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Search for the spontaneous emission of pions

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A search has been made for the spontaneous emission of neutral pions from Pb, Bi, Th, U, and ^{252}Cf. None has been observed and for the most likely candidate, ^{252}Cf, the limit is 3.3×10^{-10} of spontaneous fission with a 90% confidence level.

A significant amount of interest has been generated recently by the suggestion of Ion, Ivascu, and Ion-Mihai[1,2] that π emission might accompany spontaneous fission. Normally in the fission of the heavy elements about 200 MeV is available, which is more than sufficient to create a pion. Both charged pions and neutral pions could be produced, but the π^0 has a lighter mass and so is likely to have a higher branching ratio; it is also easier to detect via the characteristic 2γ decay mode which has a branching ratio of 98.8%. The most convenient candidate is ^{252}Cf; it is readily available and has a significant rate for spontaneous fission. In a recent publication Ion, Ion-Mihai, and Ivascu[3] have estimated that the π^0 rate in ^{252}Cf might be as high as 10^{-14} of the spontaneous fission rate.

There have already been two reports on experimental searches with ^{252}Cf. Cerruti *et al.*[4] from Saclay used two lead glass detectors and obtained a limit for the branching ratio of 5×10^{-9} with respect to spontaneous fission. Similarly Beene, Bemis, and Halbert[5] from Oak Ridge used the "Spin Spectrometer" and obtained a limit $\Gamma_\pi/\Gamma_{SF} < 1\times10^{-9}$ with 90% confidence limit.

We report here on a recent search at TRIUMF for π^0 decay, using our two large NaI detectors TINA and MINA. An important advantage is that the equipment was set up using π^0 production from π^- charge exchange at rest in hydrogeneous material. Thus the response of the equipment to an actual π^0 is accurately known.[6] Another improvement is that we have also investigated some other possible candidates. One of the problems for all searches is that the kinetic energy of the π^0 can in theory extend from 0 to 50 MeV or so. However, the rate for spontaneous fission is extremely sensitive to the energy available, so one can anticipate that the π^0 is going to take very little of the available energy. We thus have used the 180° geometry to ensure that even zero energy pions would be detected. For a coincidence required, with the detectors at a relative angle of ψ, it can be easily shown that

$$E_T\times E_M=\frac{M_{\pi^0}^2}{4\sin^2(\frac{1}{2}\psi)}\ ,$$

where E_T and E_M are the γ-ray energies detected in TINA and MINA, respectively. This relationship holds no matter what the π^0 kinetic energy. The detection efficiency is slightly energy dependent, however, and for our geometry was 11.6% at zero kinetic energy and 6.2% at 10 MeV.

The search was conducted on two separate occasions with consistent (null) results. The equipment was set up on the M9 beam line at TRIUMF and was first used for studies of the atomic reactions of pionic hydrogen.[7,8] The experiments were scheduled at the end of a beam period so that the equipment could be left undisturbed for several weeks. Two minor modifications were made after the set up. To improve the detection efficiency the two NaI crystals were moved together as close as was possible, leaving only a small gap between the two collimators. We also placed a large cosmic ray shield over both detectors. It was originally designed to shield the TRIUMF TPC from cosmic rays,[9] and was constructed of 12-mm-thick plastic scintillator, covering an area 2.0 m×4.6 m. This reduced the background by a factor of 35. Normally we require a beam π^- in coincidence and time the arrival of the neutral events from the stop. For this experiment we suppressed the stop requirement, of course, and used a TINA-MINA coincidence gate of 15 ns. Apart from these minor changes all electronics, cables and phototubes were left untouched, including the charged veto detectors between the NaI crystals. The layout is illustrated in Fig. 1.

