β^+ Decays of ^{37}Ca: Implications for the Efficiency of the ^{37}Cl Solar ν Detector

A. García,[a] E. G. Adelberger, P. V. Magnus, and H. E. Swanson
Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195

O. Tengblad and ISOLDE Collaboration
PPE-Division, CERN, CH-1211 Geneva 23, Switzerland

D. M. Moltz
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

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We studied ^{37}Ca β^+ decays using a mass-separated ^{37}Ca beam and a proton telescope with 16-keV resolution. Delayed p's were detected in coincidence with γ's to identify p decays of ^{37}K daughter levels to excited states of ^{36}Ar. We observed 43 previously undetected proton groups, yielding an integrated B(GT) twice as large as that observed previously. Although our result increases the efficiency of the ^{37}Cl detector for counting solar ν's by 6%, its main effect is to reduce uncertainties in this efficiency arising from discrepancies between previous ^{37}Ca β decay and ^{37}Cl(p,n) results.

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The Homestake Mine solar neutrino detector [1] is based on counting individual atoms of ^{37}Ar produced by ν_e interactions in perchloroethylene. The efficiency of this detector is determined by the $^{37}\mathrm{Cl}(\nu_e,e^-)^{37}\mathrm{Ar}$ cross section for states with E_x up to ≈ 8.4 MeV, where ^{37}Ar becomes effectively unbound to $^{33}\mathrm{S}+\alpha$. To the extent that isospin symmetry is exact, these cross sections are determined by the ft values of the ^{37}Ca β^+ decays to the ^{37}K isospin analogs of the ^{37}Ar levels [2,3]. This procedure is expected to be quite reliable, as it depends only on the assumption of good isospin in the nuclear wave functions. ^{37}Ca β^+ decays have been studied with 30–50-keV resolution by Sextro, Gough, and Cerny [4], who detected the β-delayed p's produced by those ^{37}Ca decays that feed particle-unbound states of ^{37}K. Figure 1 shows the resulting B(GT) values, defined by

$$\frac{K}{f(E_i)t_i} = B_i(\mathrm{F}) + B_i(\mathrm{GT}) , \qquad (1)$$

where $K = 6170 \pm 4$ s, t_i and E_i are the partial half-life and energy release for decay to the ith level of ^{37}K, B_i(F) and B_i(GT) are the Fermi and Gamow-Teller reduced transition strengths defined in Ref. [5], and the statistical rate function $f(E_i)$ is computed using the prescription of Wilkinson and Macefield [6].

The required B(GT) values can also be estimated from the 0° cross sections of the ^{37}Cl(p,n) reaction at intermediate energies. Here one does not need assumptions about isospin symmetry, but instead makes a much stronger assumption about the (p,n) reaction mechanism, namely, that the 0° cross section is proportional to B(GT). The ^{37}Cl(p,n) reaction has been studied at $E_p = 120$ MeV with relatively poor resolution ($\Delta E \sim 600$ keV) by Rapaport *et al.* [7]. As can be seen in Fig. 1, the (p,n) B(GT) values *differ significantly* from the β^+ decay values of Sextro, Gough, and Cerny. Adelberger and Haxton [8] conjectured that much of this discrepancy could have been caused by a subtle error in interpreting the delayed proton data, namely, that Sextro, Gough, and Cerny assumed that all delayed proton groups corresponded to p decays of ^{37}K levels to the ground state of ^{36}Ar. Adelberger and Haxton illustrated this point with a shell-model calculation. Although only 1.8% of the delayed p's were predicted to result from ^{37}K decays to ^{36}Ar(1.97), incorrectly assigning these p's to $^{37}\mathrm{K} \rightarrow {}^{36}\mathrm{Ar}(0.00)+p$ decays distorted the B(GT) distribution in a way that qualitatively reproduced the discrepancy between the delayed proton and (p,n) results.

In this Letter we report a high-resolution, low-background study that identified decays feeding excited states of ^{36}Ar, and yields the first unbiased measurement of the ^{37}Ca β^+-decay scheme. A 60-keV mass-separated ($\Delta m/m \approx 1/7000$) ^{37}Ca beam from the ISOLDE 3 on-line isotope separator [9] at CERN (~ 6 s^{-1} at our counting station) was produced by bombarding a Ti foil target, heated to 1800 K, with a 2.6-μA 600-MeV proton

