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DEPENDENCE OF NEUTRON EMISSION SPECTRA ON THE EXCITATION ENERGY OF SPONTANEOUS FISSION FRAGMENTS

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Abstract: Multiparameter precision measurements of differential energy spectra of ^{252}Cf spontaneous fission neutrons have been carried out for different masses, kinetic energies and exitation energies of the fragments at different emission angles. These data have been analyzed on the assumption of the evaporation model. The dependence of the average neutron energies have been studied for different masses and the fragments' total kinetic energies. Average energies of the neutrons emitted by spontaneous fission fragments have been compared with those of the neutrons from nuclear reactions.

(fission, ^{252}Cf, prompt fission neutrons, fragments mass and kinetic energy)

Introduction

The shape of the emission spectra of fission neutrons is determined first of all by the stage of fission in which the emission takes place. Conventionally it is possible to distinguish several stages: the emission from the fissioning nucleus (descent from the barrier to the scission point, during scission of the nucleus), neutron emission in the process of acceleration of the fragments, at establishing their equilibrium shape and the emission at the last stage by cascade evaporation from equilibrium heated fragments. The emission spectra from excited nuclei fragments are connected both with the individual properties of the corresponding nuclei and with their excitation energy. The contribution of these components is determined by measuring and analyzing neutrons' angular and energy distributions and correlation of them with the mass A, the kinetic energy Ek and the excitation energy of the fragmets E*.

The available in literature /1-5/ information on the dependence of the average energies of the spectra En on A and Ek is incomplete and insufficiently precise. Theoretical calculations were done only for the dependence En(A) /6-7/.

In the given work multiparameter measurements have been carried out the dependence of ^{252}Cf spontaneous fission neutrons' emission spectra on the mass, the kinetic energy and the exitation energy of fragments.

Method and apparatus

Measurements were carried out using a multiparameter spectrometer of spontaneous fission neutrons.

The fission sourse was made of high-purity ^{252}Cf by the vacuum self-transfer method on an aluminium oxide film 50 g/cm^2 thick. The diameter of the active spot was 3 mm, the intensity of the source, 10^5 fiss/s.

The electrons knocked out by fission fragments from the aluminium oxide film were registered by means of a detector based on a microchannel plate (MCP). Such a detector enabled to register all the fission events and gave a time reference to the moment of fission with precision better than 100 ps.

The fragments moving within the limits of a small solid angle were registered by two detectors on the base of MCP located diametrically opposite on the same axis with the sourse at a distance 9 cm from it. The velocity and the energy of the fragments after emission of the neutrons were determined by the time-of-flight method.

The neutron energy was also determined by the time-of-flight method. A stilben crystal 50x30 mm with a photomultiplier FEU-30 was used as a neutron detector.

The efficiency was determined continuously in the course of the experiment. Due to use of the detector with a full registration of the fission fragments it was possible simultaneously with a differential by angle neutron spectrum to accumulate an integral one the shape of which is an international standard. Such a method enabled to determine precisely the efficiency of the neutron detector in the low energy region and to exclude the influence of the threshold's instability on its determination.

Neutrons and gamma-quanta were separated by the pulse shape. The suppression coefficient at the threshold 0.5 MeV was equal 10^4 and at the threshold 0.15 MeV it equalled 10^2. The variance determined by the half-width of the gamma-quanta distribution was 0.37 ns for the whole energy range.

For the reduction of neutron scattering all the construction elements were made as small as possible: the thickness of vacuum chamber was 0.3 mm, the thickness of the MCP - 0.5 mm. This enabled to reduce the contribution of the scattering and absorption effects to a value less 2%.

The neutron spectra measurements were duplicated on three flight bases: 37.5, 75.0, 150.0 cm; besides in order to increase the reliability of the measurements two neutron detectors arranged collinearly were used simultaneously. The measurements were done for angles 2, 6, 15, 30, 45, 60, 75, 90 degrees. The angular resolution was 2,6 and 11 degrees in different experiments.

