Search for neutral pions from the spontaneous fission of ^{252}Cf

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A search for π^0's arising from the spontaneous fission of ^{252}Cf using the LAMPF π^0 spectrometer has yielded no evidence for this process. We obtain an upper limit of 1.4×10^{11} with a 90% confidence level for the branching ratio of π^0's produced at rest in the spontaneous fission of ^{252}Cf.

A search for π^0 decay arising from the spontaneous fission of ^{252}Cf was conducted at the Clinton P. Anderson Meson Physics Facility (LAMPF) using the LAMPF π^0 spectrometer [1]. The basis for this investigation is the recent theoretical work by Ion, Ivascu, and Ion-Mihai [2,3], which has given rise to the interesting suggestion that natural pionic radioactivity occurring as a branch of spontaneous fission may be observable. Although the process is energetically possible for all nuclei with $Z > 80$, it is not expected to be common. This is due to the fact that, as a result of the Coulomb field at the scission point, most of the fission Q value is released as kinetic energy of the fragments. Only a small fraction of the energy released is available for exciting internal degrees of freedom in the fragments. The Bucharest Group combines the energetics with considerations of phase space to conclude that the branch for pion emission relative to spontaneous fission is as large as 10^{-4} in some short-lived nuclei. They calculate the branching ratio for the readily available ^{252}Cf to be 1.26×10^{-4} [3].

Several previous searches found no evidence for neutral pionic radioactivity from spontaneous fission. Cerruti *et al.* [4] used two collinear blocks of lead glass to convert π^0 decay photons and contain the resulting charged-particle shower. Beene *et al.* [5] used an array of NaI(Tl) detectors that covered a large fraction of 4π. Stanislaus *et al.* [6] used two large, collinear NaI(Tl) detectors. Julien *et al.* [7] used an array of lead-glass detectors in an underground laboratory. The smallest upper limit previously reported is $\Gamma_\pi/\Gamma_{sf} < 10^{-12}$ (95% C.L.) for ^{252}Cf [7].

The LAMPF π^0 spectrometer is well suited for this experiment. By present standards it provides excellent energy resolution, it is not sensitive to particles that compete with the π^0 signal (particularly neutrons), and it is capable of handling the rates associated with fission source strengths in the few mCi range. The spectrometer functions by the coincident detection of both photons emitted in the (98.8%) decay $\pi^0\rightarrow2\gamma$. Each photon is converted into a charged-particle shower by one of three lead-glass conversion planes on each arm of the spectrometer. The shower particles leave tracks in multiwire proportional chambers behind each conversion plane; these tracks are analyzed to determine the conversion vertex. Thin plastic scintillation detectors placed beyond each set of wire chambers serve as timing counters. The laboratory angle between the two photons, which is related to the total energy of the original π^0, is reconstructed from the vertices. A second determination of the total energy is also obtained (with lower resolution) from summing the energy deposited in the converter planes, scintillators, and lead-glass calorimeters in which the showers are stopped.

A schematic layout of the spectrometer and source is shown in Fig. 1. The experiment was located in the cave of the pion and particle physics east (P^{3}E) secondary beam channel at LAMPF. The arms of the spectrometer

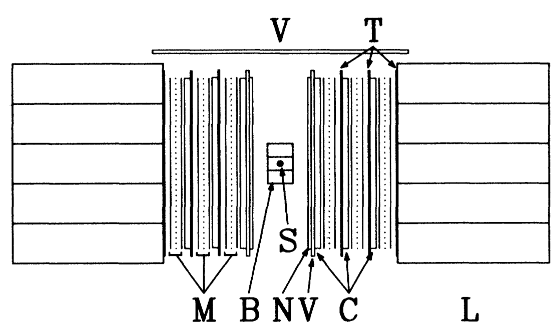

FIG. 1. Side view of the experimental arrangement. The source S is surrounded by 5%-boron-loaded polyethylene shielding B. The two arms of the spectrometer are symmetric about the source; various elements are identified on one side only for clarity. The various veto counters V are in front of and over the photon converters. The Pb-glass elements of the spectrometer are the converters C and calorimeters L. Multiwire proportional chambers M lie between each converter and its trigger scintillator T. A polyethylene sheet N lies in front of each arm to degrade neutrons and charged particles.

were set with an opening angle of 180°. The distance between a centrally placed fission source and the front face of the first photon conversion plane of either arm was 13.5 cm. The source was surrounded by 5% boron-loaded polyethylene to attenuate neutrons. Source-related charged particles and some cosmic rays were vetoed by 1.27-cm thick plastic scintillation detectors mounted in front of the calorimeters on each arm. Near-zenith cosmic rays that missed the front-mounted veto detectors but interacted in the trigger scintillators were vetoed with two 15-cm×100-cm×0.6-cm thick plastic scintillation detectors placed over the two arms of the spectrometer and bridging the gap between them. The hardware trigger for π^0 events is the coincidence of relatively large amounts of energy (5 MeV) deposited in the lead-glass elements, pulses in the scintillator elements of both arms, and the absence of large pulses in any of the veto scintillators.

