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Further Search for the Decay $\mu^+ \rightarrow e^+ + \gamma$*

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A new experiment for determining the upper limit for the branching ratio R of the process $\mu^+ \rightarrow e^+ + \gamma$ relative to the normal decay mode $\mu^+ \rightarrow e^+ + \nu + \bar{\nu}$ yields a value of R of less than 1.2×10^{-6} with a 90% confidence level.

Several reports have recently appeared[1-3] describing experiments for determining the upper limit for the branching ratio R of the process $\mu^+ \rightarrow e^+ + \gamma$ relative to the normal decay mode $\mu^+ \rightarrow e^+ + \nu + \bar{\nu}$. The most accurate of these,[3] finding the branching ratio to be less than 2×10^{-6} with a 90% confidence level, was limited equally by accidental counting between uncorrelated particles and from real counts originating from the radiative muon decay, $\mu \rightarrow e + \nu + \bar{\nu} + \gamma$. The experiment herein reported was designed to eliminate interference from the radiative decay in an attempt to increase the sensitivity of the experiment for detecting the decay into a 53-Mev electron and a 53-Mev gamma ray.

Our approach differed from those of previous experimenters in that we chose to use large sodium iodide crystals to detect γ rays and electrons in the 53-Mev region. The superior resolution of NaI crystals for high-energy gamma rays allowed us to discriminate against lower energy electron-gamma coincidences from the $e + \nu + \bar{\nu} + \gamma$ decay without an appreciable loss in efficiency for detecting coincidences at 53 Mev. Calculations of the coincidence rates for the $e + \nu + \bar{\nu} + \gamma$ process expected for our geometry and energy resolution from the work of Fronsdal and Überall[4] indicated that this source of error would be a few orders of magnitude smaller than in previous experiments.

Although the phosphor lifetime of Tl activated sodium iodide crystals is long (0.25μsec) the large light output at 53 Mev enabled us to obtain resolving times of 3mμsec full width at half maximum with 100% counting efficiency.

The essentials of the experimental arrangement are sketched in Fig. 1. A beam of 250 Mev/c π^+ mesons, produced by the external beam of the Lawrence Radiation Laboratory synchrocyclotron and focused to a cross section 4 in.$\times$1 in., was slowed by passage through $10\frac{1}{4}$ in. of carbon and brought to rest in a 2 in. length of plastic 2 cm high and 4 in. wide. $C1$ and $C2$ were plastic scintillators and $C3$ and $C4$ were NaI crystals, $4\frac{1}{2}$ in. in diameter and 6 in. in length, for registering the energies of the 53-Mev electrons and the coincident 53-Mev gamma rays expected from the desired events.

Fast coincidence circuit No. 1 indicated in the electronic block diagram of Fig. 2 gave the count rate of $C3$, $C4$, $C1$, $\bar{C2}$. This condition was satisfied by the passage of an electron of any energy, resulting from the secondary μ decay, through $C1$ and into $C3$ in coincidence with a photon which skipped $C2$ and was detected in $C4$. Fast coincidence circuit No. 2 counted electrons in $C4$ and photons in $C3$, while fast coincidence circuit No. 3 was a duplication of No. 2 but with the pulse from $C3$ delayed by 8mμsec to give a measure of the chance coincidence rate. In practice circuits 2 and 3 were alternately placed out of time alignment. To insure long time stability the coincidence circuits were operated with a resolving time of 5mμsec at 100% counting efficiency. Their triggers were gated on and off with the cyclotron radiofrequency of 18 megacycles/second at a 50% duty cycle and were also off between the 300μsec long beam pulse of the machine. The rf gating was such that the circuits were off during the time that the π^+ beam arrived at the target thus preventing the detection of photons from neutral pions produced in the target by charge exchange. The gating also eliminated a large fraction of the background produced by fast neutrons and was essential to the use of such large crystals near the cyclotron in our experiment.

