AVERAGE NUMBER OF NEUTRONS EMITTED IN THE FISSION OF Th^{229} *BY THERMAL NEUTRONS*

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IN order to measure the mean number ν of neutrons emitted by Th^{229} fissioned by thermal neutrons, we used a thorium sample weighing 1.5 mg and containing approximately 10% of Th^{229}. The sample was a spot 20 mm in diameter and 0.5 mg/cm^2 thick on a thin platinum foil. The foil carrying the sample was placed in a flat ionization chamber on the axis of the slow neutron beam from the RFT reactor. Both the fission fragments from Th^{229} and the fast neutrons emitted by the excited fragments at the instant of fission were detected. BF_3 counters were used to detect the neutrons. Any multiplicative correction factors which should be applied to the experimental result were eliminated by making similar measurements on a sample of U^{235} and obtaining the ratio of $\nu(Th^{229})$ to $\nu(U^{235})$, the latter being known with good accuracy.[1] Details of the method are given in reference 2.

Since the cross section for the fission of Th^{229} by thermal neutrons is small (45 ± 11 barns[3]), and since we had only 150 micrograms of Th^{229} at our disposal, we used a current of 2 to 4×10^5 neutrons/cm^2 sec to obtain a noticeable effect in the ionization chamber. Since the spot had a fairly large diameter (20 mm), we used a neutron beam with a cross section of 3 cm^2. Under these conditions, the detector counted a considerable number of scattered neutrons, not arising from fission in our sample. The neutron current was so chosen, that when there were several counts per second in the ionization chamber, the background of accidental coincidences between pulses from the fission fragments and pulses from scattered neutrons did not exceed the number of true coincidences between fission fragments and fast fission neutrons. There were several tens of the latter per second (the detector efficiency was about 5%).

Since our thorium sample was extracted from a considerable amount of U^{233}, the sample was carefully cleaned by chromatographic methods to rid it of uranium traces. Special control experiments showed that the uranium contamination in the sample was no more than a few hundredths of a percent. Thus the presence of U^{233} could not have contributed to the observed effect by more than 1%, while the error in $\nu(Th^{229})$ due to the different values of $\nu(Th^{229})$ and $\nu(U^{233})$ is a few tenths of a percent.

Several series of measurements yielded the following ratio of the average number of neutrons emitted in one fission of Th^{229} induced by thermal neutrons to the same number for U^{235}:

$$\nu(Th^{229})/\nu(U^{235}) = 0.864 \pm 0.008.$$

Taking $\nu(U^{235})$ to be 2.47 ± 0.03 (reference 1), we obtain

$$\nu(Th^{229}) = 2.13 \pm 0.03.$$

It is interesting to note that slow neutrons with an energy of 0.5 ev to several tens of electron volts have a larger effect on Th^{229} than they do on U^{235}. If the incident neutron beam is filtered through 1 mm of cadmium, the rate of fission in the chamber with Th^{229} goes down by a factor of 10, while in a chamber with U^{235} the rate goes down by a factor of 200. The fission rate with the cadmium filter is thus about 20 times bigger in Th^{229} than it is in U^{235}. Filtering the neutron beam through 2.2 g/cm^2 of boron carbide decreases the fission rate in Th^{229} by a factor of 300 to 400, while the rate in U^{235} goes down by a factor of 2000. The boron carbide filter is 5 times more effective in reducing fission rate for U^{235} than it is in Th^{229}. One can suppose that the cross section for the fission of Th^{229} by neutrons having an energy equal to several electron volts is at least no smaller than the cross section for fission by thermal neutrons. This should have no effect on the value of $\nu(Th^{229})$ quoted above, since the measurements on which this value is based were carried out with an unfiltered beam. Even if the Th^{229} were to have some resonances in the cross section for fission by neutrons of a few electron volts, the value of ν near the resonances should not differ markedly from its value for thermal neutrons, as shown by several authors.[4-6]

In conclusion, the authors consider it their pleasant duty to thank G. N. Iakovlev and S. V. Pirozhkov for preparing the clean thorium samples.

