon)/4\sqrt{E_f}.\varepsilon \, d\varepsilon$$

If the emission spectra of neutrons is of Maxwellian type, one gets the Watt distribution:

$$N(E)\,dE = \left(e^{-E_f/T}/\sqrt{\pi E_f T}\right).\, e^{-E/T}.\, \sin h\left(2\sqrt{EE_f}/T\right)$$

This Watt distribution with its simple average E_f /0.75 MeV/ does not fit the experimental data, indicating a c.m. emission spectrum, broader than a single Maxwellian and hence possibly the necessity for a more realistic averaging process for the different E_f values, as suggested in Ref.1.

Moreover, c.m. spectra are better represented by a sum of two Maxwellian distributions of different average energy and thus the laboratory spectra can be viewed as a sum of at least four Watt distributions, the result of which is close to a Maxwellian distribution. See Ref. 1.

Note that the same situation is valid for the case of c.m. evaporation spectra, that is the sum of evaporation spectra transformed into laboratory system can be approximated rather well by one Maxwellian spectrum /Meadows/. These observations confirm the considerations of the first part of this paper.

Effect of a c.m. anisotropy on the energy spectra

One has to take into account also the effect of a possible anisotropy of the c.m. fission neutron spectrum /Hill, Wheeler/. Here we quote Terrell's result for a spectrum

$$\varphi_{c.m.}(\varepsilon,\vartheta) = \varphi_{c.m.}(\varepsilon)\,(1 + b\cos^2\Theta)$$

Then laboratory spectrum is

$$N(E)dE = \int \frac{\varphi(\varepsilon)\left[1 + b\left(E-E_f-\varepsilon\right)^2/4\varepsilon E_f\right]}{4\left(\varepsilon E_f\right)^{1/2}\,(1+b/3)}\,dE$$

It can be observed that an anisotropy of this type causes a perturbation in the energy spectra, but for low energies leaves the $E^{1/2}$ dependence unchanged, even allowing for the possibility of a fit to a Maxwellian with changed T and with not so good overall agreement.

The main effect of an anisotropy with $b > 0$ is twofold:

a/ a decrease in the neutron yield between 0.7 and 3 MeV, b/ an increase elsewhere at the expense of the average energy. Thus in principle the anisotropy can cause the effect observed by Meadows and other authors, namely a surplus number of neutrons at low energies relative to a Maxwellian fit at other energies. This possibility was not verified until recently.

V. TERREL'S $T(\nu)$ RELATION

An inadequate averaging process can cause deviations of some of the experimental data from the simple form of the relation between the average neutron energy and the average number of neutrons proposed by Terrell From the relation between the laboratory and c.m. neutron energies one gets for the averaged values of these energies

$$\bar{E} = \bar{E}_f + \bar{\varepsilon}$$

where

$$\bar{\varepsilon} \sim \bar{T} = \langle \bar{E}_r^{1/2}/a^{1/2} \rangle_{AV} \sim \left[(\bar{\nu}+1)\, E_o/2a \right]^{1/2}$$

$\bar{T}$ is an averaged, representative value of the parameters of the assumed evaporation spectra.

$$\bar{E}_r = \bar{E}_i^* - B_n - \bar{\varepsilon} \sim (\bar{\nu}+1)\, E_o/2$$

where ν and E_o are the average number and the average excitation energy change per emitted neutron, respectively.

For the value of E_f Terrel obtained 0.78±0.02 and later 0.74±0.02 MeV. The fact that E_f remains essentially unchanged for a wide range of Z and A, although the total fragment kinetic energy divided by the total number of nucleons $E_f = E_k/A = 0.121Z^2/A^{4/3}$ increases with Z, may be connected with the compensating decrease of the mass ratio with increasing Z.

However, these considerations seem to stray too far from the exact averaging process by a $\rho(E^*, E_k, N, Z) * \varphi_{c.m.}(\Theta, \vartheta, E^{\prime\prime}, N, Z)$ distribution. We can state that Terrell's $T(\nu)$ expression for the T parameters of the laboratory energy spectra

$$\bar{E} = 3/2\ T \sim a + b\sqrt{\bar{\nu}+1}$$

is a rough general guide and is probably a good expression for the case of different excitations of the same fissioning nuclei, if the fragment mass yields and the kinetic energy distributions do not change drastically with the variations of the excitation. A too precise test of this expression for different fissioning nuclei seems to be meaningless on the other hand.

