CM-P00055939

CERN-PRE-78-111

THE SUPERALLOWED DECAY OF ^{35}Ar : A PERSISTENT ANOMALY

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ABSTRACT

The branching ratio for the decay of ^{35}Ar to the first excited state in ^{35}Cl has been measured to be $1.34 \pm 0.08\%$ using the ISOLDE on-line isotope separator. Combining this result with previous data leads to the value $(98.28 \pm 0.06)\%$ for the branching ratio of the ground state (superallowed) transition. This does not resolve the apparent anomalousness of the derived Cabibbo angle for this transition, which now stands at $\theta_v < 0.10$ with a 95% confidence level.

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RADIOACTIVITY ^{35}Ar from $V(p,6p,11n)$, chem. mass separation. Measured I_γ ; deduced ft value, Cabibbo angle. Natural target, Ge(Li) detector.

(Submitted to Nuclear Physics A)

July 1978

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1. INTRODUCTION

The coupling constant of vector β -decay has been determined with apparent precision from the analysis of ft values for $T=1$, $0^+ \rightarrow 0^+$ superallowed β -transitions¹⁻³⁾. Although there is some uncertainty associated with small theoretical corrections⁴⁻⁶⁾, the concordance among the fourteen known transitions leads one to believe that there are no severe difficulties in extracting a reliable result, certainly within an accuracy of one part in a thousand⁶⁾.

By contrast, β -transitions between $T=\frac{1}{2}$ analogue states are less straightforward. The non-zero nuclear spins cause the axial vector current to contribute along with the polar vector, and this means that a measurement of the ft value is insufficient by itself to determine the vector coupling constant. To overcome the deficiency, the ratio of axial to polar vector contributions can be determined from a measurement of electron asymmetry in the decay of polarized nuclei. However, though many transitions could be studied in this way, the experimental techniques required are sufficiently complex that only three cases have so far been examined: the decays of n , ^{19}Ne and ^{35}Ar . The first two yield values for the coupling constant that are consistent with the $0^+ \rightarrow 0^+$ transitions, but the third is distinctly anomalous.

The anomaly has been known for some time⁷⁾, but quite recently it was noted⁸⁾ that the observed 3% discrepancy would be exactly removed if the Cabibbo angle were to have vanished for ^{35}Ar . Such an effect might be attributed to symmetry restoration, which Salam and Strathdee⁹⁾ have speculated could occur in high electromagnetic fields. Certainly the critical field that they propose for the onset of restoration is of the same order of magnitude as that calculated¹⁰⁻¹²⁾ for the electromagnetic field

within any nucleus. However, no mechanism has presented itself to explain why the field should be above the critical value in ^{35}Ar , yet below it for other nuclei where the Cabibbo angle is presumably well behaved.

Since attention was drawn to the possible significance of the ^{35}Ar anomaly, several experimental reexaminations of ^{35}Ar have been published: two report on the decay energy^{13,14)}, and one on the half-life and branching ratio¹⁵⁾. These results confirm those used earlier⁸⁾ for both energy and half-life, leaving little possibility that either quantity is still sufficiently in error to account for the discrepancy. The most recent branching ratio measurement does differ somewhat from previous results. While the difference is far from enough to resolve the overall discrepancy, it illustrates the experimental difficulties inherent to a branching ratio determination that relies upon the annihilation radiation to measure the total number of positron decays. Impurities present in the experimental sample can also contribute to the annihilation radiation, and if undetected these can easily distort the result.

We report here the first branching ratio measurement for ^{35}Ar that incorporates the use of an isotope separator to effectively eliminate competing activities.

2. EXPERIMENTAL PROCEDURE

Argon isotopes were produced in spallation reactions by bombarding a 38-g/cm^2 vanadium target (in the form of VC power) with $1\text{ }\mu\text{A}$ of 600 MeV protons from the CERN synchrocyclotron. The temperature of the target was held at about 2100°C , so that most of the elements produced by the bombardment diffused out of the target - some (such as argon) very rapidly. They then had to diffuse through a cooled (to 30°C) copper tube before reaching a plasma

ion source; this tube had the effect of passing argon nuclides but retaining all neighbouring elements (through condensation or chemical reactions).

The beam extracted from the ion source was separated into its constituent atomic masses by the ISOLDE electromagnetic isotope separator.

The selected A=35 beam was focussed on a section of stationary magnetic tape that was looped out from a standard tape cassette. From this collection position the tape passed through a slot in an aluminum block before returning to the cassette. Periodically, the separator beam was interrupted, the tape drive activated and the collected sample moved to a position at the centre of the aluminum block. The block dimensions were such that the positrons from the decay of ^{35}Ar , which range up to 5 MeV, were all annihilated. Gamma rays from the decay, together with the annihilation radiation, were recorded by using a Ge(Li) detector located nearby.