The energies of the electrons and photons were

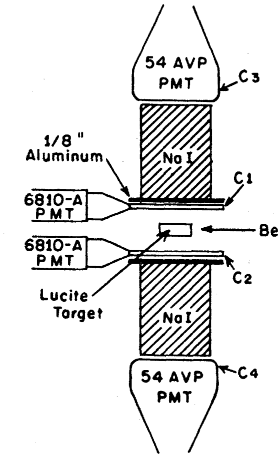

Fig. 1. Experimental arrangement.

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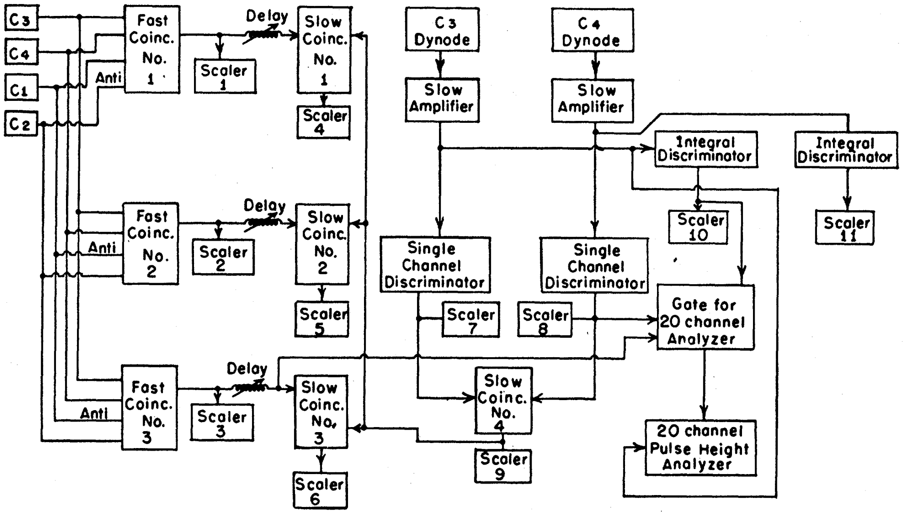

FIG. 2. Electronic block diagram.

determined by integration and amplification of the pulse from dynode 5 of the photomultipliers viewing the NaI scintillators. Two single channel discriminators with a 20% window selected those events with energies of 53 Mev from the 2 crystals. The discriminator outputs were placed in slow coincidence and the resulting output applied to the coincidence circuits 1, 2, and 3. Scalers 4, 5, and 6 then counted events which were in fast coincidence and of the correct energies.

Scalers 7, 8, 10, and 11 monitored the number of decaying muons, denoted by n. The number then, of those beta rays from the μ spectrum, $\mu \rightarrow e+\nu+\bar{\nu}$, that would fall in the energy channel is given by

$$N_\beta = n\alpha\beta d\Omega,$$

where $d\Omega$ is the solid angle of the detectors, α that fraction of the spectrum of appropriate energy, and β the photofraction for the detection of 53-Mev electrons in the NaI. The number of 53-Mev electrons detected that proceed through the mode $\mu \rightarrow e+\gamma$ is

$$N_e = nR\beta d\Omega,$$

and the number in coincidence with the 53-Mev photon

$$N_{e\gamma} = N_e \beta g,$$

where the photofraction for a 53-Mev electron is assumed roughly equal to that of a 53-Mev photon and g is the coincidence efficiency (assumed unity for a point source). R then becomes

$$R = \frac{N_{e\gamma}}{N_\beta} \frac{\alpha\beta}{\beta^2 g}.$$

Although α and β can be separately calculated from the shape of the muon beta spectrum and the properties of the NaI, the product

$$\alpha\beta = \frac{N_\beta}{n d\Omega} = \frac{\text{No. in channel}}{\text{total No. counted}},$$

are experimentally determined. The agreement is excellent. Our values for α, β, and g are 0.35, 0.4, and 0.8, respectively.

The experiment was carried out over a two week period with a total of $N_\beta = 9\times 10^6$ counts. When the 88 counts $N_{e\gamma}$ from the misaligned coincidence circuits were subtracted from the 78 aligned counts, the result was -10 ± 16 events. This yielded a value for R of less than 1.2×10^{-6} with a confidence level of 90%.

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