Photon Asymmetry for Radiative μ Capture in Calcium*

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We have measured the photon asymmetry parameter for radiative μ capture in Ca^{40}, for photon energies from 57 to 75 MeV. The result obtained seems inconsistent with predictions based on the $V-A$ theory.

The internal bremsstrahlung accompanying μ capture corresponds to the basic process

$$\mu^- + p \to n + \nu_\mu + \gamma. \quad (1)$$

Because of parity nonconservation, the γ rays should be emitted with angular distribution

$$f(\theta) = 1 + \alpha_\gamma P \cos\theta,$$

where θ is the angle between the γ-ray momentum and the μ spin polarization (magnitude P). α_γ is the asymmetry parameter. It has been shown[1] that if the γ ray is radiated only by the μ current, its asymmetry α_γ with respect to the μ spin is equal to the γ-ray circular polarization. In particular, for the standard $V-A$ interaction, the γ rays are all right-handed and $\alpha_\gamma = +1$.[2]

When strong-interaction effects and contributions from the nucleon currents are taken into account, some deviations from this picture are expected. For the elementary process (1), the induced pseudoscalar contribution decreases the values of the γ-ray circular polarization and of the asymmetry parameter α_γ to $+0.7$ near the high end of the energy spectrum.[3] Rood and Tolhoek[4] have extended these considerations to radiative μ capture in Ca^{40} nuclei. Using the standard set of coupling constants which agrees with the observed rate for ordinary μ capture in gaseous hydrogen,[5] they predict $\alpha_\gamma = +0.75$, averaged over the γ-ray energy interval from 57 to 75 MeV. Moreover, they point out that this value has very little dependence on nuclear structure.

The experimental apparatus is shown in Fig. 1(a). Negative μ's contained in a 153-MeV/c beam from the Nevis synchrocyclotron were brought to rest in the target, a Ca^{40} plate 7 in. $\times$5 in. $\times 1\frac{1}{2}$ in., which was surrounded by the C-shaped anticoincidence counter 5. The flux of particles through counters 1 and 2 was typically $\sim 120\,000$ sec^{-1}. The rate of μ^- stops, electronically defined as $1 \cdot 2 \cdot 3 \cdot 4 \cdot \bar{5}$, was ~ 5000 sec^{-1}. The target was placed in a vertical magnetic field of 446 G that caused the μ spin to precess with a period of 165 nsec, corresponding to approximately half of the μ mean lifetime in Ca^{40}. This allowed us to measure α_γ by observing the modulation produced in the γ-ray time distribution by the precession of the μ spin.

The γ-ray detector was a 10-in.-thick cylindrical NaI(Tl) crystal with a diameter of $9\frac{3}{8}$ in., viewed by a single 8-in. 60AVP photomultiplier. This assembly was surrounded by four veto counters V (on the sides, on top, and in front) to reject charged particles. A 6-in.-diam, 2-in.-thick Pb collimator prevented γ rays originating in the target from entering the crystal near the edge.

A γ-ray signal was electronically defined as $\gamma = [\mathrm{NaI}]_{>E_0} \bar{V} \bar{1}$, where $[\mathrm{NaI}]_{>E_0}$ represents a signal from the NaI(Tl) counter exceeding a given threshold E_0 (typically set at ~ 40 MeV during the experiment). Counter 1 was used in anticoincidence to reject signals simultaneous with a beam particle, e.g., those generated by the absorption of π^-'s in the moderator or target.

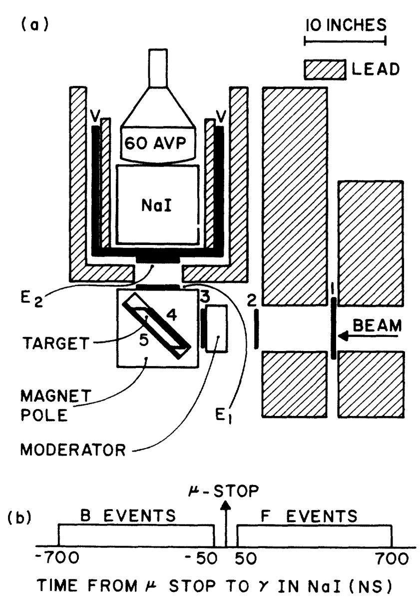

FIG. 1. (a) Overhead view of experimental arrangement. (b) Timing diagram.