VI. SPECTRA AT HIGHER EXCITATION ENERGIES

The study of the $T/\bar{\nu}/$ relation leads directly to the problem of investigating neutron spectra at higher excitation energies /above 10 MeV/. Despite the experimental difficulties a considerable number of such experiments on fission neutrons have been carried out [7-11]. The "microscopic" information of great importance, such as the dependence of average neutron energies on the fragment mass, has been obtained, but in general this gives no direct information for the evaluation of the total neutron spectra.

The theoretical considerations should be similar to those for the case of low excitation energies, but the problem of the poorly known dependence of the previously mentioned weighting functions and that of the characteristics of the spectrum shapes of the neutron cascade processes make them expecially difficult.

After these short remarks I should like to turn back to a discussion of the problem of the evaluation of experimental neutron spectra of fissioning nuclei at lower excitation energies.

VII. RESULTS OF SOME NEW CALCULATIONS

Though we can not speak of a basic progress in the theoretical understanding of neutron spectra, the comparisons of results of different approximate calculations can give some guide for further studies.

On the basis of the approximations described in the first part of this paper, we have made some pure theoretical calculations in the c.m. system of fragments, with the assumption of different spectrum types. By using realistic c.m. average energies and weighting functions for spontaneous fission of ^{252}Cf and for the thermal fission of ^{235}U we have obtained total neutron spectra in numerical forms.

What conclusions can be drawn from this calculation?

1/ All of the total spectra could be described rather well, by a simple Maxwellian spectrum, but the fits in different energy intervals give different values of T. See Table 1.

2/ As mentioned by Meadows, the effect of anisotropy seems to be the most probable cause of the extra neutrons at low energies relative to the Maxwellian distribution /see Figs. 1-5/, but for more precise conclusions more detailed investigations are needed.

3/ The calculations direct attention to some possibilities of understanding the deviations in the values of spectrum temperatures obtained by the different authors for different energy ranges.

4/ The deviations of the experimental data from a single Maxwellian could indicate a description with two Maxwellian of different T parameters.

The conclusions with respect to the energy and angular distribution of neutrons are summarized in a paper to be published in Phys. Letters [25]. Because of the lack of energy-angular distribution data below 0.5 MeV the theoretical calculations likewise refer neutron energies larger than 0.5 MeV.

VIII. CONCLUSIONS

After this review of only some of the main features of the present situation of the fission neutron spectra, it must be stated that this paper is far from being a comprehensive or complete one. The intention has been to point out some interesting aspects of problem which may have some actuality and which should be settled in a more definite way. From this point of view we have to keep in mind that both nuclear fission itself and neutron emission from fission reactions are very complex processes and the simplifications that arise out of this complexity have only a limited range of validity.

On this basis the following comments can be made on the subject.

1/ From the theoretical point of view similar experiments to those of Bowman et al., Skarsvåg and Bergheim, and others, but over extended energy ranges and for specific fragment excitations and kinetic energies, would be of great importance, and could give more decisive information on the problem of a possible c.m. anisotropy, or on the problem of the existence of scission neutrons.

2/ Energy spectrum measurements with proper precision over extended energy intervals also would be very informative, if special care would be given to the accuracy of

a/ the detection of fragments of all kinds and different kinetic energies,

b/ the proper averaging for the different angles /these remarks may not apply to earlier measurements/,

c/ the more detailed spectrum analysis not only by deducing an overall T parameter for the spectra but also by evaluating it for definite energy ranges,

d/ the effect of the different background problems.

3/ More spectrum measurements of fission of higher energies are required for the experimental study of $T/\bar{\nu}/$ relations. Perhaps these are too unrealistic desires at present, but results of this type would greatly help theoreticians to escape from the stagnancy into which work on the solution of the problem of fission neutron spectra has fallen.

