recognized the following interesting properties. The following three different cases at $\sqrt{S}=4.8$ GeV and $M_L=1.8$ GeV all produce almost identical $\theta_{\rm coll}$ distributions: (i) $M_{\nu_L}=0$, $E_c=0.75$ GeV, and $V-A$ current for the heavy lepton (see Fig. 2); (ii) $M_{\nu_L}=0.5$ GeV, $E_c=0.65$ GeV, and $V-A$; and (iii) $M_{\nu_L}=0$, $E_c=0.65$ GeV, and $V+A$ current for the heavy lepton. A somewhat related observation has been made independently by Park and Yildiz.[7] See also the newer data of Perl *et al.*[8]

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# Angular Correlation of Neutrons from Spontaneous Fission of $^{252}$Cf

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(Received 18 August 1975)

The $n$-$n$ angular correlation for neutrons emitted in spontaneous fission of $^{252}$Cf has been measured. Discrepancies are observed when these and other experimental observations are compared with Monte Carlo calculations based on the evaporation model. It is suggested that the discrepancies could be attributed to enhanced neutron emission along the fission axis.

It is well established[1,2] that a large fraction (75–90%) of the neutrons emitted promptly in spontaneous or thermal-neutron fission can be accounted for in terms of evaporation from the fully accelerated fission fragments. However the origin of the remaining 10–25% of the neutron emission remains in question and it has been suggested that these neutrons may be emitted at the instant of scission[1,2] or during the acceleration period of the fragments.[3] Models of the neutron emission rest mainly on experimental observations of the velocity and angular distributions of the prompt neutrons, the angular distributions being referred to the axis defined by the direction of the light fragment.

Another observable in the neutron emission process is the neutron-neutron angular correlation, that is the $n$-$n$ coincidence rate as a function of angle between emitted neutrons. Such a measurement was reported for thermal-neutron fission of $^{235}$U by De Benedetti *et al.*[4] in 1948. However no further measurement of this observable appears to have been reported since then. The $n$-$n$ angular correlation experiment does not require the detection of fission fragments, and hence stronger and thicker sources may be used than in angular distribution measurements. On the other hand, the observations are automatically averaged over all orientations of the fission axis, which implies some loss of detail. The correlation is nevertheless sensitive to the characteristics of neutron emission and provides a useful additional method for testing models of emission process. We have measured the $n$-$n$ angular correlation of prompt neutrons from the spontaneous fission of $^{252}$Cf. In order to compare results with predictions based on the evaporation model we have also made Monte Carlo calculations simulating our experiment and the measurement of the neutron angular distribution.[1]

The $n$-$n$ angular correlation was measured using a source consisting of 2 $\mu$g of $^{252}$Cf in the form of four 15-mm-long rods, each sealed in a 1-mm-diam platinum-iridium container. The neutron detectors were an NE213 liquid scintillator (38 mm diam$\times$25 mm length) and an anthracene crystal (25 mm diam$\times$25 mm length) each mounted on a magnetically shielded photomultiplier tube. Pulse-shape discrimination was used to reject $\gamma$ events and the detectors were operated at a proton detection threshold of 0.7 MeV. The pulse-shape discrimination rejection efficiencies of both detectors, as measured for Compton electrons from $^{60}$Co $\gamma$ rays, were better than 99.9%. The proton detection thresholds were calibrated using monoenergetic neutron beams obtained from the reaction $^7$Li$(p,n)^7$ Be. One detector and the source were fixed in the horizontal plane and the other detector was rotated about a vertical axis through the source to vary the $n$-$n$ correlation angle $\theta$. The time-delay spectrum was recorded and the true coincidence rate was determined from the peak in this spectrum. The accidental coincidence rate, estimated from the remainder of the time spectrum, never exceeded 10% of the true rate.

The distances from the source to the two scintillators were 30 cm for the measurements made at $\theta \geq 45°$. For $\theta < 45°$ one detector was moved back to 40–50 cm and a shadow shield was inserted between the two detectors to attenuate spurious coincidences arising from neutron scattering from one detector to the other. This scattering background was carefully investigated and the geometry and length of the shield were chosen to limit it to a negligible level.

The singles count rates $N_1$ and $N_2$ of the two detectors and the coincidence rate $N_c(\theta)$ at angle $\theta$ were determined in the experiment. Let $N_f$ be the fission rate of the source, $\bar{\nu}$ the average neutron yield per fission, and $\Omega_1$ and $\Omega_2$ the solid angles subtended by the two detectors. Then, since $\Omega_1$ and $\Omega_2$ are small,

$$N_1 = \Omega_1 \epsilon_1 \bar{\nu} N_f / 4\pi \text{ and } N_2 = \Omega_2 \epsilon_2 \bar{\nu} N_f / 4\pi ,$$

where $\epsilon_1$ and $\epsilon_2$ are the average efficiencies of the detectors for detecting a fission neutron. The coincidence rate is given by

$$N_c(\theta) = \Omega_1 \Omega_2 \epsilon_1 \epsilon_2 \bar{\nu} N_f P(\theta) / 4\pi ,$$

where $P(\theta)$ represents the number of fission neutrons emitted per unit solid angle at angle $\theta$ to, and in coincidence with, the $\nu$th fission neutron.