Two timing sequences were employed. In the first, the sample was collected for 4 seconds, and counted for 15 seconds, during which time 15 sequential γ -ray spectra were recorded, each for 1 second. This served as a check on possible contaminant activities. The second sequence involved collecting for 2 seconds, then recording four sequential 1-second γ -ray spectra. These were used in the actual measurement of the intensity of ^{35}Ar β -delayed γ -rays relative to the annihilation radiation.

Gamma-ray energy and collection-efficiency calibrations were accomplished with sources of ^{22}Na and ^{137}Cs , whose absolute strengths had been determined previously. Each source had been prepared on a short length of magnetic tape and was inserted in the aluminum block, simulating as nearly as possible the actual conditions pertaining to the ^{35}Ar samples.

3. RESULTS AND ANALYSIS

The decay scheme of ^{35}Ar is shown in fig. 1. Our objective was to measure the intensity of the 1219.4 keV γ -ray relative to the total positron decay intensity of ^{35}Ar .

Fortunately, the β -delayed γ -ray observed in the decay of ^{22}Na is at 1274 keV, which is very close in energy to the peak of interest from ^{35}Ar . Since the ^{22}Na branching ratio is already known accurately^{16,17)}, we used our standard source measurement to determine the ratio of the detector efficiency at 1274 keV relative to that at 511 keV, viz. $\epsilon_{1274}/\epsilon_{511}$. The results are summarized in the first two parts of table 1. Corrections were applied to the data to take account of annihilation in flight, and real coincidences between 1274 keV γ -rays and the annihilation radiation. Our methods for dealing with these corrections have been described previously¹⁸⁾ and are similar to those used in an earlier study¹⁹⁾ of ^{35}Ar .

The short interpolation to 1219 keV, the ^{35}Ar γ -ray energy, was accomplished through an independent standard-source measurement of the energy dependence of the detector's efficiency, confirmed by the in situ ^{22}Na and ^{137}Cs calibrations. The result expressed as $\epsilon_{1219}/\epsilon_{1274}$ appears in part 2 of table 1, and indicates only a 3% change in efficiency between the well-established ^{22}Na point and that for ^{35}Ar .

In the first of two isotope separator experiments the decay of the annihilation radiation was followed for 15 seconds - more than 8 half-lives of ^{35}Ar - with a total of $\sim 5 \times 10^4$ counts being recorded. Least-squares analysis of the data confirmed the absence of a second decaying component, although a constant 511 keV background appeared, apparently associated with the synchrocyclotron beam; the background rate was $\sim 1\%$ of that due to ^{35}Ar at the start of the counting period. The normalized χ^2

for this two-component fit was 1.3, which corresponds to a confidence level of about 25%.

Having established the background rate and the purity of the sample, we then used the 4-second decay sequence to determine the relative γ -ray intensities; these data comprised $\sim 4 \times 10^5$ events with 511 keV and $\sim 1.4 \times 10^3$ with 1219 keV. The outcome of this measurement, together with the calculated corrections and the resultant branching ratio, are listed in the third part of table 1. The result is then compared with other absolute branching ratio measurements^{15,19,20)} in table 2.

4. CONCLUSIONS

The average value given in table 2 for the β_1^+ absolute branching ratio can now be combined with relative γ -ray intensity measurements^{15,19-21)} to obtain branching ratios for β_2^+ , β_4^+ and β_5^+ , and the sum of all these values, when subtracted from 100%, yields the ground state (superallowed) β_0^+ branching ratio that appears in table 3. The statistical techniques used in averaging these quantities, and the other quantities subsequently discussed in this section, are the same as those used¹⁾ in surveying $0^+ \rightarrow 0^+$ decays.

