β-Decay Asymmetry Parameter for ^{35}Ar: An Anomaly Resolved

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A remeasurement of the β-decay asymmetry parameter for ^{35}Ar decay to the ground state of ^{35}Cl has been performed. The result, $A_0=0.49\pm0.10$, leads to a value for the quark mixing angle $\theta_C=0.28\pm0.08$ rad, in agreement with the accepted value 0.23 ± 0.01 and strong disagreement with the anomalous result $\theta_C<0.10$ (95% confidence level) determined from previous measurements of this asymmetry parameter.

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A precise value of the weak vector coupling constant G_V can be obtained from the comparative half-lives of the superallowed, $0^+\rightarrow 0^+$, pure Fermi transitions in nuclear β decay. The value obtained is smaller than the value for the coupling constant of the purely leptonic muon decay, G_μ, by the factor $\cos\theta_C$, the cosine of the quark mixing angle (Cabibbo angle). The value $\theta_C=0.233\pm0.011$ determined from the pure Fermi transitions agrees well with the value $\theta_C=0.229\pm0.016$ determined from high-energy semileptonic hyperon decays.[1,2]

A value for the Cabibbo angle can also be determined from the mixed, $J(\neq 0)\rightarrow J$, $T=\frac{1}{2}$ mirror transitions; however, an auxiliary measurement must be performed to determine the axial-vector matrix element in each case. This can be done from an angular-correlation experiment between, for example, the emitted electron or positron's momentum and the initial nuclear spin,[3] $A\langle\mathbf{j}_i\rangle\cdot\mathbf{p}_e$. The constant A is known as the β-decay asymmetry parameter. For the decay $^{35}\text{Ar}\rightarrow{}^{35}\text{Cl}(\frac{3}{2}^+)+e^+ +\nu_e$, the asymmetry parameter A_0 is related to the axial-vector matrix element $\langle\sigma\rangle$ by

$$A_0=(\tfrac{2}{5}\rho^2-\tfrac{12}{5}\rho)/(1+\rho^2), \tag{1}$$

where $\rho=G_A\langle\sigma\rangle/G_V\langle 1\rangle$, $\langle 1\rangle$ is the Fermi matrix element which can be precisely calculated, and G_A is the axial-vector coupling constant. [Equation (1) is valid in the approximation where momentum-transfer–dependent terms are ignored. Higher-order corrections to A_0, such as that arising from "weak magnetism," are of order 10^{-3} and negligible for present purposes.] When ρ is combined with the comparative half-life ft, $G_V=G_\mu\cos\theta_C$ can be calculated as

$$(1+\Delta_R)G_V^2=k/[ft(1+\delta_1)(1-\delta_c)(1+\rho^2)], \tag{2}$$

where $k=2\pi^3\ln[2\hbar^7c^6/(m_ec^2)^5]$, δ_c is a correction for the imperfect isospin symmetry, δ_r is a nucleus-dependent radiative correction, and Δ_R is a nucleus-independent radiative correction.[4-6]

The asymmetry parameter has been measured for only three nuclei: ^{35}Ar (see Fig. 1), ^{19}Ne, and n. The derived values for θ_C from ^{19}Ne and n (both spin $\frac{1}{2}$) are 0.27 ± 0.05 and 0.232 ± 0.014, respectively, in agreement with the accepted value.[5] However, $A_0(^{35}\text{Ar})$ has remained anomalous for many years despite repeated measurements of all relevant parameters.[7,8] The data yield $\theta_C<0.10$ (95% confidence).[8]

A mechanism to decouple the down and strange quarks with a strong magnetic field was proposed by Salam and Strathdee.[10] Towner and Hardy[5] pointed out that this may be the explanation of the ^{35}Ar anomaly; perhaps the magnetic field associated with the spin-$\frac{3}{2}$ ^{35}Ar nucleus is sufficient[11] to decouple the down and strange quarks. However, a recent measurement of the comparative half-life for the transition $^{24}\text{Al}(4^+)\rightarrow{}^{24}\text{Mg}(4^+)$ resulted in a value of θ_C consistent with the pure Fermi transitions.[12]