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Energy range MeV	T for different basic spectra				
	MAX.	MAX-AN.	BOW	BOW-AN	CAS.
^{252}Cf					
0.003 - 15	1.405+0.007	1.384+0.005	1.458+0.003	1.435+0.006	
0.5 - 15	1.374	1.385+0.007	1.446	1.457+0.003	
1 - 15	1.365	1.375+0.006	1.442	1.453	
0.003 - 10	1.449+0.008	1.391+0.010	1.473	1.430+0.009	
0.59 - 10	1.410	1.402+0.020	1.458	1.470+0.003	
With scission neutrons	1.428		1.468		
1.2 - 10	1.397	1.388+0.020	1.453	1.466	
0.003 - 7.5	1.496+0.009	1.422+0.012	1.478+0.005	1.405+0.013	* 1.50+0.007
0.5 - 7.5	1.445	1.458+0.009	1.451	1.463+0.005	* 1.46+0.006
1 - 7.5	1.422	1.437	1.439	1.452	* 1.45+0.005
0.003 - 6	1.521	1.424+0.015	1.481+0.006	1.390+0.016	
0.5 - 6	1.470	1.482+0.009	1.450	1.461+0.006	1.306+0.021
1 - 6	1.450+0.006	1.466	1.435	1.448	1.268
0.003 - 2	1.671+0.007	1.295+0.040	1.592+0.003	1.249+0.044	
0.5 - 2	1.599+0.007	1.595	1.579+0.014	1.582+0.010	1.938+0.025
1.2 - 2	1.560	1.574	1.510+0.017	1.527+0.016	1.861+0.027
0.003 - 1	1.741+0.005	1.063+0.050	1.594+0.004	1.006+0.050	
0.59 - 1	1.667	1.615+0.004	1.656	1.613+0.004	2.123+0.018
^{235}U					
0.003 - 15	1.342+0.005		1.288+0.008		

* With spectrum of Ref. 2 averaged from 0^{o} up to 85^{o}, only.

