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Angular distribution of neutrons from fission fragments*

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A statistical model is used to calculate the angular distribution of neutrons evaporated from fission fragments. The calculated anisotropy is of the order of 10% in the c.m. system.

[RADIOACTIVITY, FISSION ^{252}Cf(sf) calculated angular distribution of fission neutrons.]

The spectrum and angular distribution of neutrons emitted in the fission of ^{252}Cf have been measured by Bowman *et al.*[1] One of the important conclusions of their analysis is that the neutrons can be considered to be emitted isotropically in the c.m. frame of the fragment. Wilhelmy *et al.*[2] have found that fission fragments possess a large ($J \sim 8$) angular momentum aligned perpendicular to the fission axis. This magnitude of angular momentum should cause some degree of anisotropy in the neutron angular distribution, although subsequent analyses of neutron experiments have continued to assume isotropic emission.[3,4]

The purpose of this communication is to present a statistical model calculation of the angular distribution of evaporation neutrons from fission fragments. In this calculation the angular momentum J and its projection M (on the fission axis) were determined at each stage of the cascade. We assume the initial spin distribution to be of the form $(2J+1)\exp^{[-(J+\frac{1}{2})^2/B^2]}$ with $B=6$. The initial spin projection is assumed to be $M=0$.[2] The evaporation cascade is followed by a Monte-Carlo procedure in which the probability P_{lm} of emitting a neutron with a given orbital angular momentum l and projection m is proportional to

$$\sum_{J_f} \int_0^{E-B_n} d\epsilon\, \rho_{J_f}(E-\epsilon-B_n) T_l(\epsilon) |\langle J_f, M_f, l, m_l | JM\rangle|^2 .$$

The sum is over all values of J_f that can couple to J for the given l value. The level density assumed was that of a Fermi gas with an angular momentum dependence of $(2J+1)\exp^{[-(J+\frac{1}{2})^2/2\sigma^2]}$ with $\sigma=4$.[2] The neutron transmission coefficients $T_l(\epsilon)$ were taken from Ref. 5. The neutron spin was neglected since it was judged to have no significant effect on the angular distribution and its inclusion would have significantly increased the amount of computer time spent. The final angular distribution was taken to be $W(\theta)=\sum_{l,m} P_{lm} |Y_{lm}(\theta,\phi)|^2$. The anistropy, defined as $W(\theta)/W(90°)-1$ is plotted in Fig. 1(a) as a function of θ, the angle in the co-

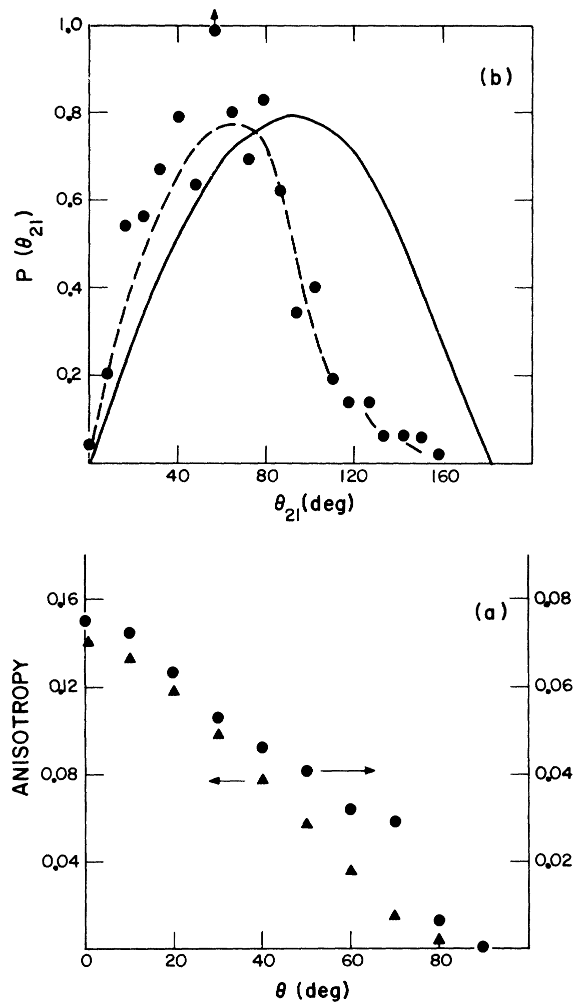

FIG. 1. (a) $W(\theta)/W(90°)-1$ as function of θ, the fragment c.m. angle. The circles are for $B=6$ (right-hand scale), triangles for $B=11$ (left-hand scale). (b) $P(\theta_{21})$: the relative probability of the two neutrons having an angle θ_{21} between them. The solid line is a $\sin\theta$ distribution (no correlation). The broken line is drawn to guide the eye. The curves are arbitrarily normalized.

ordinate system of the fragment. For comparison, the anisotropy is also presented for $B=11$. We see that it is approximately double. For $B=6$ the anisotropy is almost independent of the number of evaporated neutrons, but for $B=11$ it decreases significantly with increasing number of emitted neutrons. The plotted results (Fig. 1) assume two evaporated neutrons.

In view of recent neutron-neutron correlation experiments[3,6] we have used this procedure to determine the relative angular correlation between two neutrons. Considering a cascade in which two neutrons are involved, we have allowed a neutron to be emitted at each stage at an angle distributed according to the appropriate probability function $|Y_{lm}(\theta,\phi)|^2$. The angle between the two neutrons of the cascade has then been calculated and stored. The relative probability of one neutron being emitted at an angle θ_{21} relative to the other, $P(\theta_{21})$, is plotted in Fig. 1(b). We note that the distribution is narrower than that of two randomly emitted neutrons ($\sin\theta$). However, the large width (full width at half-maximum ~ 80°) is too wide to explain the results of Pringle and Brooks.[6] These results support an earlier conclusion[3] that angular momentum does not have a large effect on neutron-neutron correlation measurements. These correlations will be even smaller in cascades in which more than two neutrons are emitted.

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[1]H. R. Bowman, S. G. Thompson, J. C. D. Milton, and W. J. Swiatecki, Phys. Rev. 126, 2120 (1962).

[2]J. B. Wilhelmy, E. Cheifetz, R. C. Jared, S. G. Thompson, H. R. Bowman, and J. O. Rasmussen, Phys. Rev. C 5, 2041 (1972).

[3]A. Gavron and Z. Fraenkel, Phys. Rev. C 9, 632 (1974).

[4]Z. Fraenkel, I. Mayk, J. P. Unik, A. J. Gorski, and W. D. Loveland, Phys. Rev. C 12, 1809 (1975).

[5]G. S. Maui, M. A. Melkanoff, and I. Iori, French Atomic Energy Commission Report No. CEA-2380, 1963 (unpublished).

[6]J. S. Pringle and F. D. Brooks, Phys. Rev. Lett. 35, 1563 (1975).