ASYMMETRY OF NEUTRONS FROM MUON CAPUTRE IN SILICON, SULFUR, AND CALCIUM*

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We have measured the asymmetry in the angular distribution of neutrons emitted following the capture of negative muons in silicon, sulfur, and calcium. The asymmetries, normalized to 100% muon polarization, varied from near zero for low neutron energies to $+0.32 \pm 0.05$, $+0.30 \pm 0.08$, and $+0.20 \pm 0.08$ for energies greater than 15.6 MeV for silicon, sulfur, and calcium, respectively, in disagreement with the results of most other recent experiments.

The angular distribution of neutrons emitted following the capture of polarized negative muons in a nucleus is of the form $P(E,\theta)=N(E)[1+A(E)\cos\theta]$, where P is the probability of neutron emission into unit solid angle at the angle θ and into unit energy interval at the energy E, E is the energy of the emitted neutron, θ is the angle between the direction of the muon polarization at the time of capture and the direction of emission of the neutron, N is a coefficient depending on energy, and A is the asymmetry, which is also a function of the energy.

The measured asymmetry A may be expressed as the product of the muon polarization at the time of capture P_μ and the intrinsic asymmetry α for completely polarized muons. α is a function of the weak-interaction coupling constants and is particularly sensitive to the induced pseudoscalar coupling constant. However, determination of the weak-interaction coupling constants from the value of α is complicated by the dependence of the value of α on the nuclear wave function and on the interaction of the emitted neutron with the residual nucleus. The value of α has been computed for spin-0 nuclei using the closure approximation and with the omission of terms proportional to the initial momentum of the capturing proton.[1] Averaged over neutron energy, it is found to be -0.39. A similar calculation has been performed using the Fermi-gas model in which terms proportional to the initial proton momentum are included.[2] In this case, the asymmetry of the highest energy neutrons is found to be -0.11 and decreases in magnitude as the neutron energy decreases. These calculations do not include final-state interactions, which may affect the magnitude of the observed asymmetry. The reliability of the theoretical predictions of the asymmetry is subject to question, since knowledge of the nuclear physics is inadequate for an exact calculation. As shown in the preceding paper, all of the models used represent the spectrum poorly, which may suggest that these models are not adequate for calculating the asymmetry, especially at the high energy of the spectrum.

Experiment.—The apparatus used in this experiment was that shown in Fig. 1 of the preceding paper. As discussed in that paper, muons were stopped in the target and the resulting neutrons and electrons were detected in counter 5. Pulse height and digital timing spectra of the neutrons were recorded. A particular pulse height represents the minimum energy of the neutron that produced the pulse. The asymmetry associated with each pulse height was determined by analysis of the corresponding timing spectrum.

The vertical magnetic field present at the target varied less than 1% over the target volume, and was adjusted to provide a muon precession rate of 2.9 MHz for silicon and of 5.7 MHz for sulfur and calcium.

The 1600-channel analyzer was divided into eight bins of 200 channels each. Each group of 200 channels was used to record a digital timing spectrum. One of the eight bins was used for decay electrons, and the other seven were assigned according to the pulse height produced in counter 5 by a neutron. The time interval covered by 200 channels was 4 μsec for silicon and 2 μsec for sulfur and calcium, so that at least three lifetimes were observed for each target.

Stringent dead-time conditions were imposed on both the start and stop inputs of the digital timing circuitry. This prevented distortion of the timing spectra due to random background, or to ambiguous events such as the stopping of two muons too close in time to each other or the observation of two events in the liquid scintillation counter too close in time to each other. The digital timing analyzer and the associated dead-time logic were checked with randoms tests at various rates, and no structure in the time spectrum of accidental coincidence events could be detected at any input rate.

The contribution of decay-electron bremsstrahlung gammas to the number of neutron-identified events was determined in a positive-beam run. In the lowest energy silicon bin, approximately 1.7% of the neutron-identified events were due to these gammas; in the higher energy bins, the number was statistically insignificant.

Time spectra of gamma rays resulting from negative-muon capture in calcium were also recorded, in a separate run. These gammas were due to decay-electron bremsstrahlung and to nuclear de-excitation gamma rays. The lowest pulse-height group exhibited an asymmetry $A = -0.0051 \pm 0.0055$. The higher gamma pulse-height bins were also consistent with zero asymmetry. In the lowest energy calcium bin, approximately 0.6% of the neutron-identified events were due to gamma rays. In the higher energy bins, the gamma-ray contaminations were consistently lower than this value. It is expected that the contaminations for the other targets are similar.