The treatment of the measurements consisted of two stages. During the first one carried out on line with a computer, the mass A, the kinetic energy E, the velocity of the fragment Vf and the time of flight of the neutron T, were determined. An accumulation was done of a matrix of fragment-fragment coincidences on the Nf(A,E,I) coordinates, where I is the number of the detector, a matrix of fragment-fragment-neutron coincidences on the Nn(T,A,E,I) coordinates and a matrix of velocities Vf(A,E,I). For each event are given: a compensation of the time-amplitude dependence of the time "zero", a correction of the fragments' energies taking into account the effect of neutron recoil. As a result of the treatment the neutron spectra were presented as a distribution of the neutron flux density

$$\rho(Vn,\varphi)=T^3\ n(r,\mathcal{E},L^3),$$

where L is the distance of a neutron' flight
r - the number of registered fragments,
n - the number of registered neutrons,
$\mathcal{E}$ - the efficiency of the a neutron detector,
Vn- the velocity of neutron.

Results and discussion

To obtain the emission spectra one must know precisely the velocity of the emitting source. This enables to find out what part of neutrons is emitted from a fully accelerated fragment. For this purpose the yields and the srectra of the neutrons emitted from the fragments at angles 0 and 90° in the l.s. to the direction of their movement were compared. The yields of the neutrons measured at the angle of 90° and the ones calculated for the angle 90° from the experimental data at the angle of 0°, differ by 7% in supposition that this effect is connected with the so called "scission neutrons". The average number of these neutrons is about 3% of the total number which is somewhat less that the value previously obtained /8/ and coincides with the results of the measurements /9,10/ carried out by a different method of registrating the fragments.

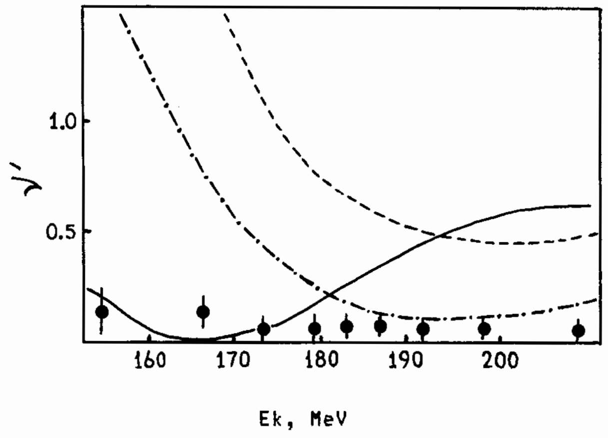

Fig. 1. The number of the "scission" neutrons in dependence on the fragment's mass (A) for a sum of Ek; the data of works: ---- /2/, -·- /3/, —— /11/, the data of this work: ●

Analogous comparisons of the yields and spectra of the neutrons for 0° and 90° were carried out also for separate groups of fragments. In Fig. 1 a dependence is presented of the difference of neutron yield (0-90°) on the total kinetic energy of the fragments Ek for all the masses, and in Fig. 2 the same kind of dependence on the fragments' masses for all the Ek, as the number of the "scission" neutrons (ν') isotropic in the l.s. The experimental neutron yields at the angle 90° are somewhat greater than the calculated ones for 0°, however the difference does not exceed substantiously the systematic errors of the measurement. The obtained data differ considerably from the results of other studies /2,3,11/. The difference

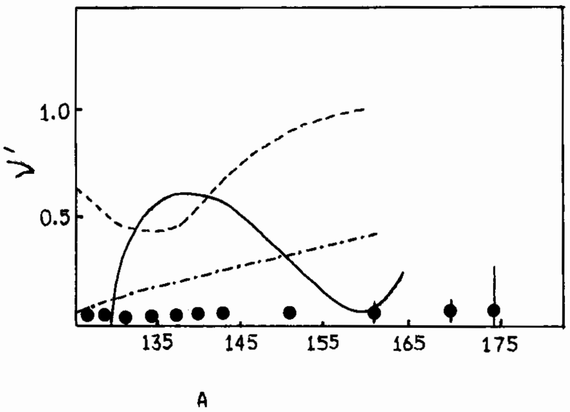

Fig. 2. The number of the "scission" neutron in dependence on the total kinetic energy (Ek) for the sum of fragments' masses; the data of works: ---- /2/, -·- /3/, —— /11/, the data of this work: ●

of the results is connected with the fact that in the given work a neutron spectrometer of high energy resolution in a wide energy range was used, the neutron detector's efficiency was carefully determined directly in the course of the experiment, with accounting of the influence of neutron recoil in each registered event (it influences most strongly on comparison of the spectra at 0° and 90°, where with a wrong accounting of the recoil effect, the errors for separate groups of fragments may reach 100%), as well as with other characteristics of the setup, the conditions of measurements and with introducing a number of different corrections: for time resolution of the neutron and fragment channels, for recoil from the neutrons uncorrelated with the angle, for real collimation, etc.