A γ signal was delayed by 50 nsec before triggering a 650-nsec-wide gate. If a μ-stop signal, delayed by 750 nsec, was in coincidence with the gate, it defined a "foreground" event F; and if an undelayed μ-stop signal was in coincidence with the gate, it defined an accidental background event B [see Fig. 1(b)]. (Much of the background was due to high-energy neutrons from a neutral beam stop, for an adjacent beam, located behind our NaI crystal.) Upon the occurrence of either of these events, the time interval between the μ stop and the γ signal and the integrated pulse height from the NaI counter were recorded.

The NaI counter was calibrated with the γ rays produced in the reactions $\pi^- p \rightarrow \pi^0 n$ ($\pi^0 \rightarrow \gamma\gamma$) and $\pi^- p \rightarrow \gamma n$, occurring when negative pions were brought to rest in a LiH target[6] used in place of the Ca^{40} target. The stability of the crystal was checked every few hours with radioactive sources of known energies.

A coincidence between the two 5-in.-diam counters E_1 and E_2 with counter 1 in anticoincidence [Fig. 1(a)] defined a μ-decay electron. The time interval between the occurrence of a μ stop and a decay electron was measured by the same time-to-amplitude converter and pulse-height analyzer used for the γ signals.

During approximately 750 h of effective data-taking time, we recorded $\sim 2.7 \times 10^7$ decay electrons, and 123 587 F and 17 674 B events, corresponding to 1.2345×10^{10} μ stops.

Energy distributions.—Figure 2 shows the experimental energy distribution of the neutral radiation following a μ^- stop in calcium, obtained as the difference between the energy spectra of the F and B events. The ratio B/F increased from ~0.2 at 50 MeV to ~0.65 at 75 MeV.

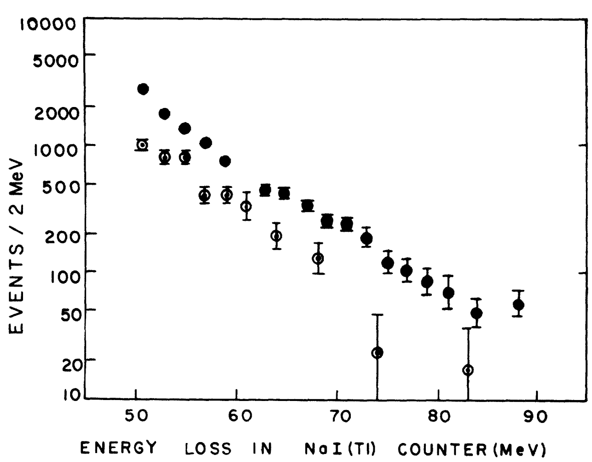

FIG. 2. Distribution of energy losses in the NaI(Tl) counter from μ^- stops in calcium, after subtraction of the accidental spectra, without Pb plug (solid points) and with Pb plug (circles) in the collimator. Data points below 50 MeV have not been plotted since they are affected by the electronic threshold.

The distribution of Fig. 2 is contaminated by two sources of neutral events other than photons from radiative μ capture: (a) γ rays from decay electrons, which radiate most of their energy in the target and which fail to reach the anticoincidence counter V; (b) high-energy neutrons from ordinary μ^- capture in Ca^{40}, which undergo an inelastic collision in the NaI crystal and deposit there a large fraction of their energy. We have studied the decay-electron contamination (a) in a special run, during which positive π's (which quickly decay into μ's) were brought to rest in the calcium target. Under these conditions, the difference between the F and B energy spectra yielded a null result above 57 MeV.