Asymmetry analysis and results.—The time spectra of the decay electrons were used to determine the polarization of the muons in the muon atomic ground state, since the relationship between the polarization of the muons and the asymmetry of the decay electrons is well known.[3] The muon polarizations were 12.5, 9.0, and 10.2% for silicon, sulfur, and calcium, respectively. Larger polarizations were obtained by selecting higher momentum muons, but the polarizations we used represented an optimal compromise with counting rate. The muon spin direction formed angles of approximately 20° with the incident-muon momentum direction for all three targets. These angles are consistent with the expected forward polarization of the beam.

In addition to the decay electrons from the tar-

Table I. Asymmetry results. The number of real events observed, the asymmetry, the normalized asymmetry, and the number of standard deviations by which the asymmetry differs from zero are presented as a function of the pulse height observed in the neutron counter. E_{min} and E_{max} are the bin-pulse-height limits in terms of proton-equivalent MeV.

Target	E_{min} MeV	E_{max} MeV	Number of Real Events	Asymmetry A		Normalized Asymmetry α		Std. Dev. from Zero
Si	Electrons		13326000	-0.0417	±0.0004	-0.333		-97.0
	7.73	11.49	364107	+0.0038	±0.0029	+0.030	±0.023	+1.31
	11.49	15.62	138242	+0.0237	±0.0049	+0.186	±0.038	+4.88
	15.62	19.54	51302	+0.0456	±0.0085	+0.357	±0.067	+5.36
	19.54	24.55	25108	+0.0292	±0.0133	+0.228	±0.104	+2.19
	24.55	29.41	8759	+0.0498	±0.0258	+0.390	±0.202	+1.93
	29.41	35.34	4363	-0.0161	±0.0427	-0.126	±0.334	-0.38
	35.34	52.53	2612	+0.1043	±0.0763	+0.817	±0.597	+1.37
S	Electrons		7809000	-0.0300	±0.0006	-0.333		-53.6
	7.73	11.49	309574	+0.0088	±0.0031	+0.096	±0.034	+2.80
	11.49	15.62	115063	+0.0158	±0.0053	+0.172	±0.058	+2.98
	15.62	19.54	38893	+0.0250	±0.0096	+0.272	±0.105	+2.60
	19.54	24.55	20757	+0.0402	±0.0142	+0.437	±0.155	+2.83
	24.55	29.41	6872	+0.0092	±0.0285	+0.100	±0.310	+0.32
	29.41	35.34	3236	+0.0374	±0.0496	+0.407	±0.540	+0.75
	35.34	52.53	1676	-0.0578	±0.0987	-0.629	±1.074	-0.59
Ca	Electrons		4072000	-0.0340	±0.0008	-0.333		-43.0
	7.73	11.49	257994	+0.0055	±0.0034	+0.053	±0.033	+1.60
	11.49	15.62	92803	+0.0158	±0.0059	+0.152	±0.057	+2.69
	15.62	19.54	32177	+0.0275	±0.0104	+0.264	±0.100	+2.64
	19.54	24.55	16094	+0.0009	±0.0158	+0.009	±0.151	+0.06
	24.55	29.41	5540	+0.0695	±0.0303	+0.667	±0.291	+2.29
	29.41	35.34	2725	-0.0741	±0.0481	-0.711	±0.462	-1.54
	35.34	52.53	1602	+0.1019	±0.0850	+0.979	±0.816	+1.20