The sources were placed between the crystals in the small gap between the detectors. The majority of the sources had no impact on the detectors but ^{252}Cf is an intense source of neutrons and these create a noticeable background. (We used 5.4 μg of ^{252}Cf which is equivalent to 2.9 mCi and produces 1.2×10^7 n/s.) We therefore tried using the ^{252}Cf with and without neutron shielding between the source and NaI crystals. About 15 cm bricks of borax were used and this reduced the neutron counting rate in detectors, but of course would also have attenuated the γ rays from any π^0 events by about 30%. Corrections were made for this in the final analysis. Similarly, the other sources were relatively thick and so there was self-absorption and the transmission of the π^0 γ rays would have been about 50%. Again the necessary corrections were applied.

Periods with no source were alternated with periods of several days with the various materials between the two detectors. The data were analyzed afterwards using the techniques developed for our pionic chemistry experiments. Histograms of $E_T\times E_M$ are generated and com-

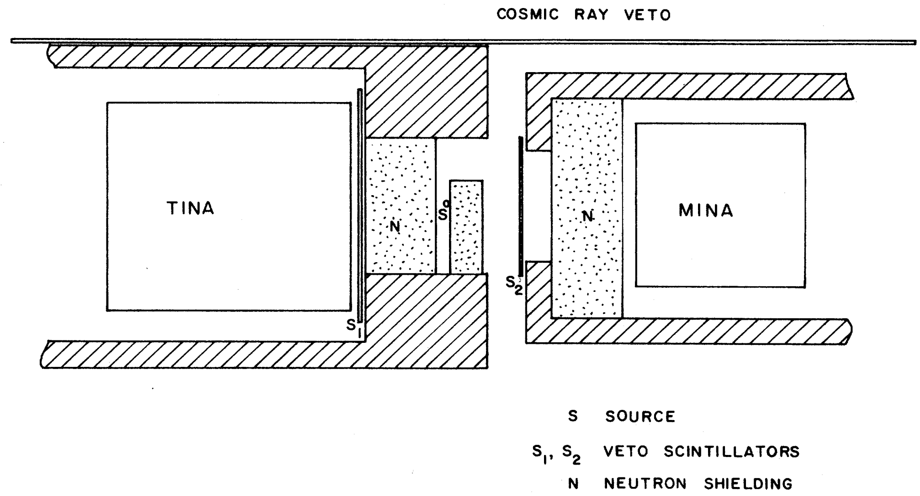

FIG. 1. Side view of the experimental setup.

pared with those of real π^0 events. Normalized histograms of the background could be subtracted from the histograms taken when the source was present. An alternative analysis was to use the fact that the shape of the background was very different from the known response of the equipment to a π^0. Thus the spectra were fitted with a π^0 response function, plus a background. Both techniques worked well and gave consistent null results in all cases. For the final result we took the values derived from the fitting technique which gave slightly greater sensitivity.

Some histograms of $E_T \times E_M$ are illustrated in Fig. 2. The histogram (a) is a π^0 response taken for π^- charge exchange at rest (which produces a 2.9 MeV π^0). The width of the peak is caused by the energy resolution of the detectors for γ rays in the energy range of 50 to 90 MeV. Each crystal has a resolution of typically 5% to 7% depending a little on the geometry. Histograms for ^{252}Cf are shown with [Fig. 2(b)] and without [Fig. 2(c)] the neutron shielding. The cosmic ray background has been subtracted off but the effect of the neutrons is clearly visible at low energy. The histogram for natural uranium is also illustrated [Fig. 2(d)], and is consistent with zero over the whole energy range. The data for bismuth, lead, and thorium are similar.

The final results together with details on the sources are given in Table I. As mentioned earlier, since the π^0 is expected to take very little energy, the rates given are for the emission of π^0's with kinetic energy less than 10 MeV. For this purpose we have used an average π^0 detection efficiency of 8.9%. In the unlikely situation of a π^0 being emitted with an energy of 40 MeV, the limits given would go up by a factor of 4. For stable nuclei we can quote a limit only on the rate per nucleus per second for π^0 production. For radioactive nuclei it is also possible to quote a branching ratio limit and for those with a known branch for spontaneous fission, it is possible to compare with this decay mode. Since spontaneous fission is the related process, this is the most meaningful comparison. For ^{238}U we find that $\Gamma_\pi/\Gamma_{SF} < 3.1 \times 10^{-4}$ (90% C.L.). This is the first search with this element. For ^{252}Cf we obtain $\Gamma_\pi/\Gamma_{SF} < 3.3 \times 10^{-10}$ with 90% confidence limit. This is somewhat more sensitive than the two previous searches, with the added advantage that our equipment was actually set up with real π^0 events.