This Letter reports on a recent remeasurement of the asymmetry parameter for the $^{35}\text{Ar}(\frac{3}{2}^+)\rightarrow{}^{35}\text{Cl}(\frac{3}{2}^+)$ decay. A 5-nA beam of 10-MeV polarized protons, with average polarization of 50%, was obtained from the Lawrence Berkeley Laboratory's 88-in. cyclotron. The beam energy was chosen to lie above the 6.7-MeV threshold for ^{35}Ar production by a (p,n) reaction on ^{35}Cl, but below the 10.4-MeV threshold for ^{34}Cl production by a (p,d) reaction on ^{35}Cl. ^{34}Cl has a similar positron end-point energy and half-life to ^{35}Ar and was the only potentially troublesome contaminant close to the ^{35}Ar threshold.

Polarized protons entered a hollow Lexan target cell ($9.5\times11.4\times7.0$ cm^3) containing a He+CCl$_4$ gas mixture at 470 and 95 Torr, respectively, through a 0.013-cm Mylar entrance foil (3.2 cm diam). The reaction

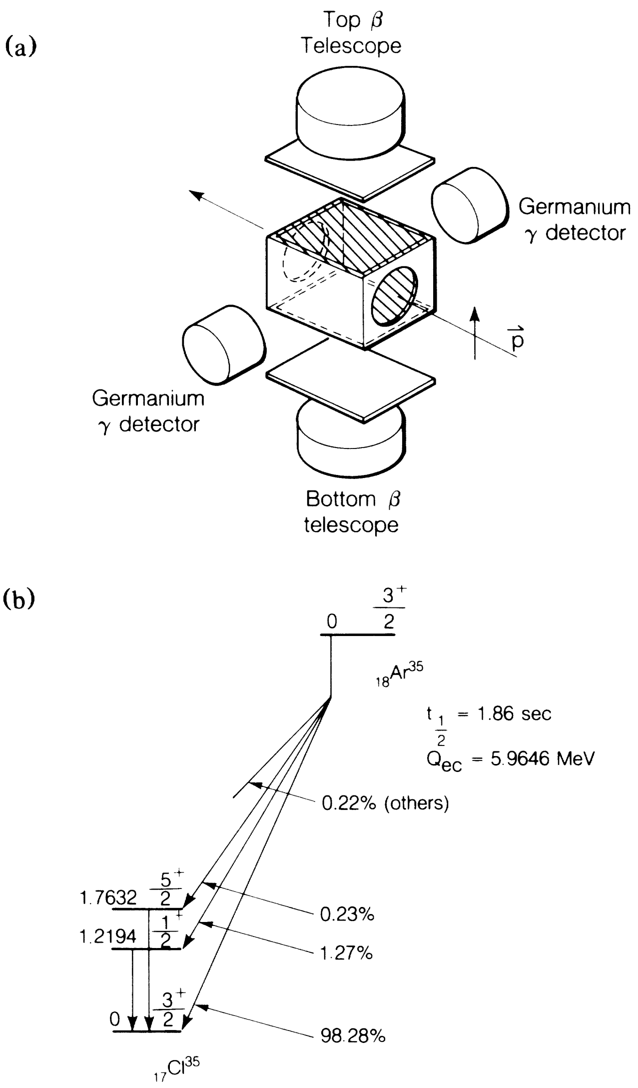

FIG. 1. (a) Schematic of the experimental setup. (b) The decay scheme for ^{35}Ar. Branching ratios, end-point energy, and half-life have been measured repeatedly (see Refs. 7–9, for example).

^{35}Cl(p_{pol},n)^{35}Ar proceeded with a polarization transfer of approximately 12%, resulting in an ^{35}Ar polarization of $(6\pm1)\%$.[13] The proton beam left the target cell through a Mylar exit foil and was stopped in a shielded carbon block far downstream from the cell.

