


Intensity of a weak 519-keV γ ray following β decay of the superallowed emitter ^{34}Ar determined via the $^{33}\text{S}(p,\gamma)^{34}\text{Cl}$ reaction

H. I. Park,^{*} J. C. Hardy[†], M. Bencomo[‡], V. E. Jacob, and I. S. Towner
Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

K. T. Macon[§], W. P. Tan[§], M. Brodeur, A. Boeltzig[§], B. Frentz[§], S. L. Henderson, J. Long, S. McGuinness,
 O. Olivas-Gomez[§], P. O'Malley, G. Seymour[§], and B. Vande Kolk[§]
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA

A. Kayani
Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008, USA

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The predominant branch in the β decay of ^{34}Ar is the superallowed $0^+ \rightarrow 0^+$ transition to the ground state of ^{34}Cl . To determine its important branching ratio one must first establish the ratios for the competing Gamow-Teller branches based on the measured intensities of γ rays subsequently emitted from the excited states they populate in ^{34}Cl . The strongest of these branches populates the 1^+ state at 666 keV in ^{34}Cl , which has three possible γ -decay paths. We report here a measurement of the decay of this state, which we populated via resonant proton capture in the reaction $^{33}\text{S}(p,\gamma)^{34}\text{Cl}$. We find that the intensity of the 519-keV γ -ray path is 1.46(19)% relative to that of the 666-keV path. This result is critical to new precise measurements of the superallowed decay of ^{34}Ar .

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I. INTRODUCTION

The superallowed $0^+ \rightarrow 0^+$ β decay of ^{34}Ar is a particularly interesting case. Unlike most of the other well-measured superallowed transitions, it has an equally well-measured mirror-decay partner, $^{34}\text{Cl} \rightarrow ^{34}\text{S}$. This offers a rare opportunity to use the ratio of the two measured ft values in a particularly sensitive test [1] of the model used to calculate the nuclear-structure-dependent corrections that are used to help convert the measured ft values into a result for V_{ud} , the up-down mixing element of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [2].

In a bid to improve the precision of this test, new measurements of both the ^{34}Ar half-life [3] and its superallowed branching ratio [4] have recently been completed and published. Both depended on a detailed knowledge of the decay scheme of ^{34}Ar , including especially the β -delayed γ rays emitted from the most strongly populated 1^+ state at 666 keV. Figure 1 helps explain why.

Considering the half-life measurement first, we note that it is based on analysis of the decay of emitted positrons, which unavoidably must include contributions not only from the decay of ^{34}Ar but also from the growth and decay of its short-lived daughter, the ground state of ^{34}Cl . To sort out their relative contributions it is necessary to establish whether

there is any “leakage” between the decay of ^{34}Ar and that of its daughter [3]. In Fig. 1 we see that the 519-keV transition provides just such leakage, since it feeds the long-lived isomeric state at 146 keV and never contributes to the superallowed ground-state decay of ^{34}Cl . The relative intensity of the 519-keV transition is thus essential input for a precise half-life measurement.

The ^{34}Ar superallowed branching-ratio measurement depends even more critically on the intensity of the 519-keV transition. That measurement [4] utilizes the observed intensities of β -delayed γ -ray transitions from 1^+ states in ^{34}Cl to establish the branching ratios for the Gamow-Teller β transitions that populate those states. Their total, when subtracted from 100%, then yields the branching ratio for the superallowed β branch, which naturally has no telltale γ ray of its own since it populates the ground state. The measured γ -ray spectrum yields intensities or limits on all relevant transitions with one exception. The 519-keV peak is about four orders of magnitude weaker than the annihilation radiation, and so, being lost in its tail, it cannot be quantified with precision.

The present measurement was designed specifically to characterize the γ -decay branches from the 666-keV level in ^{34}Cl and, in particular, to pin down the relative intensity of the 519-keV transition, since values for it in the literature unhelpfully range from 7(4)% [5] to <1% [6]. This range would lead to a 0.3% uncertainty in the superallowed branching ratio. Our new results have already been incorporated into the recently published papers just described on the decay of ^{34}Ar [3,4], which are thus able to quote uncertainties of less than 0.1%.