get, there were decay electrons from the lead shielding in the vicinity of the target, from the plastic scintillant of counter 9 (due to the dead time of its discriminator), and from other sources not correlated in time to the stopping of the muon. The equation fitted to the decay electron data was of the form $I(t)=N\exp(-Rt)[1+A\cos(\omega t+\varphi)]+N_{\rm Pb}\exp(-R_{\rm Pb}t)+N_{\rm C}\exp(-R_{\rm C}t)+B$, where I is the number of events per unit time, N is the amplitude of real events, A is the asymmetry, $N_{\rm Pb}$ is the amplitude of decay electrons from lead, $N_{\rm C}$ is the amplitude of decay electrons from carbon, B is the amplitude of random events, R, $R_{\rm Pb}$, and $R_{\rm C}$ are the disappearance rates of muons in the target, in lead, and in carbon, ω is the angular precession frequency of the muons, and φ is the precession phase. The amplitudes $N_{\rm Pb}$ and $N_{\rm C}$ were sufficiently small compared with N that their associated asymmetries were not statistically significant and have therefore been omitted from the equation. The values of A and N/R found for each of the targets are given in Table I. $N_{\rm Pb}/N$, $N_{\rm C}/N$, and B/N were typically 3, 1, and 0.5%, respectively.

The equation fitted to the time spectra of the muon-capture neutrons was of a form similar to that used for the decay electrons, except that the amplitude of the captures in carbon was negligible and that a rf modulation of the random background, due to bunching of the protons in the cyclotron, was detectable. The equation fitted to the capture-neutron data was of the form $I(t)=N\exp(-Rt)[1+A\cos(\omega t+\varphi)]+N_{\rm Pb}\exp(-R_{\rm Pb}t)+B[1+A_1\cos(\omega_1 t+\varphi_1)]$. A_1 is the fractional rf-modulation amplitude, ω_1 is the angular radio frequency, and φ_1 is the phase of the radio frequency. The other symbols have the same meaning as for the decay electron spectra. The values of A, α, and N/R found for each of the pulse-height intervals for each of the three targets are given in Table I. The values of chi squared for all of the neutron bins were consistent with good fits to the data. The value of $N_{\rm Pb}/N$ was typically 0.8. Since the muon lifetime in lead is short compared with the lifetimes in the targets used, the lead background decayed promptly and was not a significant problem. B/N ranged from 0.046 at low energies to 0.34 for energies above 15.62 MeV. A_1 was typically 0.14. $\omega_1/2\pi$ was 20.45 MHz, which was sufficiently high compared with the muon precession frequency that there is no possibility of confusion between the two.

Two sets of data in which the fitted background has been subtracted from the data, and the remainder divided by $N\exp(-Rt)$, are shown in Fig. 1. Each point represents the appropriately weighted sum of five channels. The solid curves are the least-squares fits to the data. The upper graph is the extracted sinusoidal component for the silicon decay-electron data, and the lower graph is the extracted sinusoidal component for the silicon neutrons yielding pulse heights between 15.62 and 19.54 proton-equivalent MeV.

The values of α are plotted as a function of median bin pulse height, measured in terms of proton-equivalent MeV, in Fig. 2. Note that all three targets exhibit positive asymmetries which approach zero for small pulse heights. The most significant bin is the 15.62- to 19.54-MeV silicon bin, which exhibits a positive asymmetry that is more than 5 standard deviations from zero.

Since the sign of the observed asymmetry is the opposite of the theoretically predicted one, the possibility of an experimental mechanism yielding a false positive asymmetry has been explored. No particles other than neutrinos are expected to exhibit positive asymmetries. The possibility that the random background contains a sinusoidal component with a frequency near the precession frequency is eliminated by the fact that two different precession frequencies were used. The possibility that the asymmetry was induced by the digital timing system is eliminated

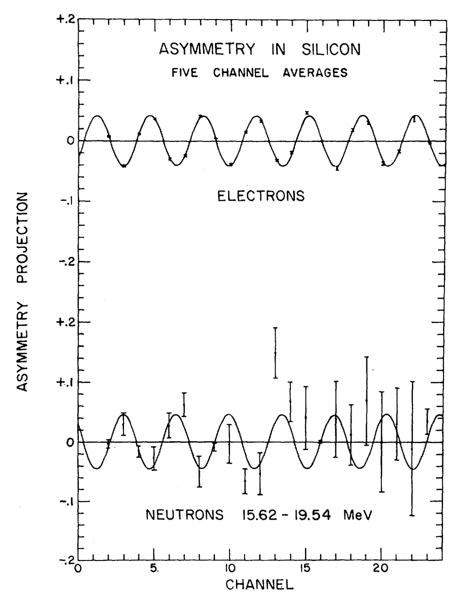

FIG. 1. Extracted asymmetry projection. The fitted background has been subtracted from the data, and the remainder divided by $N\exp(-Rt)$.