The proton beam's polarization was measured before and after the run with a carbon-foil polarimeter. The stability of the polarization was monitored during the run by the stability of the asymmetry for the decay to the ground state of ^{35}Cl. The polarization remained stable, to within 10%, throughout the 45-h run. When the proton beam was unpolarized, the asymmetry of ^{35}Ar vanished.

The target was inside a uniform magnetic field of 30 G that maintained the ^{35}Ar polarization during the counting period. The polarization was found to rise quickly from zero and then level off as the magnetic field was increased from 0 to 30 G. No systematic effect was observed when the magnetic field was reversed midway through the run. The helium acted as a buffer to slow diffusion of ^{35}Ar to the target-cell walls where depolarization might have occurred, and to minimize embedding of ^{35}Ar in the walls.

The positrons from the target passed through 0.025-cm Mylar foils (9.5×11.4 cm^2) on the top and bottom of the cell. They were detected in a ΔE-E telescope system, consisting of plastic-scintillator detectors, located above and below the target cell (see Fig. 1). Light pipes transported the scintillation light to photomultiplier tubes located outside the magnetic field region. A ΔE scintillation detector ($10.2\times10.2\times0.16$ cm^3) was situated between the target cell and each main positron E detector (10.2 cm diam and 3.8 cm thick). A valid detector signal only occurred if there was a coincidence between the E detector and its associated ΔE detector. This arrangement suppressed γ-ray signals and noise in the main detectors. An anticoincidence between opposite positron E detectors removed backscattering positrons from the asymmetry measurement.

The positrons associated with the decay to the first excited state of ^{35}Cl ($B=1.3\%$) were distinguished from the ground-state signal ($B=98.3\%$) by a coincidence requirement with a 1219.4-keV γ ray. To treat the ground-state signal analogously to the excited-state signal, coincidence with a 511-keV annihilation γ ray was required. A prompt coincidence was obtained when a positron came to rest in an E detector and annihilated.

The γ rays were detected by two high-purity germanium detectors. Each detector has an active volume of 109 cm^3 and an efficiency of approximately 25% compared to a 7.6×7.6-cm^2 NaI(Tl) detector. The germanium detectors were chosen instead of higher-efficiency NaI detectors to suppress detection of γ rays from annihilation-in-flight positrons in the plastic detectors. These positrons produce a prompt coincidence with their annihilation γ rays. The contribution from these events to the coincidence of positrons with a γ ray in an energy acceptance window of 8 keV centered about 1219.4 keV was (6–8)%. The contribution with the much poorer-resolution NaI detector would be unacceptably high.

A microcomputer controlled the system, which was sequenced through a series of steps every 9.55 s. The proton beam was sent into the target for 3.2 s and then blocked with a beam stop. During a delay of 150 ms, mechanical camera shutters, located between the light pipes and photomultiplier tubes of the positron E detectors, were opened. The shutter protected the phototubes from the intense light generated when the proton beam was on. A 3.2-s counting period ensued; the target was then pumped out for 2.0 s and then refilled with fresh

