EXPERIMENTAL DETERMINATION OF THE NUMBER OF FAST NEUTRONS IN THE FISSION SPECTRUM

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EXPERIMENTAL DETERMINATION OF THE NUMBER OF FAST NEUTRONS IN THE FISSION SPECTRUM

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With an insignificant moderator content in the reactor core, neutrons in the energy region above 3-5 MeV practically coincide in spectrum with fission neutrons and may be used to study the spectral characteristics of fission neutrons.

In the present work the neutron spectrum was investigated in the energy range 0.6-24 MeV, which is established inside the core of a fast reactor made of highly enriched uranium. The core has the form of a right circular cylinder

Table 1

Reaction	E_{eff}, MeV	σ_{eff}, mbarn	$\bar{\sigma}$, mbarn	$\bar{\sigma}/\sigma_{\text{eff}}$
$Np^{237}(n,\ f)$	0.60	1550	940 ± 50	0.61 ± 0.03
$U^{238}(n,\ f)$	1.60	600	183 ± 12	0.305 ± 0.020
$In^{115}(n,\ n')In^{115M}$	1.45	370	123 ± 18	0.33 ± 0.05
$Fe^{54}(n,\ p)Mn^{54}$	2.65	320	42.5 ± 5.8	0.133 ± 0.018
$Ni^{58}(n,\ p)Co^{58}$	3.15	620	58 ± 8	$(9.4 \pm 1.4) \cdot 10^{-2}$
$Zn^{64}(n,\ p)Cu^{64}$	4.4	320	15.0 ± 2.3	$(4.7 \pm 0.7) \cdot 10^{-2}$
$Fe^{56}(n,\ p)Mn^{56}$	7.5	115	0.53 ± 0.05	$(4.6 \pm 0.5) \cdot 10^{-3}$
$Mg^{24}(n,\ p)Na^{24}$	7.7	200	0.70 ± 0.09	$(3.5 \pm 0.5) \cdot 10^{-3}$
$Ti^{48}(n,\ p)Sc^{48}$	8.0	65	0.135 ± 0.030	$(2.1 \pm 0.5) \cdot 10^{-3}$
$J^{127}(n,\ 2n)J^{126}$	10.5	1350	0.90 ± 0.13	$(6.6 \pm 1.0) \cdot 10^{-4}$
$Al^{27}(n,\ \alpha)Na^{24}$	8.3	130	0.32 ± 0.04	$(2.5 \pm 0.3) \cdot 10^{-3}$

Reaction	E_{eff}, MeV	σ_{eff}, mbarn	$\bar{\sigma}$, mbarn	$\bar{\sigma}/\sigma_{\mathrm{eff}}$
$Tl^{208}(n,\ 2n)Tl^{202}$	9.8	1450	1.5 ± 0.3	$(1.0 \pm 0.2) \cdot 10^{-3}$
$Ag^{107}(n,\ 2n)Ag^{106M}$	11.5	950	0.22 ± 0.04	$(2.3 \pm 0.4) \cdot 10^{-4}$
$F^{19}(n,\ 2n)F^{18}$	13.6	97	$(4.3 \pm 0.6) \cdot 10^{-3}$	$(4.4 \pm 0.6) \cdot 10^{-5}$
$O^{16}(n,\ 2n)O^{15}$	20.8	18.5	$(3.5 \pm 1.5) \cdot 10^{-6}$	$(1.9 \pm 0.6) \cdot 10^{-7}$
$C^{12}(n,\ 2n)C^{11}$	23.3	17.5	$(3.0 \pm 1.0) \cdot 10^{-7}$	$(1.7 \pm 0.6) \cdot 10^{-8}$

with an experimental channel along the axis, in which the measurement was carried out. In addition to U^{235}, its composition includes Fe (20 at.%), Mo (10 at.%) and U^{238} (10 at.%). To determine the neutron spectrum, the threshold-indicator method was used. Spectrum-averaged cross sections $\bar{\sigma}$ were measured for the threshold reactions presented in Table 1. Measurements of fission cross sections were performed using fission chambers; the cross sections of other reactions were measured by the activation method. The induced activity was determined on a single-crystal gamma spectrometer with a NaJ(Tl) crystal measuring 80 × 80 mm, from the magnitude of the photopeaks in the spectra of the irradiated samples.

To determine σ, the photoefficiency of the spectrometer was calibrated using gamma sources of known strength. The neutron flux in the channel was found by measurement with a Pu^{239} fission chamber. In doing so, the fission cross section of Pu^{239} was taken equal to 1.85 barn. For most of the reactions used, sufficiently reliable data are available ($^{1-3}$) on the energy dependence of the cross section, which made it possible to find effective values of the cross section.