We define a ratio

$$R(\theta) = N_c(\theta)/N_1 N_2 = 4\pi P(\theta)/\bar{\nu} N_f .$$

Thus $R(\theta)$ is proportional to the angular correlation $P(\theta)$, independent of the experimental geometry ($\Omega_1$ and $\Omega_2$), and insensitive to small variations in instrumental stability insofar as these affect $\epsilon_1$ and $\epsilon_2$.

The experimental results are plotted in Fig. 1 together with a prediction of $R(\theta)$ based on an evaporation model including a 10% scission neutron component. The prediction was generated by a Monte Carlo calculation for $4\times10^4$ simulated fissions. The first stage of the calculation simulated the neutron emission from the source as follows. In each fission, pre-emission fragment masses were selected by sampling a mass distribution based on two sets of experimental data.[5,6] The (fully accelerated) velocities of the fragments in the laboratory frame were determined from the data of Whetstone.[6] For each fragment, the average neutron yield $\bar{\nu}$ and the variance $\sigma_\nu{}^2$ were determined from the data of Signarbieux *et al.*[7] The actual number of neutrons emitted by each fragment was chosen by sampling a Gaussian $(\bar{\nu}, \sigma_\nu{}^2)$ distribution. A fraction[1] (10%) of the neutrons, randomly chosen, was designated as scission neutrons. It was assumed[1] that this component was emitted isotropically from a source stationary in the laboratory frame, while the remaining 90% of the fission neutrons were emitted isotropically in the frames of the fully accelerated fragments. The angles of emission of both scission and fragment neutrons in the respective emitting frames were assumed to be uncorrelated. Neutron emission energies were sam-

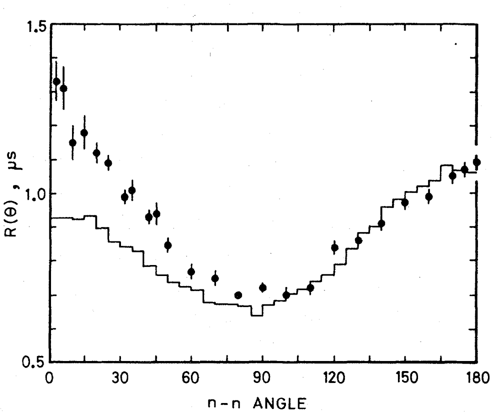


FIG. 1. The $n$-$n$ angular correlation $R(\theta)$ for $^{252}$Cf fission, showing experimental measurements (points) and Monte Carlo simulation (histogram).

pled from evaporation spectra of the form

$$N(E) = (E/T^2)\exp(-E/T),$$

where $T$ is the nuclear temperature of the fragment emitting the neutron and $E$ is the neutron energy in the appropriate frame. Fragment temperatures were determined from the data of Kluge and Lajtai.[8] An evaporation temperature $T = 1.3$ MeV was used in the case of scission neutrons.[1] In accordance with recent experimental evidence,[9] energies of evaporation neutrons were assumed to be uncorrelated. The Monte Carlo calculation was checked by computing various parameters of the simulated fission source. For example, the simulation gave $\overline{\nu} = 3.73$, and a ratio $\overline{\nu}_L/\overline{\nu}_H$, for the light and heavy fragments, of 1.15. Both values are in good agreement with experiment. The simulated neutron spectrum was also consistent with an experimental measurement.[10]

The final stages of the Monte Carlo calculation simulated the present experiment and the angular distribution measurement of Bowman *et al.*[1] The simulated angular correlation was normalized to the experimental data in the range $\theta = 80°-180°$ and is plotted in Fig. 1. The sensitivity of the simulation to the proton detection threshold was investigated by repeating the Monte Carlo calculation using thresholds 0.2 MeV lower and higher than the experimental value of 0.7 MeV. No significant change was observed in the form of the correlation. From Fig. 1 it may be seen that the simulation reproduces the form of the experimental data reasonably well at angles in the range $\theta = 100°-180°$ but not smaller angles.