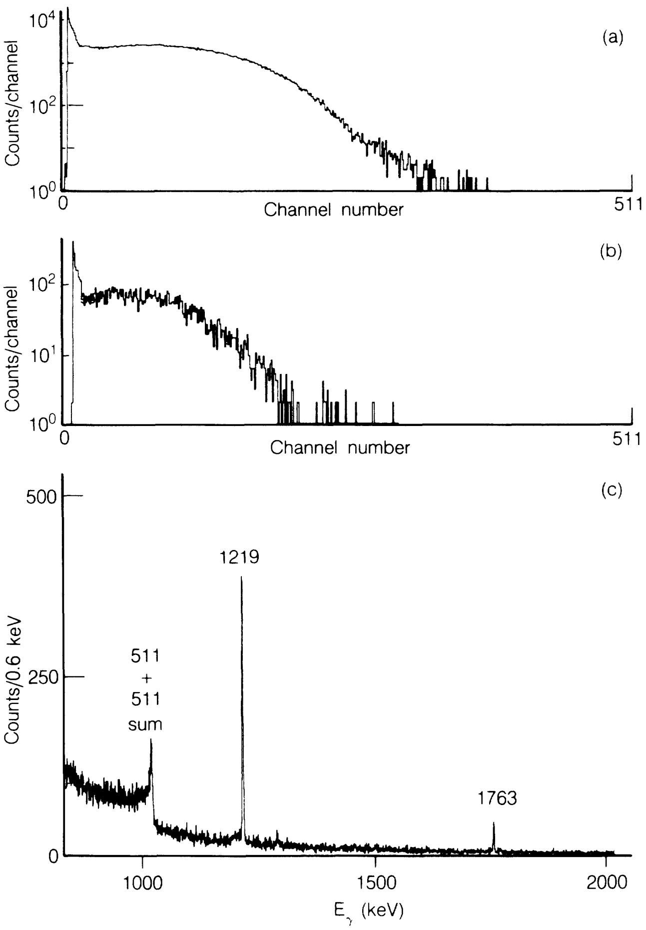

FIG. 2. (a) Positron spectrum obtained in coincidence with 511-keV γ rays. This spectrum represents the data obtained from both β detectors from 10 h of collection time. (b) The positron spectrum obtained in coincidence with 1219-keV γ rays, representing ^{35}Ar decay to the first excited states of ^{35}Cl. This spectrum represents $\simeq$40 h of data collection with both detectors. (c) γ-ray spectrum from the Ge detectors. This spectrum represents the data from a single detector from 10 h of collection time.

gas for 1.0 s. The polarization of the beam was then reversed and the entire sequence was repeated.

The β and γ spectra are shown in Fig. 2. The β spectra have end points at the expected channels, based on calibrations with ^{106}Rh and ^{207}Bi sources. The γ-ray spectrum was calibrated with a ^{60}Co source. The most prominent peaks other than the $511+511=1022$-keV sum peak are the 1219.4- and 1763.2-keV peaks associated with the first and second excited states of ^{35}Cl.

The angular dependence of the positrons is given by

$$W(\alpha)=1+AP(v/c)\cos(\alpha), \tag{3}$$

where A is the asymmetry parameter, P is the polarization of the ^{35}Ar nuclei, α is the angle between the positron momentum and the initial nuclear spin, and v is the velocity of the emitted positron. We measure the quantity

$$\Delta=\left[\frac{N_+-N_-}{N_++N_-}\right]_{\text{top}}-\left[\frac{N_+-N_-}{N_++N_-}\right]_{\text{bottom}}$$
$$=GAP, \tag{4}$$

where N_+ or N_- is the number of counts in a given β detector for ^{35}Ar polarization plus or minus, respectively, and G is a sum of top and bottom geometry factors that includes the v/c energy dependence in the angular distribution. For the positron decay to the ground state of ^{35}Cl,

$$\Delta_0=G_0A_0P, \tag{5}$$

while for the positron decay to the first excited states of ^{35}Cl, for which the asymmetry parameter is $A=1$ (a pure Gamow-Teller transition $\frac{3}{2}^+\rightarrow\frac{1}{2}^+$),

$$\Delta_1=G_1P. \tag{6}$$

The ratio $\Delta_0/\Delta_1=A_0G_0/G_1$ is independent of the ^{35}Ar nuclear polarization and allows us to determine the asymmetry A_0 up to a ratio of geometry factors. The latter were calculated with a Monte Carlo simulation, which took into account the positions of all detectors, the v/c effect, the attenuation factor for the γ rays in the Ge detectors, the dead inner core of the Ge detectors, and the reduced detection efficiency of the β's at the edges of the scintillation detectors. The simulation was done with two diffusion models for ^{35}Ar in the He buffer gas representing the two limiting cases for diffusion during the counting period. The first was a line source located where the beam passed through the target, and the second was a uniform distribution inside the target. The true model lies somewhere between these two extremes. The geometry factor is the ratio of two angular integrals; while the individual integrals varied by a few tens of percent, depending on the diffusion model, the ratio was fairly insensitive to these variations. This was even more the case for the ratio G_0/G_1. The result obtained was $G_0/G_1=1.02\pm0.02$.