Also shown in table 3 are the average experimental values for the total half life, decay energy and asymmetry. All available measurements for each are included providing their quoted uncertainties are not more than an order of magnitude greater than the most precise value. The only exception is our exclusion of the Q_{ec} measurement by Cramer and Mangelson²⁷⁾, for which there seems ample evidence^{14,24)} of error (cp. ref.²⁸⁾). From

these averages we derive the partial half life, statistical rate function and $\mathcal{F}t$ value as in ref ¹⁾. In particular, for $T=\frac{1}{2}$ decays

$$\begin{aligned}\mathcal{F}t &= ft(1+\delta_R)(1-\delta_c) \\ &= \frac{1.23062 \times 10^{-94}}{G_\mu^2 \cos^2 \theta_v (1+\Delta_R)(1+\rho^2)}\end{aligned}\quad (1)$$

where G_μ is the coupling constant for muon decay [$= (1.43582 \pm 0.00003) \times 10^{-49}$ erg cm³ using the muon lifetime from ref. ²⁹⁾], θ_v is the Cabibbo angle and ρ , which is the ratio of axial to polar vector contributions⁸⁾, is directly related to the asymmetry³⁰⁾. Of the radiative correction terms δ_R, δ_c and Δ_R , the first two are nucleus-dependent and for ³⁵Ar are calculated as in ref. ¹⁾ to be $\delta_R = 1.69\%$ and $\delta_c = 0.31\%$. The third, Δ_R , is independent of nucleus, and is taken to be $(2.38 \pm 0.17)\%$ from the analysis¹⁾ of $0^+ \rightarrow 0^+$ decays, assuming that these are characterized by a "normal" Cabibbo angle.

Through the use of eqn. 1, the ³⁵Ar results lead to a measurement of the Cabibbo angle, which is given at the 95% confidence level in the last line of table 3. Expressed in another way, if the normal Cabibbo angle ($\theta_v = 0.23 \pm 0.01$ ³¹⁾) were to be restored by changing a single measured parameter, it would require a branching ratio of 93%, a half-life of 1.88 s, a decay energy of 6026 keV or an asymmetry of 0.43. Comparison with the actual measurements listed in the first four lines of table 3 makes evident the remoteness of these values.

However, it should be remembered that there are as yet no recent remeasurements of the asymmetry. This appears to be the only remaining possibility for a trivial explanation of the ³⁵Ar anomaly.

The authors wish to thank Dr. I.S.Towner for helpful discussions.

TABLE 1

DERIVATION OF THE ABSOLUTE INTENSITY FOR THE 1219 keV
 γ -RAY FROM ^{35}Ar DECAY

1. ^{22}Na decay	
measured intensity ratio 1274/511	$(2.54 \pm 0.01) \times 10^{-1}$
corrections: annihilation in flight real coincidences	$(-0.8 \pm 0.2)\%$ $(+3.4 \pm 0.8)\%$
corrected intensity ratio 1274/ β^+ known ^{16,17} branching ratio 1274/ β^+	$(5.22 \pm 0.05) \times 10^{-1}$ 1.106 ± 0.002
2. Detector efficiency	
efficiency ratio $\epsilon_{1274}/\epsilon_{511}$	$(4.72 \pm 0.05) \times 10^{-1}$
efficiency ratio $\epsilon_{1219}/\epsilon_{1274}$	1.034 ± 0.010
3. ^{35}Ar decay	
measured intensity ratio 1219/511	$(3.30 \pm 0.18) \times 10^{-3}$
corrections: annihilation in flight real coincidences	$(-6.6 \pm 1.7)\%$ $(+6.1 \pm 1.0)\%$
corrected branching ratio 1219/ β^+	$(1.34 \pm 0.08) \times 10^{-2}$

TABLE 2

MEASUREMENTS OF ABSOLUTE BRANCHING RATIO FOR β_1^+ DECAY
BRANCH FROM ^{35}Ar

Reference	Branching Ratio (%)
Wick <u>et al</u> ¹⁹⁾	1.223 ± 0.046
Geiger & Hooton ²⁰⁾	1.22 ± 0.20
Azuélos <u>et al</u> ¹⁵⁾	1.55 ± 0.15
this work	1.34 ± 0.08
average	1.27 ± 0.05

TABLE 3
ANALYSIS OF ^{35}Ar SUPERALLOWED DECAY BRANCH

	Value	Reference
branching ratio (%)	98.28 ± 0.06	15,19-21), this work
total half life (s)	1.776 ± 0.004	13,19,20,22,23)
decay energy, Q_{ec} (keV)	5964.6 ± 0.7	13,14,19,24-26)
asymmetry A	0.22 ± 0.03	a)
partial half life (s)	1.808 ± 0.004	
statistical rate function f	3118.0 ± 2.0	
$\mathcal{F}t$ value (s)	5715 ± 13	
$1 + \rho^2$	1.0195 ± 0.0051	
θ_v	< 0.10	

a) average of four measurements, as quoted in ref. 8)

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FIGURE CAPTION

Fig. 1: Decay scheme of ^{35}Ar .

7/27/54

237

2

300

410

480

72

55.00

12

14

16

18

20

0.134

0.134

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