We carried out /12/ determination of the average velocity of the fragments at which a neutron emission takes place immediately by the irregularity of the spectrum's shape connected both with the kinematic effect and with the emission spectrum. The results of the measurements showed a good agreement of these velocities with the maximum velocities determined by the Coulomb interaction of the fragments (Fig. 3).

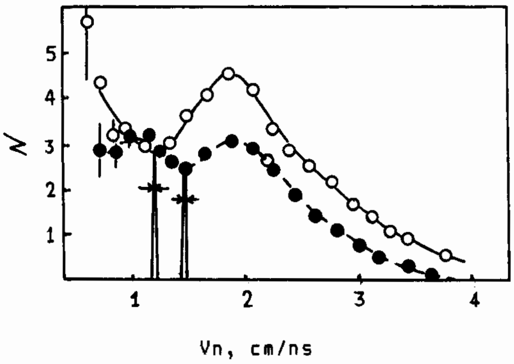

Fig. 3. The spectrum of the neutrons emitted at the angle 5°, ● M=98±5 m.u., Ek=175±5 MeV, V=1.44 cm/ns; ○ M=117±5 m.u., Ek=175±5 MeV, V=1.22 cm/ns; the arrows show the variance of the neutron's velosity.

A comparison was also done of the integral spectrum measured by the direct method and the one calculated using the data of neutron spectra in the c.m.s. of the fragments, obtained from measurements at small angles and in supposition that neutron emission takes place only within the limits of evaporation from fully accelerated fragments.

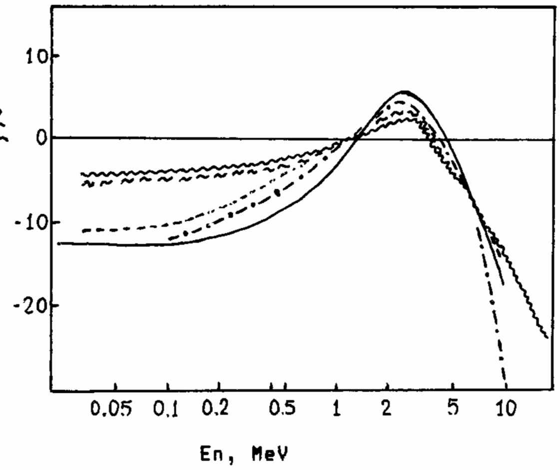

Fig. 4. Deviation of the integral spectra from the Maxwell distribution (T=1.42 MeV); the data of works: ~~~~~~ /13/, ---- /21/, -•- /22/, ∼∼∼ /23/, —— this work.

It is worth mentioning that in the energy range 1-10 MeV the integral spectrum (Fig. 4) obtained by us /10,14/ goes close enough to the evaluation of /13/. In the low energy range our integral spectrum is somewhat lower than the data of direct measurements. The difference in the low energy range may be connected with the influence of the anisotropic effect in the c.m.s., caused by the fragment's angular momentum as well as with presence of a small share of nonevaporation neutrons. Variation of the anisotropic coefficient in the form $1+\beta P_2(\cos\varphi)$, with experimental spectra at an angle 0° in the l.s. being used as basic data, does not allow to get a complete agreement of the integral spectra in the low energy range (βopt.=0.04). Introducing neutrons of nonevaporation character (about 3% of the total number) can account for the discrepancy of the spectra.

In connection with the fact that not less that 97% of the neutrons are emitted within the scope of the evaporation model, a possibility arises to analyze neutron emission spectra for certain masses and excitation energies of the fragments with the aim of studying the densities of nuclei's levels, determining the cross-sections of the reverse process and other statistical characteristics for neutron-rich nuclei of the fragments.