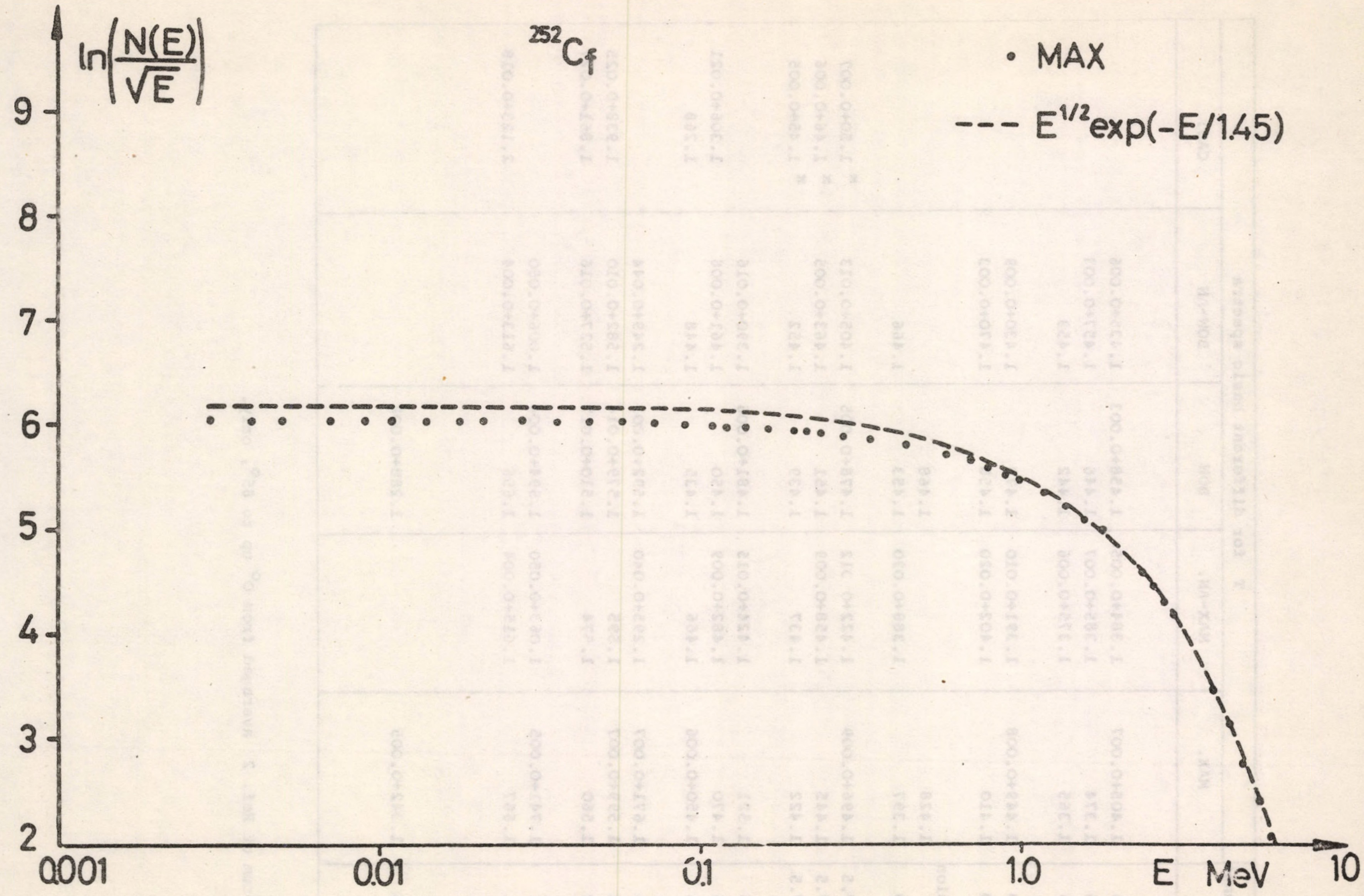

Fig. 1

● - sum of Maxwellians (MAX)