The response of the spectrometer to low-energy π^0's was checked prior to this experiment by observing π^0's created by stopping energetic π^- mesons in a polyethylene target. This calibration was carried out at the LAMPF P^3E beam line using 160-MeV π^- particles incident on about 60 cm of graphite degrader and about 2.5 cm of polyethylene. The expected π^0 energy from this reaction is 3.31 MeV. A π^0 energy spectrum, obtained using methods described in Ref. [1], is shown in Fig. 2. These data confirm that the spectrometer was functioning properly prior to collecting the fission data.

The branching ratio was calculated using the relation

$$\frac{\Gamma_\pi}{\Gamma_{sf}}=\frac{4\pi n_0}{N_{sf}\varepsilon_c^{JK} a\,\Delta\Omega}\ , \tag{1}$$

where n_0 is the number of neutral pions seen, ε_c^{JK} is the spectrometer photon conversion efficiently, a is the total photon attenuation due to material between the source and the detector, $\Delta\Omega$ is the solid angle subtended by the spectrometer, and N_{sf} is the total number of spontaneous fissions in the source.

A Monte Carlo calculation [1] that incorporates all aspects of the π^0 detection process is used to determine the solid angle for energetic π^0's. The solid angle was limited by the requirement that the charged-particle shower from a photon conversion must travel at least two radiation lengths (χ_0=4.2 cm) into the total-energy calorimeter. The calculated spectrometer acceptance for the chosen experimental configuration is shown in Fig. 3 as a function of π^0 kinetic energy. The calculated acceptance corresponds to a coverage of 13.5% of 4π for π^0's decaying at rest, and falls smoothly by an order of magnitude at 30 MeV. The Monte Carlo calculations for very-low-energy π^0's agrees well with the geometric solid angle [8] for π^0's decaying at rest. The calculation also predicts a π^0 energy resolution of about 4 MeV over the same energy range. The efficiency of photon conversion in the converter planes is discussed in Ref. [1]. The same Monte Carlo calculation was also used to generate the expected spectrometer response, shown as the smooth curve in Fig. 2, to the stopping π^- calibration data discussed above.

The photon attenuation factor a includes estimates of photon attenuation by the organic materials between the source and the first conversion planes, by the boron in the boron-loaded polyethylene bricks, and in the steel wall of the container encapsulating the source. The product of these attenuations is essentially constant at 0.74 over the range of γ-ray energies considered.

The source consisted of approximately 10.9 μg of ^{252}Cf encapsulated in a 0.32-cm thick steel case. The mass is based on the known mass of ^{252}Cf present in the source at the time of its assembly and the subsequent decay time to the start of the experiment. The activity at the start of the experiment was calculated to be 5.82 mCi, giving a

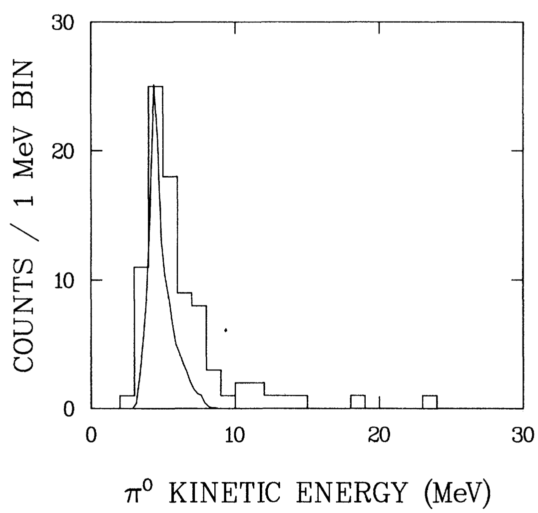

FIG. 2. Spectrum (square histogram) from a beam of 160 MeV π^- degraded by 60 cm of graphite and stopped in 2.5 cm of polyethylene. The smooth curve shows the calculated spectrometer response to the 3.31-MeV π^0's arising from stopping $\pi^- p \to \pi^0 n$.