In Fig. 5 the dependences are presented of the average energies of the neutrons on the fragment's mass summed over all the kinetic energies, as well as analogous data from an experimental /4/ and a theoretical /21/ works. Excluding the mass region of 130, quite a satisfactory agreement with the theoretical calculation is observed.

The results of measurements of differential emission spectra of neutrons in the c.m.s. are presented in Fig. 6, where average neutron energies are shown in dependence on the mass for different total kinetic energies of the fragments. A strong variation of the average energy is observed for different Ek (respectively, different excitation energies). Especially

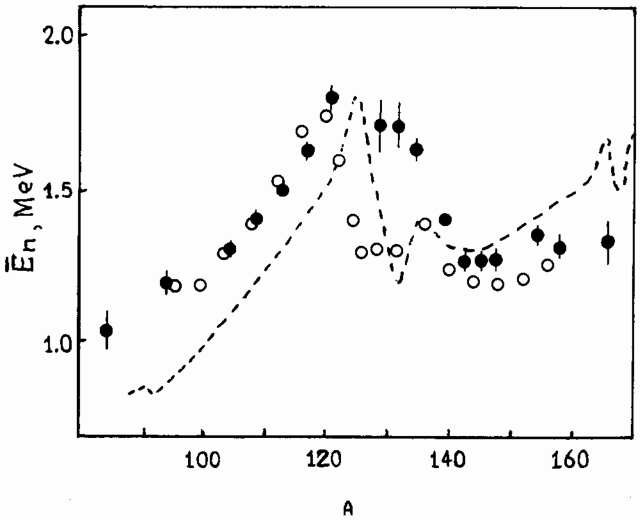

Fig. 5. Average neutron energy in the center-of-mass system of a fragment, in dependence on the fragment's mass (A), for a sum of Ek; ○ - calculation of work /7/, ---- data of work /4/, ● data of this work.

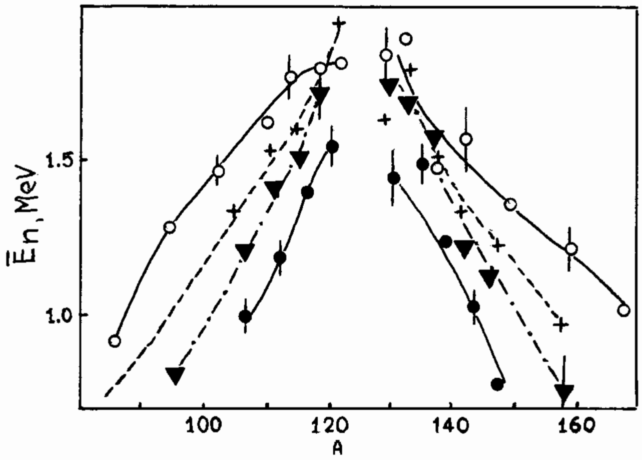

Fig. 6. Average neutron energy (En) in the center-of-mass system of a fragment as the function of the mass (A) for fixed intervals of Ek, ○ - Ek=175±5, + - Ek=186±5, ● - Ek=200±5, ▼ - Ek=192±5 MeV.

strong variation is observed in the mass ranges 145-110 a.m.u. In analyzing neutron emission spectra one should know, if there is an emission of neutrons from the fragments heated up to maximum temperatures, or, as the authors of /15/ assumed, the neutrons are emitted in the process of dissipation of the collective deformation energy into thermal energy of excitation, which strongly depends on the viscosity of the fragment's nuclear matter. One of the ways to find it out is to compare the fragments' temperature at which neutron emission takes place with the temperature of the nuclei excited in different nuclear reactions at the same full excitation energies. In Fig. 7 a dependence is shown of the average energy of the neutrons from different fragments of ^{252}Cf spontaneous fission on the excitation energy of the fragment (after emission of the first neutron). Here the data are also presented from the reactions (n,n), (n,2n), (p,n), (α,n) and from heavy-ion interactions /16-19/ for equilibrium part of the spectra. One can see that there is a satisfactory agreement in a broad energy range between two groups of data for nuclei distant from the closed shells (A=132). Comparison of the data for these magic nuclei is hindered due to almost complete absence of information for them. The obtained agreement of the spectra's average energies points to the neutron emission's taking place after the end of the process of dissipation and accumulation by the fragment of the full internal energy of excitation (10-30 MeV).

