[18] L.S. Brown and G.J. Maclay, Phys. Rev. 184, 1272 (1969).
[19] P.G. deGennes, C.R. Acad. Sc. Paris 271, B469 (1970).
[20] M.L. Levin and S.M. Rytov, Teoriya ravnovesnykh teplovykh fluktuatsii v elektrodinamike (Theory of Equilibrium Thermal Fluctuations in Electrodynamics), Nauka, 1967.
[21] M.J. Renne, Physica 53, 193 (1971); 56, 125 (1971).
[22] R.H. Winterton, Contemp. Phys. 11, 559 (1970); Usp. Fiz. Nauk 105, 307 (1971)
[23] E.I. Kats, Zh. Eksp. Teor. Fiz. 60, 1172 (1971) [Sov. Phys.-JETP 33, 634 (1971)].
[24] D. Langbein, J. Phys. Chem. Solids 32, 1657 (1971).

ENERGY SPECTRUM OF NEUTRONS OF TERNARY FISSION OF Cf^{252} NUCLEI

A.P. Graevskii, B.A. Bochagov, and L.N. Kupriyanova
Leningrad Institute of Nuclear Physics, USSR Academy of Sciences
Submitted 3 April 1972
ZhETF Pis. Red. 15, No. 9, 572 - 574 (5 May 1972)

So far there is only one reported measurement of the energy spectrum of the neutrons from ternary fission of U^{235} by thermal neutrons [1], which has shown that the average energy of the ternary-fission neutrons $\overline{E}_t$ is smaller than $\overline{E}_b$ by 8%. In the literature there are also data on the average number of neutrons $\overline{\nu}_t$ per act of ternary fission of Cf^{252} nuclei [2, 3], and also on the dependence of the agerage number of neutrons on the mass numbers of the fragments and their kinetic energy. According to the data of Adamov et al. [2], $\overline{\nu}_t = 2.83 \pm 0.67$, while the measurements of Nardi and Fraenkel [3] gave for this quantity values $\overline{\nu}_t = 3.11 \pm 0.06$.

We note that in the case of binary fission of Cf^{252} nuclei, the average number of neutrons is $\overline{\nu}_b = 3.787$ [4].

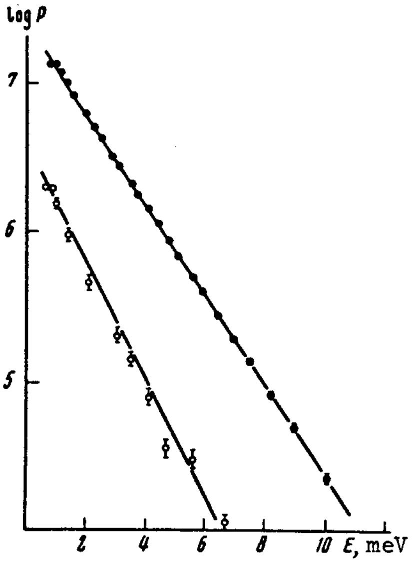
The energy spectra of the neutrons from binary fission of nuclei by thermal neutrons and from spontaneous fission of Cf^{252} nuclei have been investigated in sufficient detail.

All are well described by a Maxwellian distribution $N(E_n) \sim E_n^{-1/2} \exp(-E_n/T)$, where $N(E_n)$ is the number of neutrons with kinetic energy E_n in the laboratory frame and T is a parameter connected with the average neutron energy by the relation $\overline{E}_n = 3T/2$.

If it is assumed that in both cases the neutrons are emitted from fully accelerated fragments, then the very fact that the average number of neutrons is smaller in ternary fission indicates a smaller excitation energy of the fragments produced in this process, in comparison with the binary-fission fragments. Therefore the spectrum of the ternary-fission neutrons should be "softer" than for binary fission. The parameter T in the case of binary spontaneous fission of Cf^{252} nuclei, according to the data of [5, 6], is $T = 1.40 \pm 0.05$ [7, 8]. For the energy spectrum of the ternary-fission neutrons one should expect a smaller value of T.

We studied the energy spectrum of the neutrons from ternary fission of Cf^{252} nuclei for the purpose of verifying this assumption and obtaining additional information concerning the excitation energies of the fragments produced in this process.

The spectra of the Cf^{252} fission neutrons were measured by the time-of-flight method with a base of 0.5 m and a resolution ±2.5 nsec, determined by



Neutron spectra of binary (●) and ternary (o) fission of Cf^{252}. The straight lines represent the functions $P_i \sim \exp(-E/T_i)$, where $P = N(E)/\sqrt{F}$ and E is the neutron kinetic energy.

the width of the peak of the γ quanta accompanying the fission of the nucleus. The electronic apparatus used in the experiment is described in [9]. A Cf^{252} source on a stainless-steel substrate was placed in a vacuum chamber at a distance of 2 mm from a semiconductor detector of 18 mm diameter, reporting the α particles and the fission fragments. The signals from the detector were fed through an amplifier and a shaper-discriminator to the "stop" input of a time-amplitude converter (TAC). The neutrons and the γ quanta were detected by a plastic scintillator of 150 mm in diameter and 150 mm height, in conjunction with an FEU-65 photomultiplier, the signals from which were fed through a shaper, delay line, and a gating circuit to the "start" input of the TAC.