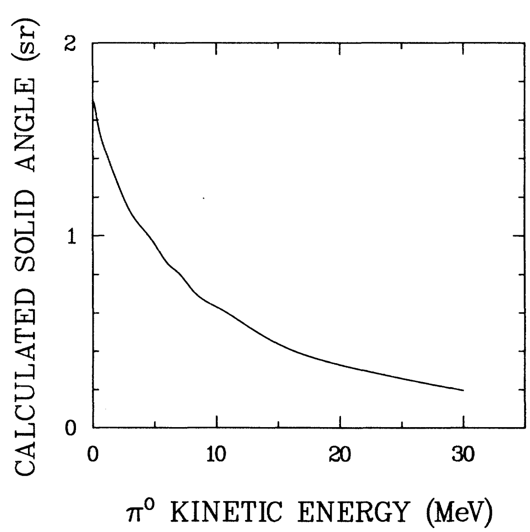

FIG. 3. Calculated acceptance function of the spectrometer as a function of π^0 kinetic energy.

spontaneous fission rate of 6.66 MHz. The total number of fissions determined to have occurred during the experiment was 2.09×10^{13}, using a calculation that considered the source decay and the average fractional livetime (91%).

The experiment was run for a total of 354.0 h source-out and 892.6 h source-in. The average trigger rate was 0.08 Hz. All data were collected while the accelerator was shut down; previous testing had shown a significant increase in the background rate when the accelerator was running even while no beams were being delivered to the P^3E cave. Data from each event that triggered the electronics was written to magnetic tape for later analysis.

A careful examination of the low-energy π^0's from the stopping π^- data revealed cuts that could be applied to the fission data to eliminate background events from true π^0 events. Restrictions on the data include the relative timing between the two arms and on the total photon energy deposited in each arm. After all restrictions to the data were applied 30 events remained in the total source-in data set. Applying the same cuts to the source-out data yielded 30.3 events when normalized to the source-in running time, giving a net of -0.3 ± 10.3 event. The source-out events may be ascribed to accidental coincidences from cosmic rays that missed the veto detectors. This result leads us to conclude that no excess rate due to π^0 decays was seen above the background. A statistical analysis [9] based on Poisson statistics gives an upper limit on the number of detected π^0's of $n_0<10.2$ with a 90% confidence level. Since an energetic π^0 created during spontaneous fission would need to penetrate an even larger potential barrier than one created at rest, we assume that any π^0 yield would be concentrated at 0 MeV. This assumption allows us to use the solid angle for 0 MeV π^0's in Eq. (1). We calculate an upper limit to the branching ratio for π^0's emitted from spontaneous fission to be

$$\frac{\Gamma_\pi}{\Gamma_{\rm sf}}<1.37\times10^{-11}\quad(90\%\ \text{C.L.})\ . \tag{2}$$

In addition to our experimental work, the rather large branching ratio predicted by the authors of Ref. [2] has led us to the literature to investigate the basis of their calculations. It appears that they have taken the fissility parameter x, which is the ratio of the spherical nucleus Coulomb energy to twice the surface energy, and modified it by subtracting the pion mass from the Coulomb energy. Thus they have a new fissility parameter for pion emission during fission, and simply use the new parameter in place of the old one. The physical motivation for this substitution is not given in their papers, and appears to be unjustified [10].

A reasonable model for neutral pion emission during fission would be to assume that the pion is produced during the penetration of the nucleus through the fission barrier, and that the barrier height is thus increased by a value equal to the mass of the pion. The situation is then illustrated by Fig. iii-6(b) of Vandenbosch and Huizenga [11], except that the energy change is 135 MeV. The barrier penetration probability at an energy ΔE, according to the Frankel-Metropolis formula [12] is

$$P\propto10^{-7.85(\Delta E)} \tag{3}$$

which gives a branching ratio equal to 10^{-1060}. Such a heuristic formulation takes the energetics more properly into account, and although it cannot be considered as being a precise theoretical estimate of the branching ratio, it should be considered a better estimate of the true likelihood of observing the event in nature.

In conclusion, our search found no evidence for π^0's created as a consequence of spontaneous fission. Our results are consistent with an upper limit to this process of $\Gamma_\pi/\Gamma_{\rm sf}<1.37\times10^{-11}$ (90% C.L.), and do not contradict a theoretical estimate of $\Gamma_\pi/\Gamma_{\rm sf}\approx10^{-14}$ [3]. This experiment represents the ultimate capability of the present spectrometer; a second-generation π^0 spectrometer [13] presently under construction may have the capability of reaching the 10^{-13} level in similar running times.

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