σ_{eff} and the corresponding threshold energy E_{eff}, satisfying the relation:

$$\int_0^{\infty} \sigma(E) N(E)\, dE = \sigma_{\mathrm{eff}} \int_{E_{\mathrm{eff}}}^{\infty} N(E)\, dE.$$

Here, as $N(E)$, in the first approximation the spectrum determined by Watt’s formula (^{4}) was adopted. The need, in a second approximation, to refine E_{eff} arose only for reactions with a threshold below 3 MeV, where this formula describes the reactor spectrum poorly.

Table 1 gives data on E_{eff}, σ_{eff}, the measured mean cross sections $\overline{\sigma}$, and the fraction of neutrons above the threshold energy E_{eff}, determined by the ratio $\overline{\sigma}/\sigma_{\mathrm{eff}}$.

The appearance of more accurate data on $\sigma(E)$ may lead to some small changes in the neutron spectrum.

Among the reactions used, the reaction $C^{12}(n, 2n)C^{11}$ is of great importance for determining the form of the hard part of the spectrum. For reliability of the measurements with this indicator, samples of spectrally pure graphite were used; these were irradiated for a short time by the reactor neutron flux up to 10^{15} cm^{-2}. After 40 min following irradiation, in the photopeak due to positron annihilation, the interfering activity disappeared and only the activity of C^{11}, with a period of 20.5 min, was recorded. The value of the decay period was checked in each measurement.

Figure 1 presents the integral spectrum of reactor neutrons

$$L(E) = \int_E^3 N(\varepsilon)\, d\varepsilon,$$

constructed from the experimental points given in Table 1, as well as the differential spectrum $N(E)$.

The mean energy of the reactor neutrons is $\overline{E} = 1.42 \pm 0.04$ MeV.

Let us now compare the measured reactor neutron spectrum with the fission-neutron spectrum of U^{235}. The most commonly used are two simple expressions for the fission-neutron spectrum of U^{235}, obtained on the basis of the hypothesis of isotropic evaporation of neutrons from moving fragments: that given by Watt in (^{4}),

$$N(E) = 0.484\, e^{-E}\, \mathrm{sh}\, \sqrt{2E} \tag{1}$$

and that proposed by Cranberg et al. (^{5}),

$$N(E) = 0.4527\, e^{-E/0.965}\, \mathrm{sh}\, \sqrt{2.29\, E}. \tag{2}$$

The Maxwellian distribution

$$N(E) = 0.770\sqrt{E}e^{-E/0.776} \tag{3}$$

is also a frequently used representation of the emission spectrum.

These expressions were obtained for describing experimental spectra measured in the region of neutron energies not exceeding 17 MeV.

Comparison of the experimental and calculated curves (see Fig. 1) shows that in the energy region below 3 MeV, as was to be expected, the reactor spectrum differs substantially from the fission spectrum, which is associated with the transfer of neutrons into the low-energy region due to inelastic processes. In the energy region above 3 MeV the qualitative form of the spectra is quite close, but there is some difference in the slope of the curves; this is not eliminated

Graph of neutron spectra

Figure 1: Graph of neutron spectra

completely even if one takes into account the difference in the energy of the neutrons producing fission. Thus, for example, the temperature T of the U^{235} fission neutrons in our case is approximately 0.02 MeV higher than in fission by thermal neutrons, if one assumes that $dT/dE = 0.015$ (^{6}) and takes into account the energy distribution of the neutrons producing fission in the reactor. Taking into account

with this correction the spectrum in the energy region 10–24 MeV already practically coincides with the curve given by formula (1). With the curves corresponding to formulas (2) and (3), the discrepancy remains noticeable. At the same time, if the neutron-removal cross section is taken to be the cross section for formation of the compound nucleus, which is almost constant in this energy region, then one may assert that neutron removal cannot substantially change the spectral distribution of fission neutrons.

Fig. 1. 1, 2—fraction of neutrons

$$L(E) = \int_E^\infty N(\varepsilon)\, d\varepsilon$$

with energies greater than E in the reactor-neutron spectrum (1) and in the fission-neutron spectrum (2), found on the basis of formula (2); **3, 4, 5, 6** —reactor-neutron spectrum (3) and the neutron spectrum of fission of U^{235}, approximated by formulas (2) (4), (3) (5), and (1) (6).

However, despite the small discrepancies, there is no doubt that fission neutrons are satisfactorily described by the evaporation model in the energy region up to 24 MeV, and it remains to determine how much farther this region extends.

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Note: Figure translations are in progress. See original paper for figures.