^{*}hpark@comp.tamu.edu

[†]hardy@comp.tamu.edu

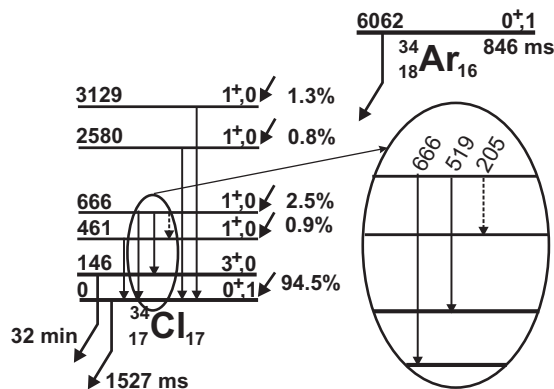


FIG. 1. Beta-decay scheme of ^{34}Ar , singling out the three possible γ -ray transitions from the 666-keV state. The 205-keV transition is shown by the dashed line because only an upper limit has been set on its intensity. The basic diagram is taken from Ref. [3]. Each level is labeled with its (J^π , T) as well as its energy, expressed in keV, relative to the ^{34}Cl ground state.

We employed resonant proton capture on ^{33}S to produce a level at 6181 keV in ^{34}Cl . This level populates our state of interest via a 5515-keV γ ray, so by gating on that γ ray we could produce a coincidence spectrum restricted to the γ rays deexciting the 666-keV level. The details of the measurement are described in the next section.

II. EXPERIMENT

A. Target preparation

Elemental sulfur and most of its compounds vaporize at relatively low temperatures, thus readily escaping from a surface layer under ion bombardment. To avoid this problem with our target, we chose to implant 70-keV negative ^{33}S ions into a 130- μm -thick tantalum foil, using the SNICS II sputter ion source, which normally injects the 6-MV Tandem Van de Graaff at Western Michigan University. The ion source was loaded with ~ 10 mg of sulfur—10% enriched in ^{33}S —mixed with silver. Before being implanted, the extracted ions passed through a 20° bending magnet, which separated out most contaminants, though not all the ^{32}S . (The latter's presence had no impact on our subsequent measurement.) The tantalum foil was mounted on a LabVIEW-controlled XY stage, which moved the foil systematically to create an implantation raster over a surface area of 1.5×1.5 cm. The implantation continued for approximately 2 days with an initial beam intensity of $12 \mu\text{A}$. The total estimated fluence was 1×10^{18} particles/ cm^2 .

B. Measurement

The $^{33}\text{S}(p,\gamma)^{34}\text{Cl}$ reaction was initiated by protons from the 5U 5-MV single-ended vertical Pelletron at the Nuclear Science Laboratory of the University of Notre Dame. The proton beam, with an energy spread of less than 1 keV, passed through a 90° dipole magnet on its way to the water-cooled ^{33}S target, which was installed at the center of the compact germanium-detector array GEORGINA [7]. After exploring

several candidate resonances, we chose the proton beam energy to be 1072 keV, which corresponds to a resonance in ^{34}Cl at an excitation energy of 6181 keV. This resonance was previously known [6] to preferentially decay to the state at 666 keV, whose decay we wished to study. Throughout our 2-week measurement the beam current was limited to a maximum of $10.0 \mu\text{A}$ to prevent damage to the ^{33}S target.

The GEORGINA array consists of five Canberra n -type germanium detectors, each with a relative γ -ray efficiency of 100%. In our measurement, the beam was stopped in the tantalum containing the target material, so one of the detectors could be placed directly downstream from the target; the other four were arranged symmetrically in close geometry around the target and slightly upstream of it. The preamplified signals from each detector were directly read by a Mesytec MDPP-16 [8] fast high-resolution time and amplitude digitizer. We began the measurement with all five detectors in operation but, unfortunately, were limited to four for most of the data taking.

C. Calibration

Immediately following the end of data collection, calibration measurements were performed with sources of ^7Be , ^{60}Co , ^{137}Cs , ^{133}Ba , and ^{152}Eu , which were sequentially placed at the target position of the GEORGINA array. Except that the beam was turned off, the configuration was identical to that used in the $^{33}\text{S}(p,\gamma)^{34}\text{Cl}$ measurement itself. For energy calibration, these sources provided us with 20 well-known γ -ray peaks covering the energy range from 120 to 1410 keV. This comfortably brackets the energies of the three possible transitions from the 666-keV state: 205, 519, and 666 keV (see Fig. 1).

Our efficiency calibration was established from three of the sources, ^{60}Co , ^{137}Cs , and ^{152}Eu , which were all commercially calibrated standards ($\pm 3\%$). The first two have simple decay schemes, but the third's decay is complicated, populating γ -ray emitting states via both electron capture to ^{152}Sm and β^- decay to ^{152}Gd . From its decay we used only the 244-, 344-, 444-, 779-, 867-, 964-, 1086-, 1090-, 1112-, 1299-, and 1408-keV γ -rays, taking careful account of coincidence summing. This provided detection efficiencies in each detector for the most important 519- and 666-keV peaks of interest and required only a short extrapolation to cover the 205-keV peak to the required precision.