----- - single Maxwellian fit from 1 MeV to 10 MeV

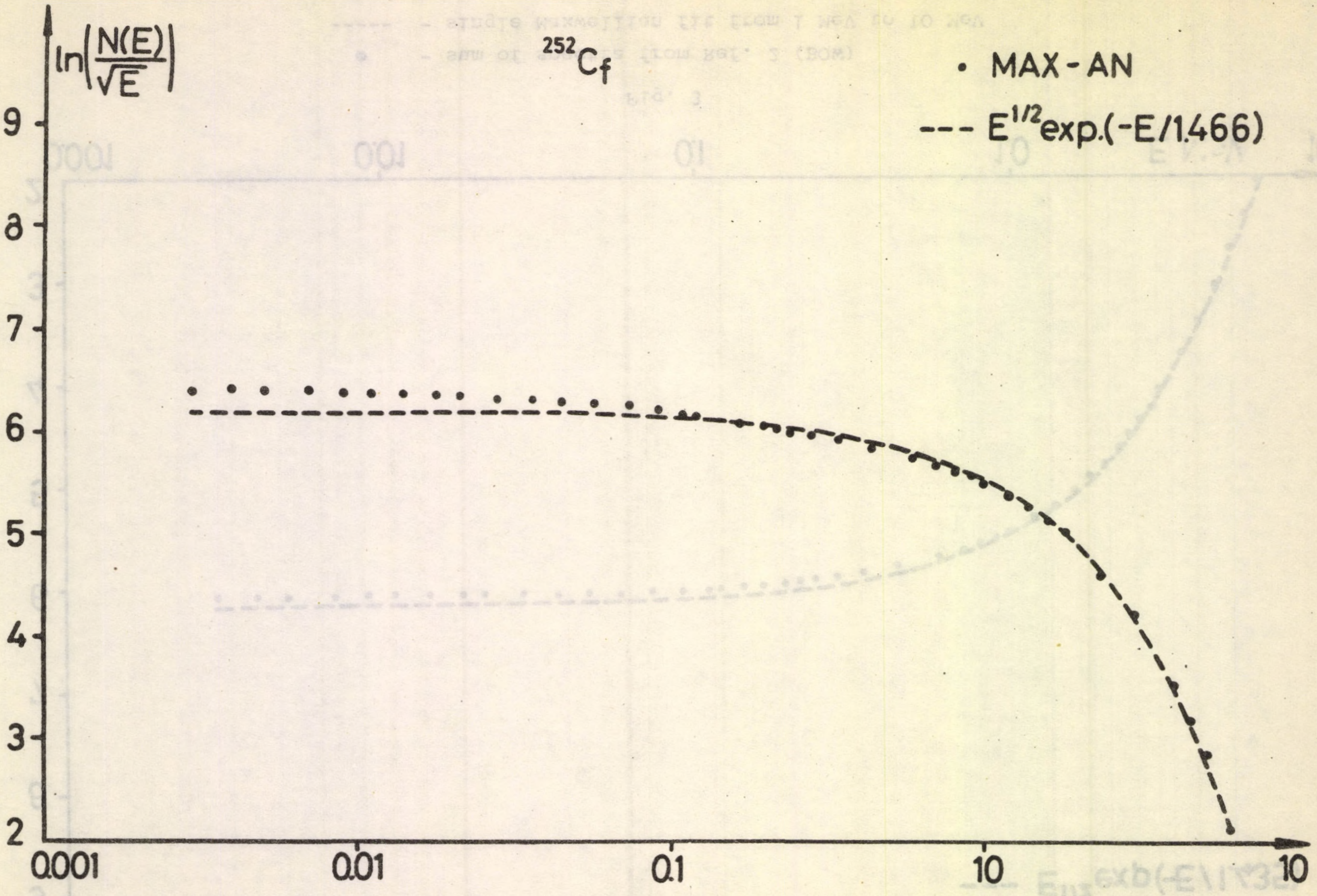

Fig. 2

● - sum of anisotropic Maxwellians $\varphi_M(\varepsilon)(1 + 0.4\cos^{16}\vartheta)$ (MAX-AN)

----- - single Maxwellian fit from 1 MeV to 10 MeV

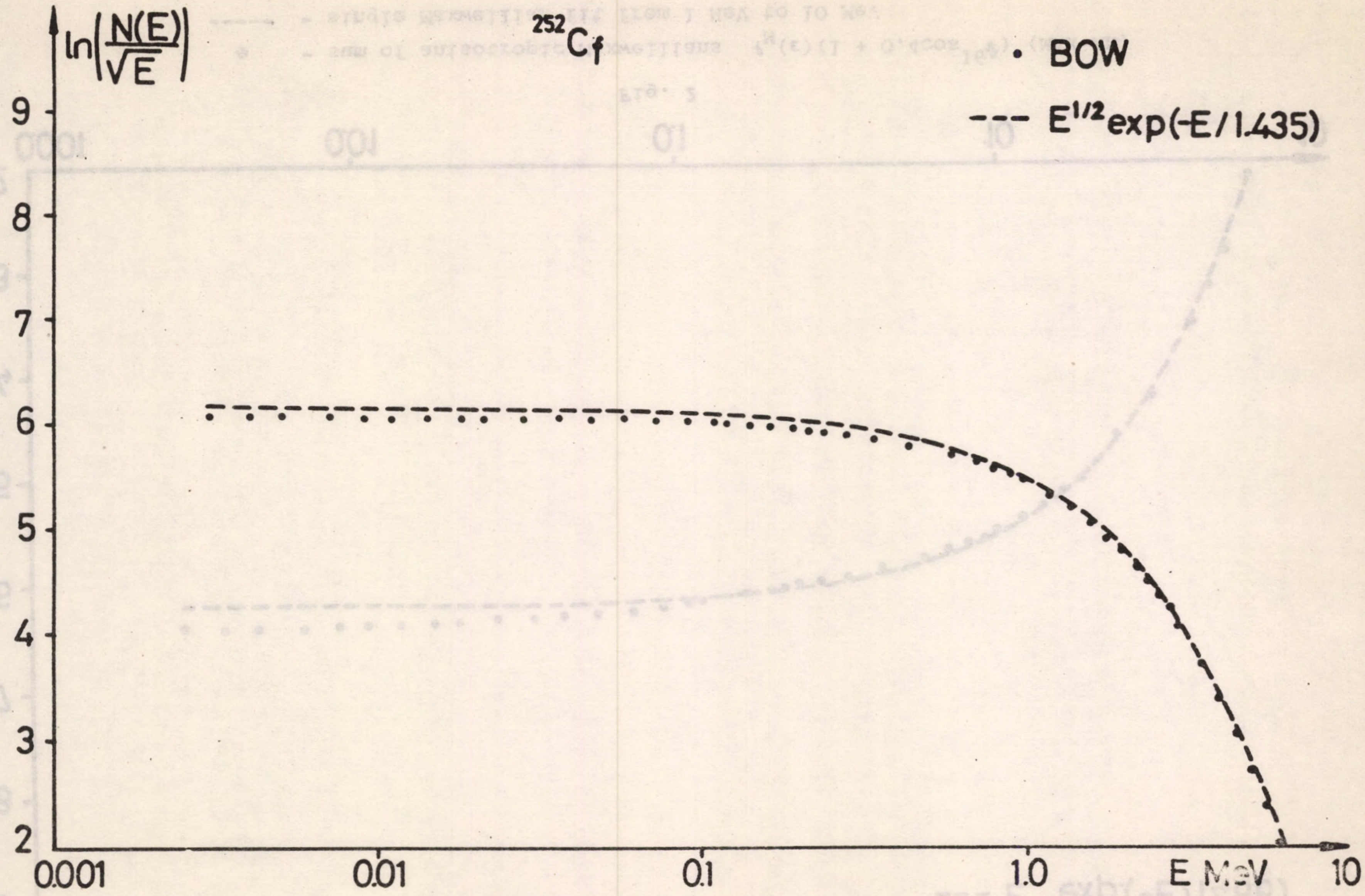

Fig. 3

● - sum of spectra from Ref. 2 (BOW)

