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Author
Garnett, J.D.

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J.D. Garnett, E.D. Commins,
K.T. Lesko, and E.B. Norman

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The Beta Decay Asymmetry Parameter for $^{35}\text{Ar}$: An Anomaly Resolved

J.D. Garnett, E.D. Commins
Physics Department
University of California, Berkeley, CA, 94720

K.T. Lesko, and E.B. Norman
Nuclear Science Division
Lawrence Berkeley Laboratory
University of California, Berkeley, CA, 94720

Abstract

A remeasurement of the beta decay asymmetry parameter for $^{35}\text{Ar}$ decay to the ground state of $^{35}\text{Cl}$ has been performed. The result, $A_0 = 0.49 \pm 0.10$, leads to a value for the quark mixing angle $\theta_c = 0.28 \pm 0.08 \text{ rad}$ in agreement with the accepted value $0.23 \pm 0.01$ and in 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 beta decay. The value obtained is smaller than the value for the coupling constant of the purely leptonic muon decay, $G_\mu$, by the factor $\cos \theta_c$, the cosine of the quark mixing angle (Cabibbo angle). The value $\theta_c = 0.233 \pm 0.011$ determined from the pure Fermi transitions\(^1\) agrees well with the value of $\theta_c = 0.232 \pm 0.003$ determined from the high energy semi-leptonic hyperon decays.\(^2\)

A value for the Cabibbo angle can also be determined from the mixed, $J(\neq 0) \rightarrow J$, $T=1/2$ 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, $A\langle \vec{j} \rangle \cdot \vec{P}_e$ (Ref. 3). The constant $A$ is known as the beta decay asymmetry parameter. For the decay $^{35}\text{Ar}(3/2^+) \rightarrow ^{35}\text{Cl}(3/2^+) + e^+ + \nu_e$ the asymmetry parameter $A_0$ is related to the axial vector matrix element $\langle \sigma \rangle$ by

$$A_0 = \frac{2 \rho^2 - \sqrt{12}}{5} \rho / (1 + \rho^2) \quad (1)$$

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. When $\rho$ is combined with the comparative half-life $ft$, $G_v = G_\mu \cos \theta_c$ can be calculated:

$$(1 + \Delta_R) G_v^2 = k / [ft(1 + \delta_r)(1 - \delta_c)(1 + \rho^2)] \quad (2)$$

where $k = 2\pi^3 \ln 2 \hbar^7 c^6 / (m_e c^2)^5$, $\delta_c$ is a correction for the imperfect isospin symmetry, $\delta_r$ is a nucleus-dependent radiative correction, and $\Delta_R$ is a nucleus-independent radiative correction.\(^4,5,6\)
The asymmetry parameter has been measured for only three nuclei: $^{35}\text{Ar}$ (see Fig. 1), $^{19}\text{Ne}$, and n. The derived values for $\theta_c$ from $^{19}\text{Ne}$ and neutron (both spin 1/2) are $0.27 \pm 0.05$ and $0.232 \pm 0.014$ respectively, in agreement with the accepted value. However $A_0^{(35}\text{Ar})$ has remained anomalous for many years despite repeated measurements of all relevant parameters. The data yield $\theta_c < 0.10$ (95% confidence).

A mechanism to decouple the down and strange quarks with a strong magnetic field was proposed by Salam and Strathdee. Towner and Hardy pointed out that this may be the explanation of the $^{35}\text{Ar}$ anomaly; perhaps the magnetic field associated with the spin 3/2 $^{35}\text{Ar}$ nucleus is sufficient 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 $\theta_c$ consistent with the pure Fermi transitions.

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

Polarized protons entered a hollow lexan target cell (9.5 cm x 11.4 cm x 7.0 cm) containing a He + CCl$_4$ gas mixture at 470 and 95 torr respectively, through a 0.013 cm mylar entrance foil (3.2 cm diameter). The reaction $^{35}\text{Cl}(\vec{p},n)^{35}\text{Ar}$ proceeded with a polarization transfer of approximately 12%, resulting in an $^{35}\text{Ar}$ polarization of $(6 \pm 1)\%$. 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 using 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 $^{35}\text{Cl}$. The polarization remained stable, to within 10%, throughout the 45 hour run. When the proton beam was unpolarized, the asymmetry of $^{35}\text{Ar}$ vanished.

The target was inside a uniform magnetic field of 30G that maintained the $^{35}\text{Ar}$ 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 zero to 30 G. The helium acted as a buffer to slow diffusion of $^{35}\text{Ar}$ to the target cell walls, where depolarization may have occurred. No systematic effect was observed when the magnetic field was reversed midway through the run.

The positrons from the target passed through 0.025 cm mylar foils (9.5 cm x 11.4 cm) on the top and bottom of the cell. They were detected in a $\Delta E$ - E telescope system, consisting of plastic scintillator detectors, located above and below the target cell (see Fig. 1). Lightpipes transported the scintillation light to photomultiplier tubes located well outside the magnetic field region. A $\Delta E$ scintillation detector (10.2 cm x 10.2 cm x 0.16 cm) 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 were a coincidence between the E detector and its associated $\Delta E$ detector. This arrangement suppressed gamma ray signals and noise in the main detectors. An anti-coincidence between opposite positron E-detectors removed backscattering positrons from the asymmetry measurement.