The discriminator-operator threshold in the fragment channel was chosen such as to exclude the count of the α particles with E_α = 6.11 MeV from the α decay of Cf^{252}. In the ternary-fission experiment, an aluminum foil 6 mg/cm^2 thick was placed between the source and the detector to exclude the count of the fragments and of the α particles with E_α = 6.11 MeV, making it possible to register only the long-range α particles from the ternary fission of Cf^{252}. The α particle energy cutoff threshold, with allowance for the threshold of the input discriminator, was 9 MeV. The spectrum was recorded with an AI-256 analyzer. The counting rate was 70 counts/sec in double fission and 0.2 count/sec in ternary fission. The measured-time interval was 100 nsec.

The figure shows the spectra of the binary and ternary fission of Cf^{252}, as measured in our experiment, in the form of the function $N(E_n) = AE_n^{1/2}\exp(-E_n/T)$. Both spectra are in good agreement with the Maxwellian one. The temperature T_b for the binary-fission spectrum turned out to be 1.40 ± 0.05 MeV, and for the ternary fission T_t = 1.1 ± 0.2 MeV. The average neutron energies obtained from the experiments were E_b = 2.10 ± 0.08 MeV for binary fission, which coincides with the data of [6], and E_t = 1.6 ± 0.3 MeV for ternary fission. Only statistical errors were taken into account. These data confirm the assumption that the ternary-fission neutrons are emitted from less excited fragments. In addition, the Maxwellian distribution of the neutron energy can serve as indirect evidence that the mechanisms whereby the neutrons emitted in ternary and binary fission are similar. In both cases the neutrons are emitted from fully accelerated fragments, at the expense of the excitation of energies of the latter.

In conclusion, the authors are deeply grateful to G.E. Solyakin for suggesting the problem and for useful discussions during the course of the work, and to G.A. Arkhipova and L.L. Vinogradov for help with the work.

[1] V.I. Nefedov et al., Yad. Fiz. 3, 465 (1966) [Sov. J. Nucl. Phys. 3, 337 (1966)].

[2] V.A. Adamov et al., Atomnaya energiya 11, 1001 (1970).
[3] E. Nardi and Z. Fraenkel, Phys. Rev. Lett. 20, 1249 (1968).
[4] P.H. White, et al., J. Nucl. Energy, 22, 73 (1967).
[5] Conde, et al., Arkiv Fysik, Bd. 29, No. 24, 313 (1965).
[6] N.I. Kroshkin and Yu.S. Zamyatin, Atomnaya energiya 29, No. 2 (1970).
[7] F. Fillmore, J. Nucl. Energy 22, 79 (1968).
[8] I.W. Meadows, Phys. Rev. 108, 411 (1967).

BOUND STATES OF ELECTRON, HOLE, AND PHONON IN A STRONG MAGNETIC FIELD

I.B. Levinson
L.D. Landau Institute of Theoretical Physics, USSR Academy of Sciences
Submitted 6 April 1972
ZhETF Pis. Red. 15, No. 9, 574 - 577 (5 May 1972)

Recently, in connection with a number of optical experiments [1, 2], interest has increased in the bound states of quasiparticles with long-wave optical phonons [3 - 5]. We show in the present paper that bound states of three particles (electron, hole, and phonon) with zero total momentum exist in a strong magnetic field H. When these states are formed the electron and hole are near the bottoms of the corresponding lower Landau bands; therefore the excitation energy of such a state lies above the threshold for the production of an electron-hole pair and a phonon:

$$\epsilon = \Delta E + \frac{1}{2}(\omega_{c1} + \omega_{c2}) + \omega_0 - W,$$

where ΔE is the width of the forbidden band, ω_{c1} and ω_{c2} are the cyclotron frequencies of the electron and of the hole, ω_0 is the phonon frequency, and W is the binding energy. The presence of such states should lead to a fine structure of the intrinsic-absorption phonon replicas.

The existence of bound states of three particles was proved under the following assumptions: 1) only an electron interacts with the phonons, and this interaction is weak (coupling constant $\alpha \ll 1$); 2) the Coulomb energy is less than the magnetic one in the sense of $L \equiv \ln(\omega_c/R) \gg 1$, where ω_c is the cyclotron frequency and R is the Rydberg energy with reduced mass m. If there are no other small parameters, i.e., $\omega_{c1} \sim \omega_{c2} \sim \omega_0$, and the electron-hole binding energy $W_c \sim RL^2$ [6] is of the same order as the electron-phonon binding energy $W_p \sim \alpha^2\omega_0$ [5], then the indicated inequalities ensure the existence of three-particle bound states, with $W \sim W_c \sim W_p$. Here $W \ll \omega_0$, so that the energy of the bound state is superimposed on the continuum of the dissociated states of the electron-hole pair; therefore the state can decay with vanishing of a

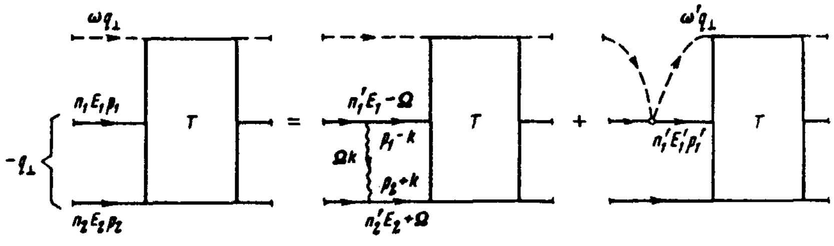


Fig. 1