In addition to the geometry correction to Δ_0/Δ_1, various small corrections were considered[14] for dead time (negligible), effective branching ratios for the energy thresholds employed (2×10^{-3}), random coincidences (negligible), and backscattering (1×10^{-2}), and a correction arising from weak magnetism and contributing a quadrupole moment in the angular distribution of positrons that might shift Δ_0/Δ_1 slightly if the spin axis were slightly different for up and down polarizations. A conservative estimate shows this last effect to give a correction to Δ_0 or Δ_1 of less than 1 part in 10^4 (completely negligible). The background counting rate was monitored by runs without CCl_4 in the target. It had no asymmetry and was 2% of the counting rate with CCl_4.

The final result, $A_0=0.49\pm0.10$, agrees with the value $A_0=0.43\pm0.01$ calculated from the accepted value for G_V. The uncertainty quoted is completely dominated by the statistical uncertainty in the number of positrons from the ^{35}Ar decay to the first excited state of ^{35}Cl. This result is in marked disagreement with the value $A_0=0.22\pm0.03$ quoted in Ref. 5. However, we note that the latter is a weighted average based on a published 1965 measurement (Calaprice *et al.*,[15] $A_0=0.16\pm0.04$) and an *unpublished* 1974 value (Mead[16]). (The 1974 experiment was never regarded as conclusive by those who did it.) The derived value for the Cabibbo angle from the measurement reported in the present Letter is $\theta_C=0.28\pm0.08$, in agreement with all other β-decay measurements.

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[1] E. A. Paschos and V. Turke, Phys. Lett. **116B**, 360 (1982).

[2] M. Roos, Nucl. Phys. **B77**, 420 (1974).

[3] J. D. Jackson, S. B. Trieman, and H. W. Wyld, Phys. Rev. **106**, 517 (1957).

[4] I. S. Towner and J. C. Hardy, Nucl. Phys. **A254**, 221 (1975).

[5] J. C. Hardy and I. S. Towner, Phys. Lett. **58B**, 261 (1975).

[6] A. Sirlin, Rev. Mod. Phys. **50**, 573 (1978).

[7] G. L. Wick, D. C. Robinson, and J. M. Freeman, Nucl. Phys. **A138**, 209 (1969), and Phys. Lett. **30B**, 240 (1969).

[8] E. Hagberg *et al.*, Nucl. Phys. **A313**, 276 (1979).

[9] P. M. Endt and C. van der Leun, Nucl. Phys. **A214**, 338 (1973).

[10] A. Salam and J. Strathdee, Nature (London) **252**, 569 (1974), and Nucl. Phys. **B90**, 203 (1975).

[11] P. Suranyi and R. A. Hedinger, Phys. Lett. **56B**, 151 (1975).

[12] E. G. Adelberger, P. B. Fernandez, C. A. Gossett, J. L. Osborne, and V. J. Zeps, Phys. Rev. Lett. **55**, 2129 (1985).

[13] This value is based on the measured value for A_1 and the geometry factor G_1 obtained from the Monte Carlo simulation. See text for details.

[14] For more details, see J. D. Garnett, thesis, University of California, Lawrence Berkeley Laboratory Report No. 24217, 1987 (to be published).

[15] F. P. Calaprice, E. D. Commins, and D. A. Dobson, Phys. Rev. **137**, B1453 (1965); see also F. P. Calaprice, thesis, University of California Report No. UCRL-17557, 1967 (unpublished).

[16] W. C. Mead, thesis, Princeton University, 1974 (unpublished).