III. ANALYSIS AND RESULTS

Data collected from the $^{33}\text{S}(p,\gamma)^{34}\text{Cl}$ measurement were processed to extract prompt γ - γ coincidence events, which were then stored in a database that could be accessed by analysis software developed at Texas A&M University. Each entry in the database consisted of the energies and time stamps of two coincident γ -rays, the time difference between their arrivals, and an identifier of the two germanium detectors from which the signals originated.

As the first step in the analysis, all detector spectra were adjusted so as to place them on a common energy scale. Next, six two-dimensional γ - γ coincidence spectra were created,

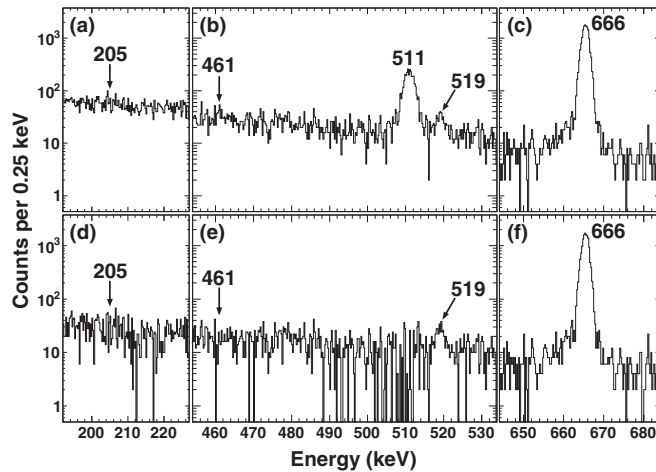


FIG. 2. (a–c) Relevant portions of the γ -ray spectrum obtained in coincidence with a single gate set around the 5515-keV γ ray, which populates the 666-keV level in ^{34}Cl . (d–f) The same portions are shown after subtraction of spectra obtained from “background” gates set on either side of the 5515-keV peak. Throughout, the energies (in keV) of the four possible deexcitation γ rays are marked [as is that of the annihilation peak in (b)].

each with $2^{15} \times 2^{15}$ channels and having 0.25 keV per channel. These spectra corresponded to the six possible pairs of our four operating germanium detectors.

The 6181-keV state we had populated in ^{34}Cl decays predominantly to the state at 666 keV via a 5515-keV transition, so by gating on the observed 5515-keV γ ray in one detector of a pair we could observe in the other detector the γ rays emitted in the subsequent decay of the 666-keV state. Peaks at 519 and 666 keV were clearly visible in each projected spectrum, and the relative intensity of the former to the latter was evaluated and found to be statistically consistent from one pair to another, thus indicating that any possible effects of angular correlations between the coincident γ rays can be neglected. As a result, we could safely add together all the projections for a given detector and determine the relative γ -ray intensities using the appropriate efficiency curve for that detector. Indeed, the relative efficiency curves of the four detectors were similar enough that we could also sum all of the detector projections into a single spectrum and use an averaged calibration curve for an analysis with the highest statistical precision.

Figure 2 shows two versions of this total spectrum. Figures 2(a)–2(c) show relevant portions of the projected spectrum when a single coincidence gate is chosen to encompass the 5515-keV γ ray. In addition to the two clearly visible peaks at 519 and 666 keV, there is a small peak at 461 keV and a larger one at 511 keV. The resonant state we populate at 6181 keV in ^{34}Cl also decays directly—albeit more weakly—to the states at 461 and 146 keV via γ rays with energies of 5720 and 6034 keV, respectively. Some Compton-scattered 5720-keV γ rays undoubtedly lie within the 5515-keV gating window, thus giving rise to the weak 461-keV coincident peak. In the case of the 6034-keV γ ray, its single-escape peak lies at 5523 keV and is partly included in the gating window.

TABLE I. Results for the relative γ -ray intensities from the decay of the 666-keV level in ^{34}Cl . Values for I_γ have been normalized to 100 for the 666-keV transition.

E_γ (keV)	$N_\gamma/N_{\gamma 666}$	$\epsilon_\gamma/\epsilon_{\gamma 666}$	I_γ	
			Experiment	Theory
666	1	1	100	100
519	0.0155(20)	1.06(2)	1.46(19)	1.50
205	<0.004 ^a	1.18(2) ^a	<0.3	0.13

^aThese values actually apply to $E_\gamma = 461$ keV. A 205-keV γ ray would be in cascade with one at 461 keV and our data allowed us to set a tighter limit on the higher-energy peak since the background rate was lower at that energy.

When the 511-keV annihilation radiation that escaped from one detector is detected in another, a 511-keV coincident peak is populated.