----- - single Maxwellian fit from 1 MeV to 10 MeV

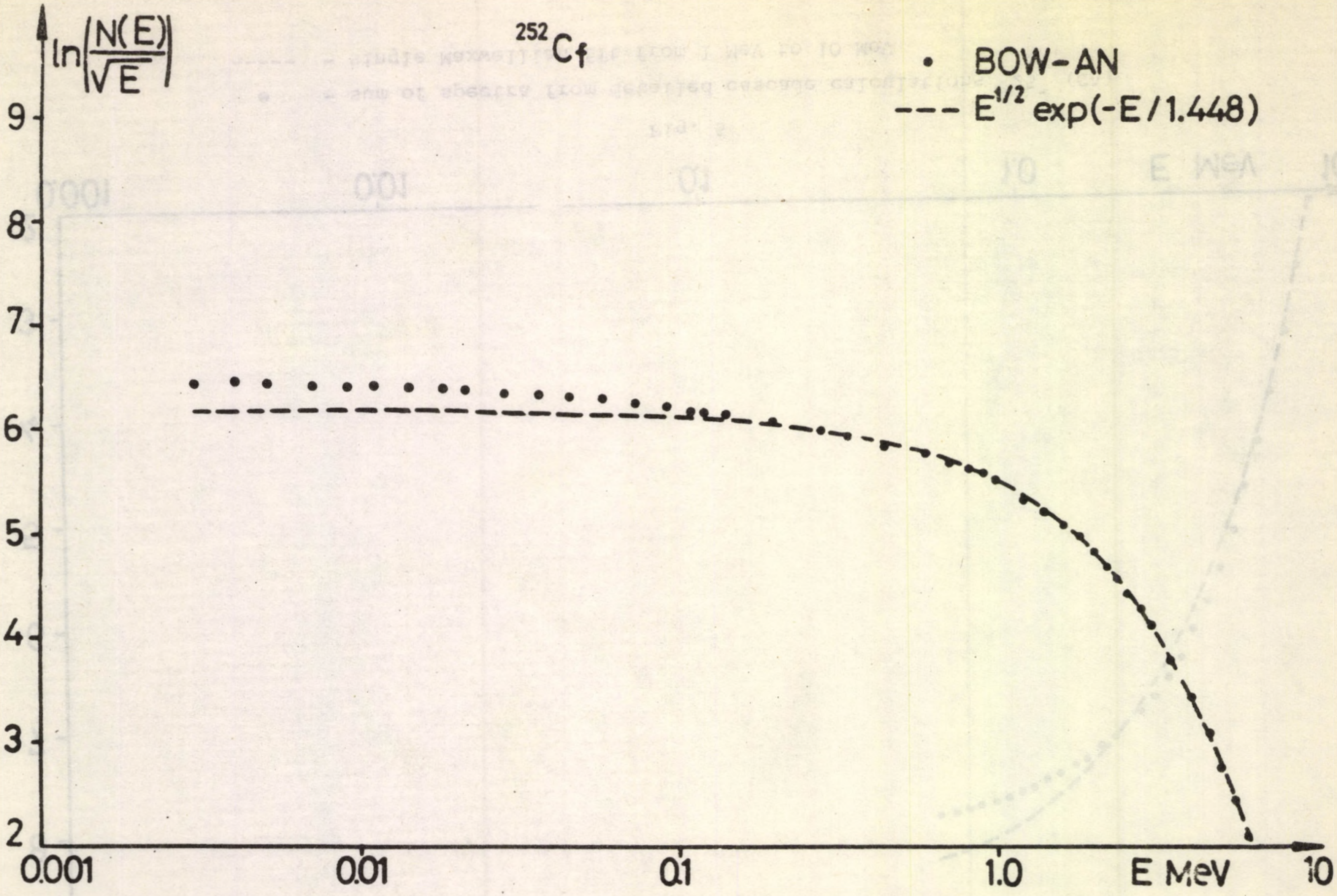

Fig. 4

• - sum of spectra from Ref. 2 with an anisotropic term $1 + 0.4\cos^{16}\vartheta$ (BOW-AN)