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

The $\gamma$ 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 cm x 7.6 cm NaI(Tl) detector. The germanium detectors were chosen instead of higher efficiency NaI detectors to suppress detection of $\gamma$ rays from annihilation-in-flight positrons in the plastic detectors. These positrons produce a prompt coincidence with their annihilation $\gamma$ rays. The contribution from these events to the coincidence of positrons with a $\gamma$ 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 sec. The proton beam was sent into the target for 3.2 sec and then blocked with a beam stop. During a delay of 150 msec, mechanical camera shutters, located between the lightpipes and photomultiplier tubes of the positron E-detectors, were opened. The shutters protected the phototubes from the intense light generated when the proton beam was on. A 3.2 sec counting period ensued, the target was then pumped out for 2.0 sec and then refilled with fresh gas for 1.0 sec. The polarization of the beam was then reversed and the entire sequence was repeated.

The $\beta$ and $\gamma$ spectra are shown in Fig. 2. The $\beta$ spectra have endpoints at the expected channels, based on calibrations with $^{106}$Rh and $^{207}$Bi sources. The $\gamma$ 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 $W(\alpha)$:

$$W(\alpha) = 1 + A P (v/c) \cos(\alpha)$$  \hspace{1cm} (3)
where $A$ is the asymmetry parameter, $P$ is the polarization of the $^{35}$Ar nuclei, $\alpha$ 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:

$$\Delta = \left( \frac{(N_+ - N_-)}{(N_+ + N_-)} \right)_{\text{top}} - \left( \frac{(N_+ - N_-)}{(N_+ + N_-)} \right)_{\text{bottom}} = GAP$$  \hspace{1cm} (4)$$

where $N_+$ or $N_-$ is the number of counts in a given $\beta$ 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,

$$\Delta_0 = G_0 A_0 P$$  \hspace{1cm} (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 $3/2^+ \rightarrow 1/2^+$),

$$\Delta_1 = G_1 P$$  \hspace{1cm} (6)$$

The ratio $\Delta_0 / \Delta_1 = A_0 G_0 / G_1$ 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 using a Monte Carlo simulation, which took into account the positions of all detectors, the $v/c$ effect, the attenuation factor for the $\gamma$ rays in the Ge detectors, the dead inner core of the Ge detectors, and the reduced detection efficiency of the betas 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 \( G_0/G_1 = 1.02 \pm 0.02 \).

The background was monitored by runs without CCl\(_4\) in the target cell. It had no asymmetry and was only a few percent of the signal. The background was due to CCl\(_4\) which leaked into the beampipes and to \(^{13}\)N produced by a (p,n) reaction on \(^{13}\)C in the mylar entrance and exit foils and in the CCl\(_4\). The positrons associated with the decay of \(^{13}\)N have a low endpoint energy (1.7 MeV) and were removed from the asymmetry measurement by making an energy cut above the \(^{13}\)N endpoint energy.

The final result, \( A_0 = 0.49 \pm 0.10 \), agrees with the value \( A_0 = 0.43 \pm 0.01 \) 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 old value, measured on several occasions to be: \( A_0 = 0.22 \pm 0.03 \) (Ref. 13). The derived value for the Cabibbo angle from this experiment is \( \theta_C = 0.28 \pm 0.08 \) in agreement with all other \( \beta \) decay measurements.

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12. This value is based on the measured value for $A_0$ and the geometry factor $G_0$ obtained from the Monte Carlo simulation. See text for details.
Figure 1a) Schematic of the experimental set-up. b) The decay scheme for $^{35}\text{Ar}$.
Branching ratios, endpoint energy, and half-life have been measured repeatedly (see Refs. 7, 8, and 14 for example.)

Figure 2a) Positron spectrum obtained in coincidence with 511 keV $\gamma$ rays. This spectrum represents the data obtained from both $\beta$-detectors from 10 hours of collection time. b) The positron spectrum obtained in coincidence with 1219 keV $\gamma$ rays, representing $^{35}\text{Ar}$ decay to the first excited state of $^{35}\text{Cl}$. This spectrum represents $\sim$40 hours of data collection using both detectors. c) $\gamma$-ray spectrum from the Ge detectors. This spectrum represents the data from a single detector from 10 hours of collection time.
Fig. 1

Top $\beta$ Telescope

Germanium $\gamma$ detector

Germanium $\gamma$ detector

Bottom $\beta$ telescope

$1.76:1.21:0.94$

$Q_{EC} = 5.9646$ MeV

$0.22\%$ (others)

$0.23\%$

$1.27\%$

$98.28\%$

$18^3\text{Ar}^{35}$

$t_1 = 1.86$ sec

$\frac{1}{2}$

$17^3\text{Cl}^{35}$

XBL 878-11127

Fig. 1
Fig. 2