To improve significantly on this limit with the type of detector used here it would be necessary to work in a mine. In the region of interest the coincidence rate was

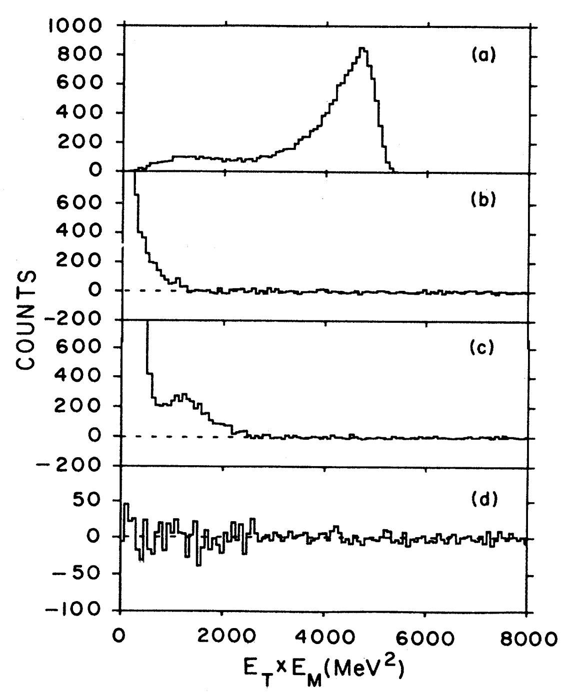

FIG. 2. The $E_T \times E_M$ spectra from (a) π^0 mesons produced by the reaction $\pi^- + p \rightarrow \pi^0 + n$, (b) ^{252}Cf with neutron shielding, (c) ^{252}Cf without neutron shielding, and (d) natural uranium. In (b), (c), and (d) the cosmic ray background has been subtracted.

TABLE I. The results of our experiment.

Material	Mass of nuclide (g)	Counting time (h)	π^0 rate (limit, 90% C.L.) (s^{-1})	BR[b] (limit, 90% C.L.)	Γ_π/Γ_{SF} (limit, 90% C.L.)
$^{nat}_{82}Pb$	123	109	3.3×10^{-27}		
$^{209}_{83}Bi$	275	73	1.9×10^{-27}		
$^{238}_{90}ThF_4$	75	82	6.6×10^{-27}	4.3×10^{-9}	
$^{238}_{92}U$[a]	447	201	8.5×10^{-28}	1.7×10^{-10}	3.1×10^{-4}
$^{235}_{92}U$[a]	3.2	201	1.2×10^{-25}	3.8×10^{-9}	1.4
$^{252}_{98}Cf$	5.4×10^{-6}	216	8.6×10^{-20}	1.0×10^{-11}	3.3×10^{-10}

[a]The source was natural uranium in metallic form.
[b]Limit on branching ratio (BR) with respect to all decays. Half-lives taken from the *Table of Isotopes* (Ref. 10).

~60 events per hour, even with the cosmic veto working. The π^0 response shape is different, but cosmic rays are a serious background and our results are not far from the practical limit for above ground measurements. However, if more information is obtained about each event, a lower limit could be reached, even at ground level. Such a technique is proposed at LAMPF,[11] using the π^0 spectrometer. In this device the γ rays are converted and the electron pairs are tracked towards a calorimeter. This eliminates all but the most perverse cosmic rays, viz., horizontal ones which pass through the source, a very remote possibility. In the next year or two we can thus anticipate significant improvements on the limit for spontaneous π^0 production.

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