Also, during this run, the rates of both π^+ stops and γ signals (due to positron bremsstrahlung only since positive μ's are not captured by the nucleus) were approximately one order of magnitude higher than the corresponding rates measured during the μ^- runs. This rules out the possibility that the events above 57 MeV in the μ^- runs (Fig. 2) may result from rate-dependent effects such as pileup of two or more low-energy signals in the NaI counter.

In another special run, we experimentally determined the neutron contamination by inserting a 2-in.-thick Pb plug into the aperture of the collimator located in front of the NaI counter. This plug absorbed ~99% of the γ rays originating in the target, while removing only about 28% of the high-energy neutrons. Figure 2 shows also the distribution of energy losses in the NaI counter under these conditions, after subtraction of the corresponding background spectrum. These data have been normalized to the same number of μ^- stops as the data from the main runs, and corrected for the neutron absorption in the Pb plug. There is evidence for neutron contamination up to ~80 MeV, which amounts to ~45% of the signal measured in the main runs.

Time spectra.—The time distribution of the decay electrons was used to determine the residual polarization of the μ's in the ground state of the Ca^{40} muonic atoms, since the decay-electron asymmetry parameter is known. Time spectra were fitted to the function

$$I(t) = [N_{Ca} \exp(-t/\tau_{Ca}) + N_C \exp(-t/\tau_C)] \times [1 + A \sin(\omega t + \varphi)] + B, \quad (2)$$

with N_{Ca}, τ_{Ca}, N_C, A, ω, and φ as free parameters, and where a carbon component has been added to account for muons stopping in the scintillation counters. N_{Ca} and N_C are the amplitudes for decay electrons from calcium and carbon, respectively; τ_{Ca} and τ_C are the corresponding lifetimes; A is the precession amplitude; ω is the angular precession frequency of the muon spin; φ is the precession phase; and B is the amplitude of the random background. B was determined directly from the time distribution of the accidental events, which was found to be consistent with a constant. We used the value $\tau_C = 2020$ nsec for the μ lifetime in carbon.[7] As a result of the fit, we have obtained the following values for some of the parameters: $\tau_{Ca} = 335.9 \pm 0.9$ nsec; $A = -0.0300 \pm 0.003$; $B/N_{Ca} = 0.034$; and $N_C/N_{Ca} = 0.07$. The value of τ_{Ca} is consistent with previous experiments.[7,8]

The decay-electron asymmetry parameter was predicted to be $\alpha_e = -0.261 \pm 0.005$ by a Monte Carlo calculation using the decay-electron energy spectrum for negative μ's in Ca^{40} derived from Huff.[9] Dividing A by α_e, we find the muon polarization $P_\mu = 0.1149 \pm 0.0025$. This value is affected by an ~15% relative systematic uncertainty, resulting from the assumption, contained in Eq. (2), that the precession term is the same for both calcium and carbon contributions. Values of P_μ ~15% higher would be obtained assuming no precession term for the carbon contribution.

The precession amplitudes A for the F events have been determined for various photon energy intervals by fitting the corresponding time spectra by a function similar to that of Eq. (2). However, in this case we expect the ratio N_C/N_{Ca} to be approximately 60 times lower than in the time distribution of the decay electrons since the μ-capture rate is, in fact, ~60 times higher in Ca^{40} than in C^{12} while the decay rates are approximately the same in both elements. Consequently, we have set the carbon amplitude $N_C = 0$. The free parameters in the fit were N_{Ca} and A, while B was determined from the time-independent distribution of B events recorded for the same energy interval. The other parameters were kept fixed at the values determined by the analysis of the decay-electron time spectra.

Values of the asymmetry parameter α, obtained by dividing the precession amplitude A by the residual μ polarization P_μ, are shown in Table I for various energy intervals. We have generally set the upper limit of the energy interval, E_{max}, at 75 MeV, since the events above this value are affected by a large statistical error resulting from the relatively large random background. The precession term projected out from the time distribution of the F events with energies between 57 and 75 MeV is shown in Fig. 3.