---- - single Maxwellian fit from 1 MeV to 10 MeV

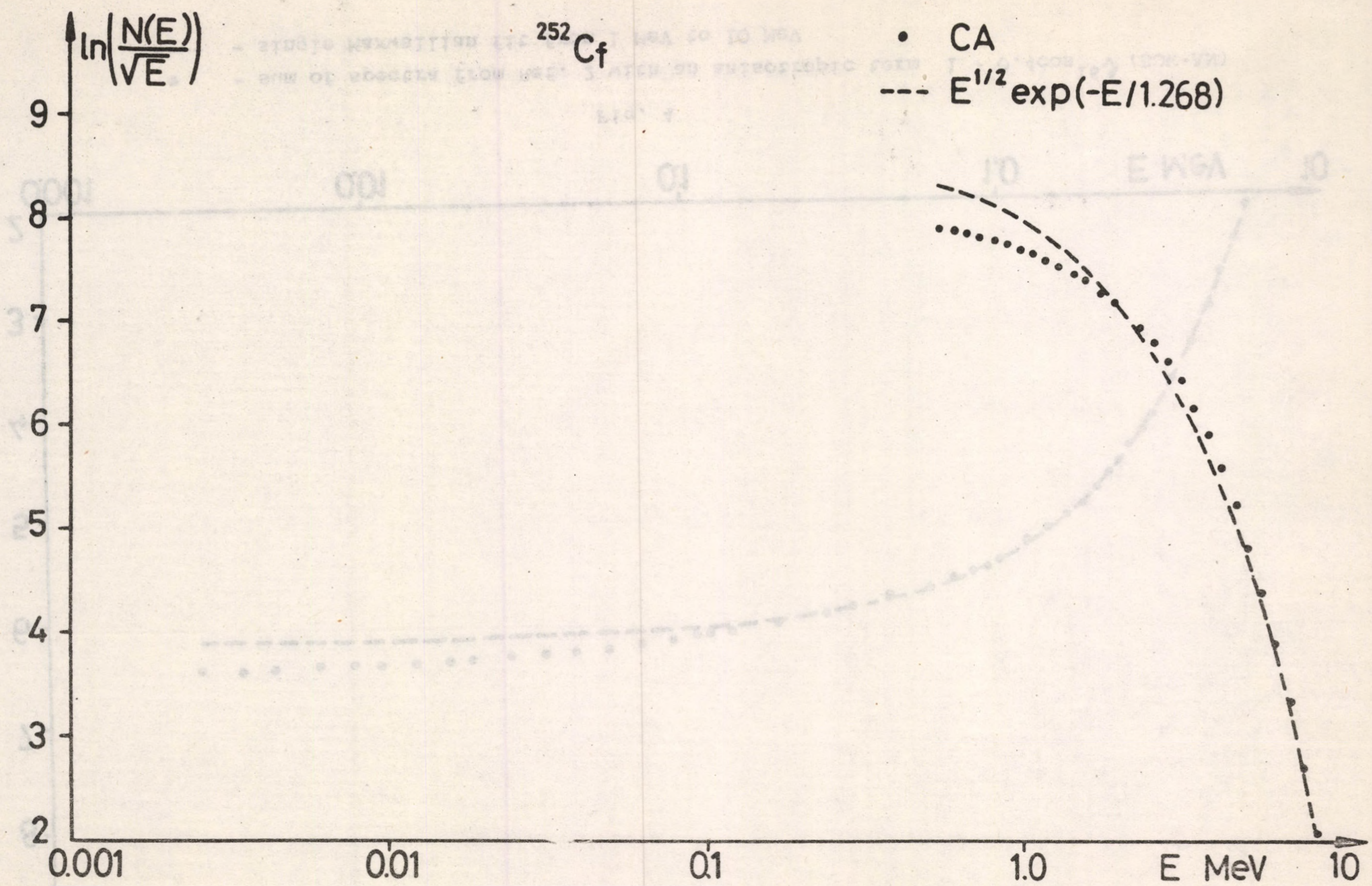

Fig. 5

● - sum of spectra from detailed cascade calculations [25] (CA)

----- - single Maxwellian fit from 1 MeV to 10 MeV

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