The angular distribution measurement of Bowman *et al.*[1] was simulated using a *neutron* detection threshold of 0.55 MeV (velocity 1.025 cm/nsec) as used in their experiment. The simulated distribution was normalized to their data in the angle range $\theta = 40°-140°$ and is shown (histogram) together with the data in Fig. 2. A curve by Bowman *et al.*[1] based on an analytical formula in which average values, independent of the fragment mass ratio, were used for the velocities, temperatures, and neutron yields of the fission fragments is also shown in Fig. 2. Whereas the curve fits the data well, the prediction of the Monte Carlo calculation is too low both at small angles, $\theta \lesssim 30°$, and large angles, $\theta \gtrsim 150°$. This discrepancy between the two calculations was investigated by modifying the Monte Carlo calculation so as to use the fixed values used by Bowman *et al.*[1] for the fragment velocities, temperatures, and neutron yields. The modified calculation gave

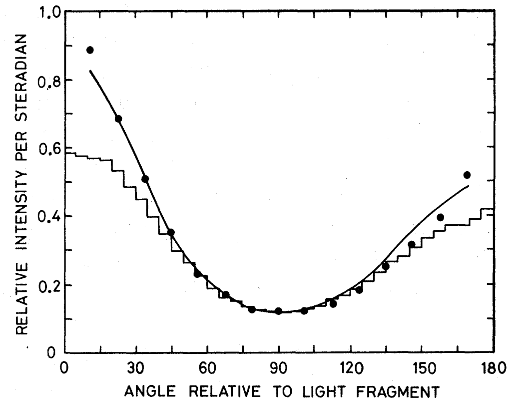


FIG. 2. Simulated angular distribution of neutrons from $^{252}$Cf fission (histogram). The points show experimental data (Ref. 1) and the curve shows the fit obtained by using an analytical model (Ref. 1). The standard deviations of the data are smaller than the point size.

results in close agreement with the curve shown in Fig. 2, indicating that the discrepancy between curve and histogram may be attributed to the different assumptions made in the two calculations. The present simulation (histogram) is more realistic insofar as it takes account of the dependence of neutron emission characteristics on the fragment masses. For this reason and notwithstanding the poorer agreement with experiment, we consider it a better representation of the angular distribution of the evaporation model.

Further calculations were made to test the sensitivity of the simulations to the scission neutron fraction. For fractions less than 10% there is little change in the distributions, while larger fractions increase the discrepancies between experiment and theory. It is also evident that the fits would not be improved by attributing[3] a fraction of the neutron emission to evaporation during the fragment acceleration period. Such a model leads to results intermediate between those with and without a scission component.

We therefore conclude that the evaporation model in the form considered here cannot explain the results of the neutron angular correlation and angular distribution measurements, and that some mechanism must operate which enhances neutron emission along the fission axis. Ericson and Strutinski[11] have considered the effect of fragment angular momentum and have shown that this might cause such an enhancement. However Gavron and Fraenkel[9] consider that this effect must be small for the case of $^{252}$Cf fission. Another possibility is that neutrons emitted at the scission stage may be directed preferentially along the fission axis. Recent studies[12] of the analogous[13] process of light charged particle emission in ternary fission have indicated an unexpectedly large axial component and it would therefore not be surprising if the same were true for scission neutrons. On the evidence now available however it is not possible to do more than speculate as to the origin of the enhanced axial emission of neutrons.

We thank the International Atomic Energy Agency, Vienna, for the loan of the $^{252}$Cf source and the South African Council for Scientific and Industrial Research for financial support and a bursary to one of us (J.S.P.).

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# Experimental Study of Weak Magnetism and Second-Class Interaction Effects in the $\beta$ Decay of Polarized $^{19}$Ne†

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(Received 18 August 1975)

The angular distribution of positrons emitted in the decay of polarized $^{19}$Ne has been measured as a test for the second-class weak interaction. The $\beta$ asymmetry parameter varies linearly with the $\beta$ energy with slope $(dA/dE)_{\rm exp} = (-0.65 \pm 0.15)\%\ \mathrm{MeV}^{-1}$. This result requires a second-class form factor comparable to the weak-magnetism term.

It has been emphasized that a favorable way to detect the second-class weak interaction[1] is by means of angular correlation measurements in nuclear $\beta$ decay.[2] With this motivation in mind we have investigated the energy dependence of the angular correlation between the initial nuclear spin and the positron direction in the decay $^{19}\mathrm{Ne} \to {}^{19}\mathrm{F} + e^+ + \nu$ ($T_{\rm max} = 2.2$ MeV, $t_{1/2} = 17.3$ sec).[3] This is a transition between members of a $\frac{1}{2}^+$ isospin doublet and such a decay is specified, to first order in recoil, by just four nuclear form factors, each of which is uniquely first or second class in origin.

Following Holstein and Treiman[2] the nuclear form factors are denoted as $a$, $b$, $c$, and $d$. The $a$ and $b$ terms arise from the vector interaction and correspond to the Fermi matrix element and weak-magnetism form factor, respectively. According to the conserved-vector-current (CVC) theory they are solely first class and, at zero momentum transfer, have the values $a(0) = 1.00$ and $b(0) = -148.60 \pm 0.03$.[4] The $c$ and $d$ terms originate from the axial-vector interaction; $c$ is essentially the Gamow-Teller matrix element and is first class, whereas $d$, the tensor form factor, is second class.

With $a$ and $b$ fixed, both $c$ and $d$ are determined from a measurement of the asymmetry parame-