TABLE I. Asymmetry parameter α of the events taken without and with the lead plug inside the collimator in front of the NaI counter. The time distribution for each energy interval consists of 43 data points, with time bins 15 nsec wide. The errors are statistical.

Lead Plug	E_{min} (MeV)	E_{max} (MeV)	N_{Ca}	B	$\alpha = A/P_\mu$	χ^2
out	40	52	2265±50	124±2	−0.322±0.066	36
out	57	75	238±5	59±1	−0.18 ±0.26	42
out	58	75	209±5	54±1	−0.28 ±0.28	44
out	59	75	185±4	50±1	−0.31 ±0.30	45
out	60	75	163±4	46±1	−0.51 ±0.32	46
out	61	75	139±4	42±1	−0.41 ±0.35	41
out	62	75	121±4	39±1	−0.35 ±0.38	47
out	57	62	116±3	20±1	−0.02 ±0.35	27
in	40	50	96±3	8.1±0.4	−0.04 ±0.34	42
in	50	70	43±2	11.4±0.5	+0.37 ±0.59	45
in	57	75	17±2	8.5±0.5	+0.15 ±1.10	41

The events between 40 and 52 MeV are largely contaminated by decay electrons, and, in fact, they show a negative asymmetry. However, the events above 57 MeV, for which we expect a negligible contamination from decay electrons, also show values of α which are negative and, typically, 1 standard deviation from 0. We believe that this result cannot be explained by the decay-electron contamination being larger than expected, since negative values of α persist even when the lower energy limit E_{min} is raised to values as

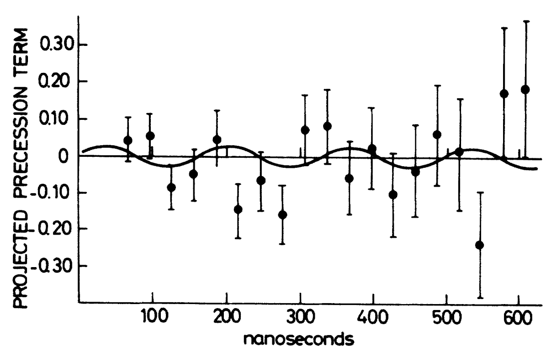

FIG. 3. Precession term projected out from the time distribution of the total number of F events between 57 and 75 MeV. The line represents the best fit to the data.

high as 62 MeV.

In the presence of the neutron contamination discussed previously, the measured asymmetry parameter α is given by the relationship

$$\alpha=(1-x)\alpha_\gamma+x\alpha_n, \tag{3}$$

where α_γ (α_n) is the photon (neutron) asymmetry parameter, and where x represents the fraction of events resulting from capture neutrons interacting in the NaI counter. For energies between 57 and 75 MeV, we find $x=0.45\pm0.05$, where we have included the small effect of diffractive neutron scattering in the lead plug, giving

$$\alpha_\gamma=(-0.32\pm0.48)-(0.82\pm0.12)\alpha_n.$$

No measurement of α_n for neutron energies above 57 MeV has been performed yet. Recent results by Sundelin and Edelstein,[10] extending to neutron energies of 50 MeV, show asymmetries which are positive at high energies, in agreement with a less precise experiment of Sculli[11] and a theoretical prediction by Bogan.[12] Table I displays the values of α_n for three energy intervals of the data recorded in the special run using the Pb plug in front of the NaI counter. Within the large statistical uncertainty, our results are consistent with the previous experiments.

If indeed $\alpha_n\geqslant0$, then

$$\alpha_\gamma\leqslant-0.32\pm0.48, \tag{4}$$

where the equality holds if $\alpha_n=0$. This result is at least 2.2 standard deviations from the theoretical prediction.[4]

Finally, it should be pointed out that the important neutron contamination discovered in this experiment was probably present also in the previous experiment of Conversi *et al.*[13] because of the similar detection technique used. Thus it is likely that the branching ratio of radiative to ordinary capture given by Conversi *et al.* is too high by approximately 45%.

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