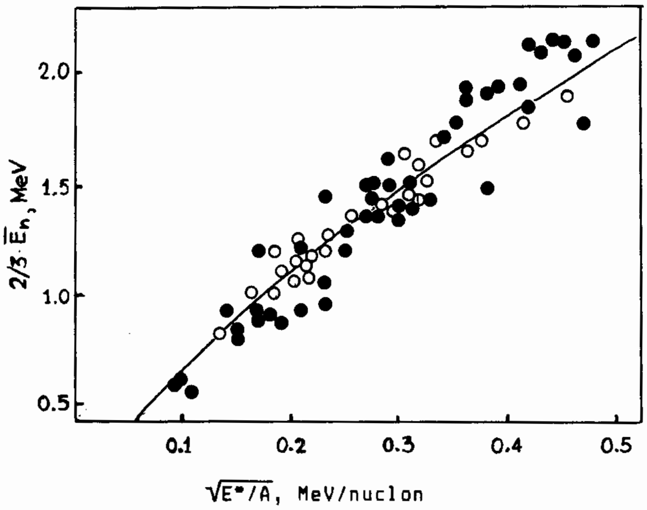

Fig. 7. Average neutron energy in dependence on the ratio of the average thermal energy of excitation E of the emitting nuclei to the mass number (A), ● - the data on reactions (p,n), (n,2n), (n,n'), (α,n) from works /17-19/, ——— - data systematics presented in work /16/ on reactions (HI,xn),etc.; ○ -the data of this work (the average energy for A in the region of the closed shell 125-135 is excluded from comparison).

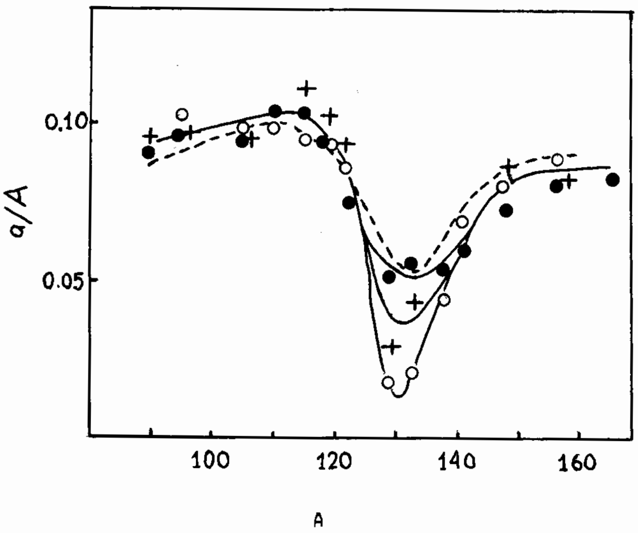

Fig. 8. The density parameter of the levels (a) as a function of the fragment's mass for definite Ek; ---- - calculation of work /20/, ● - Ek=177±5, + - Ek=186±5, ○ - Ek=196±5 MeV.

Using the said dependence En(A,Ek), as well as the obtained in this experiment dependence ν(A,Ek),the parameter of the levels density (a) was determined by means of the thermodynamic relation (n=0) for several intervals of values of the total kinetic energy of the fragments. Fig.8 presents the dependence a/A(A). It is worth paying attention to the fact that in the region of magic nuclei A=130-135 a low value of a/A is observed at great Ek (the excitation energy is low), and a gradual increase of a/A with a decrease of Ek (an increase of the excitation energy). This gives evidence of a gradual destruction of the shell effects and points to the magic fragment's getting a gradually increasing (and, in the end, a considerable) share of the total excitation energy possible already in the scission point. If the excitation energy in the scission point were small for A=130-135 at all the values of Ek, no considerable variations of the value of a/A would be observed. The dependence a/A(A) at different excitation energies for fragments had not been studied before. Note, that in the mass region 95-120 and 150-170 the value of a/A for different Ek does not change within the limits of experimental errors.

In Fig. 8 there are also presented the results of calculations /20/ that take account of the contribution of vibrational and rotational excitations into the levels' density. Excluding the near-magic region, the agreement with our experimental data is good enough.

Processing of the experimental data continues in order to obtain new information about the fission process and the statistical properties of excited fragments.

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