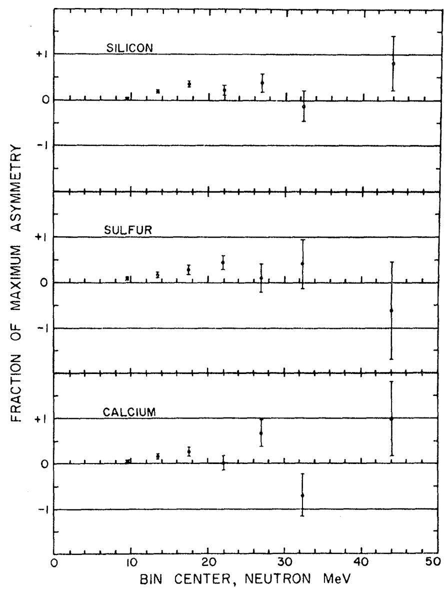

FIG. 2. Normalized asymmetry as a function of median bin-pulse height. Pulse height is measured in terms of proton-equivalent MeV.

by the good values of chi squared obtained in the randoms tests and by the fact that the asymmetry approached zero for low neutron energies. The possibility of a programming error has been ruled out by analyzing artificial data. No effect capable of inducing a significant positive asymmetry was found in the electronic logic. It was found that the ratio of capture neutrons to decay electrons was so small at large pulse heights (the ratio in silicon of the number of neutron events in the highest energy bin to the number of decay electrons was 0.0002) that a small inefficiency in the anticoincidence counter coupled with a misidentification by the pulse-shape discriminator would cause the acceptance of a significant number of electrons as neutrons, thus inducing a false negative asymmetry. However, the presence of two independent anticoincidence counters in this experiment made the fraction of events in the highest energy neutron bin due to electrons less than 3×10^{-7}.

The neutron asymmetry has been measured in a number of previous experiments[4,5] using similar techniques. The statistically most significant of these[6] have yielded negative asymmetries approaching −1.0 for high-energy neutrons. However, a new experiment[7] also obtains positive asymmetries in calcium. No reason is known for the wide divergence of neutron asymmetry results. It is difficult to explain either a positive asymmetry or a large negative asymmetry within the framework of the present theory. Although a large asymmetry of either sign could occur at a particular neutron energy due to enhancement of vector or axial-vector transitions at that energy,[8] no mechanism has been proposed which would yield a large asymmetry of constant sign over an appreciable portion of the energy spectrum.

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[1]H. Primakoff, Rev. Mod. Phys. 31, 802 (1959).

[2]R. Klein, T. Neal, and L. Wolfenstein, Phys. Rev. 138, B86 (1965).

[3]M. Bardon, D. Berley, and L. M. Lederman, Phys. Rev. Letters 2, 56 (1959).

[4]W. F. Baker and C. Rubbia, Phys. Rev. Letters 3, 179 (1959); V. L. Telegdi, in Proceedings of the Tenth Annual International Conference on High Energy Physics, Rochester, New York, 1960, edited by E. C. G. Sudarshan, J. H. Tinlot, and A. C. Melissinos (Interscience Publishers, Inc., New York, 1960), p. 713; A. Astbury, J. H. Bartley, I. M. Blair, M. A. R. Kemp, H. Muirhead, and T. Woodhead, Proc. Phys. Soc. (London) 79, 1011 (1962).

[5]E. W. Anderson, Columbia University Report No. NEVIS-136, 1965 (unpublished); V. S. Evseev, V. A. Chernogorova, F. Kilbinger, V. S. Roganov, and M. Szymczak, Joint Institute for Nuclear Research Report No. E-2516, 1965 (unpublished); V. S. Evseev, Chang Run-Hwa, V. A. Chernogorova, V. S. Roganov, and M. Szymczak, Joint Institute for Nuclear Research Report No. E-2517, 1965 (unpublished).

[6]See Ref. 5.

[7]U. Dore, M. Giannini, M. Krieger, L. Lederman, E. Schwarz, and J. Sculli, Bull. Am. Phys. Soc. 13, 678 (1968).

[8]M. Morita, "Angular Distribution of Neutrino in Muon Capture and Nuclear Structure," 1967 (unpublished).