To obtain the spectrum in Figs. 2(d)–2(f), we eliminated these unwanted contributions by setting two “background” gates on either side of the 5515-keV peak and subtracting their totaled projections, suitably normalized, from the top spectrum. Clearly the 461- and 511-keV peaks have both been removed, while the 519- and 666-keV peaks remain unchanged. This spectrum selectively illustrates the decay of the 666-keV state in ^{34}Cl .

We determined the areas of the 519- and 666-keV γ -ray peaks using GF3, the least-squares peak fitting program in the RADWARE [9] package. A combined Gaussian and skewed Gaussian function with a constant background in the peak region was sufficient to properly describe the data in the spectrum. Further evaluation of the fit for each γ -ray peak was made by our comparing the result obtained from the area of the fitted Gaussians with the total number of measured counts above the calculated background. For both peaks the agreement was within a small fraction of the calculated uncertainty. The ratio of peak areas was determined to be $N_{\gamma 519}/N_{\gamma 666} = 0.0155(20)$, where the uncertainty includes provision for both counting statistics and systematic uncertainties associated with the spectral background and our specific choice of gates in the region of the 5515-keV peak.

One more transition from the 666-keV level is energetically allowed (see Fig. 1). It would lead to the emission of two γ rays, one of 205 keV, which would populate the 461-keV 1^+ level in ^{34}Cl , and a second deexciting that level to the ground state. Neither γ ray is discernible in Figs. 2(d)–2(f) so only upper limits can be set: *viz.*, $N_{\gamma 205}/N_{\gamma 666} < 0.014$ and $N_{\gamma 461}/N_{\gamma 666} < 0.004$. Since both these limits apply to the decay channel that begins with the emission of a 205-keV γ ray from the 666-keV level, we take the tighter of the two limits as being applicable to that decay channel.

The ratios of peak areas are listed in Table I together with the corresponding detector efficiency ratios. The final γ -ray intensity for each transition is the quotient of the number in the second column divided by that in the third column, normalized to 100 for the 666-keV γ ray. Note that the limit for the 205-keV γ ray has actually been set by the more sensitive

peak-area limit and the efficiency of a possible 461-keV γ ray, with which it would be in cascade.

In the recent study of ^{34}Ar β decay [4], the measured branching ratios were found to be in good agreement with *sd* shell-model calculations for ^{34}Ar and ^{34}Cl that involved the full *sd* shell with the USD effective interactions established by Wildenthal in 1984 [10]. We used the same model to calculate the γ -decay branching from the 666-keV level, with the results given in the last column in Table I. The agreement is remarkable.

IV. CONCLUSIONS

We have investigated the intensities of γ -ray transitions from the 666-keV excited state in ^{34}Cl . Our primary goal was to determine $I_{\gamma 519}$, the intensity of the 519-keV transition to the 146-keV isomeric state relative to the dominant 666-keV transition to the ground state. Our result, that $I_{\gamma 519}/I_{\gamma 666} = 1.46(19)\%$, replaces discrepant and much less precise values

in the literature [5,6]. In addition, we have been able to set a tighter limit of $<0.3\%$ on the strength of a possible 205-keV transition, which previously stood at $<1\%$ [6].

Our result for the 519-keV transition has already made important contributions to new results for the half-life of ^{34}Ar [3] and its β -decay branching ratios [4].

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- [1] I. S. Towner and J. C. Hardy, *Phys. Rev. C* **82**, 065501 (2010).
 - [2] J. C. Hardy and I. S. Towner, *Phys. Rev. C* **91**, 025501 (2015).
 - [3] V. E. Iacob, J. C. Hardy, H. I. Park, M. Bencomo, L. Chen, V. Horvat, N. Nica, B. T. Roeder, and A. Saastamoinen, *Phys. Rev. C* **101**, 015504 (2020).
 - [4] V. E. Iacob, J. C. Hardy, H. I. Park, M. Bencomo, L. Chen, V. Horvat, N. Nica, B. T. Roeder, A. Saastamoinen, and I. S. Towner, *Phys. Rev. C* **101**, 045501 (2020).
 - [5] P. M. DeLuca, J. C. Lawson, E. D. Berners, and P. R. Chagnon, *Nucl. Phys. A* **173**, 307 (1971).
 - [6] F. B. Waanders, J. P. L. Reinecke, H. N. Jacobs, J. J. A. Smit, M. A. Meyer, and P. M. Endt, *Nucl. Phys. A* **411**, 81 (1983).
 - [7] A. Aprahamian, P. Collon, and M. Wiescher, *Nuclear Phys. News* **24**, 5 (2014).
 - [8] Mesytec, <https://www.mesytec.com/products/nuclear-physics/MDPP-16.html>.
 - [9] D. C. Radford, <http://radware.phy.ornl.gov/main.html>.
 - [10] B. H. Wildenthal, *Prog. Part. Nucl. Phys.* **11**, 5 (1984).