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NUCLEAR ORIENTATION IN RADIATIVE K CAPTURE

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As is well known, the nucleus becomes oriented as a consequence of parity nonconservation in beta decay. For the case of an allowed beta-transition of a nonoriented nucleus, the average value $\langle \mathbf{J} \rangle$ of the angular momentum of the daughter nucleus is given by

$$\langle \mathbf{J} \rangle = {}^1/_3 (j+1) \zeta \mathbf{v}, \qquad (1)$$

where j is the angular momentum of the daughter nucleus, $c\mathbf{v}$ is the velocity of the β electron (the neutrino direction is not observed), and ζ is the coefficient in the formula

$$w = 1 + \zeta \mathbf{v} \cdot \langle \mathbf{J} \rangle / j,$$

which describes the electron angular distribution for decays of oriented nuclei.[1-3] This orientation is responsible for effects in the electromagnetic transitions of the daughter nucleus such as the circular polarization of photons,[3] and the polarization of conversion electrons.[4]

An analogous orientation of the nucleus also takes place in radiative orbital electron capture $e + p \rightarrow n + \nu + \gamma$ (see reference 5). The nuclear orientation is given in this case by Eq. (1), in which $c\mathbf{v}$ is the photon velocity and ζ is the coefficient that appears in positron emission.

To prove this premise, let us consider the matrix element $V_{m_1 m}$ for radiative K capture with the nucleus going from the state $j_1 m_1$ into jm. Accurate to within an overall multiplicative factor, we have

$$V_{m_1 m} = (jm \mid O_i \mid j_1 m_1)\, \bar{u}_\nu(q)\, O_i\, (\hat{p} - \hat{k} + im)\, \hat{e} u_e(p)),$$

where $(jm \mid O_i \mid j_1 m_1)$ is the nuclear matrix element, $u_\nu(q)$ is the amplitude of a neutrino with four-momentum q, $u_e(p)$ is the electron amplitude, e is the polarization vector of the photon, and k is its four-momentum. The polarization density matrix of the daughter nucleus is of the following form (accurate up to an overall multiplicative factor):

$$\rho_{mm'} = \sum_{m_1} (jm \mid O_i \mid j_1 m_1)\, (jm' \mid O_j \mid j_1 m_1)^* \operatorname{Sp} Q, \qquad (2)$$

$$\operatorname{Sp} Q = \operatorname{Sp} \{(\hat{p} + im)\, \hat{e}\, (\hat{p} - \hat{k} + im)\, O_j \hat{q} O_i\, (\hat{p} - \hat{k} + im)\, \hat{e}\},$$

where $\bar{O}_j = \gamma_4 O_j^+ \gamma_4$. Since for K capture $\hat{p} = \gamma_4 p_4$, hence

$$\operatorname{Sp} Q = \operatorname{Sp} \hat{k} \bar{O}_j \hat{q} O_i. \qquad (3)$$

In the case of positron emission $\rho_{mm'}$ is also of the form (2) and

$$\operatorname{Sp} Q = (\hat{p}_+ + im) \bar{O}_j \hat{q} O_i, \qquad (4)$$

where p_+ is the positron four-momentum. For an extremely relativistic positron ($m = 0$, $p_+^2 = k^2 = 0$) Eq. (4) goes over into (3), thus proving Eq. (1) with $\mathbf{v}$ equal to the photon velocity. (We have here the same relationship as in the formulas for photon polarization.[6])

At first sight it may seem peculiar that the pseudovector $\langle \mathbf{J} \rangle$ is proportional to the vector representing the photon momentum since photon emission proceeds through a parity conserving mechanism. In actuality, the nucleus becomes polarized because the virtual electron can be absorbed by the nucleus only in a state with a definite polarization, namely in the direction of its momentum, which in turn is opposite to the direction of the momentum of the emitted photon.

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