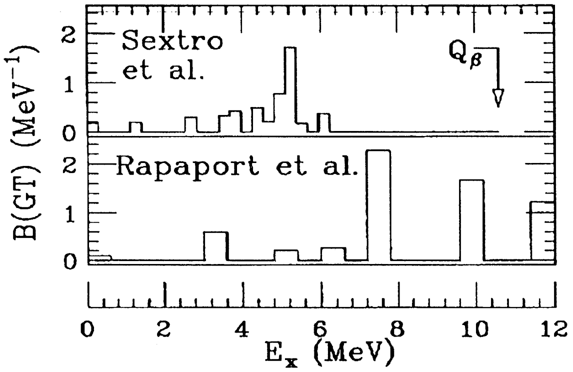

FIG. 1. Comparison of B(GT) distributions for $^{37}\mathrm{Cl}(\nu_e,e^-)$. Upper panel: ^{37}Ca β-decay data of Ref. [4]. The arrow denotes the maximum E_x that can be fed in β^+ decay. Lower panel: ^{37}Cl(p,n) data of Ref. [7]. The disagreement between these two results motivated our work.

beam. The radioactive beam was implanted into the entrance window of a gas detector that formed the first element of a proton telescope. This telescope was surrounded ($\Delta\Omega/4\pi=0.65$) by two 12.7-cm×15.2-cm NaI detectors that counted p-γ coincidences and allowed us to distinguish p decays that left ^{36}Ar in the ground state from those that fed excited states of ^{36}Ar.

Our telescope consisted of a gas ΔE detector, followed by a 150-mm^2, 300-μm-thick Si E detector and a 450-mm^2, 1000-μm-thick veto counter. The gas detector presented a very low areal density to the delayed p's. A 50-μg/cm^2 polypropylene entrance window separated the beam-line vacuum system from the $\sim$9 torr of isobutane gas that filled the telescope. The 5-mm active region of the ΔE counter was defined by two grounded grids of 50-μm tungsten wires on either side of a grid of 10-μm wires held at 610 V. Protons lost sufficiently little energy in the entrance window and the ΔE counter (only 25 keV at $E_p=1$ MeV) that high-resolution spectra ($\Delta E \sim 16$ keV) could be obtained directly from the E-counter signal. Eight parameters (five energy plus three time-to-amplitude converter signals) were recorded for each E-ΔE coincidence event. Events were identified as p's if they satisfied a two-dimensional E-ΔE gate and left no energy in the veto detector. The veto eliminated events ($\approx 11\%$ of the total) where energy was deposited in the E counter by a p and a β from the same event.

Our delayed p spectrum, shown in Fig. 2, reveals 54 different groups, only 11 of which were observed in previous work. The continuum in Fig. 2, readily visible below channel 1000, is due to small "tails" on the peaks. Ancillary measurements using monoenergetic p's from the University of Washington tandem accelerator showed that these tails were due to p's passing through the edges of the uncollimated Si detector. We therefore analyzed our spectrum by fitting peaks on top of a smooth background. [Note that this could only *underestimate* the B(GT) strength, because very weak lines would be lost in the background.]

The fraction of events in each peak coincident with 1.97-MeV γ rays was sufficiently well determined, except for the lowest intensity lines, that individual groups could be unambiguously assigned to p decays populating the ground or excited states of ^{36}Ar, to construct a β^+-decay scheme involving 40 final states in ^{37}K. Our proton energy calibration was based on the E_x of well-known ^{37}K levels that decayed to either the ground or 1.97-MeV levels of ^{36}Ar, and on the pulse height [10] for ^{241}Am α particles. In the region for which ^{36}Ar+p scattering data are available ($E_x \leq 7.0$ MeV) all but two of our 29 daughter ^{37}K levels could be identified with previously observed resonances [11-14] in ^{36}Ar(p,p), ^{36}Ar(p,p'), or ^{36}Ar(p,γ) (see Table I).

Before converting the relative intensities of the various proton groups into B(GT) values, we must account for ^{37}Ca decays that do not produce delayed p's. This obviously occurs in the decays to the ground and 1371-keV states of ^{37}K as these levels lie below the proton threshold. We account for the ground-state transition using isospin symmetry, i.e., assuming that it has the same B(GT) value as the ^{37}Ar$\rightarrow$ ^{37}Cl electron capture [5]. We have no direct means of knowing the B(GT) value for the ^{37}Ca$\rightarrow$ ^{37}K(1371) transition as our attempt to detect the 1371-keV γ rays in a singles Ge spectrum was unsuccessful because of background. Therefore we assume that the superallowed transition has a known reduced transition strength $B(\mathrm{F})+B(\mathrm{GT})=3.10$, where $B(\mathrm{F})=3$ follows from isospin conservation and $B(\mathrm{GT})=0.10$ is a shell-model prediction [5]. Although charge-dependent shell-model calculations [15] predict that B(F) is reduced by only a few tenths of a percent due to isospin mixing, we cannot exclude the possibility that the $J^\pi=(\frac{3}{2},\frac{5}{2})^+$ 5106-keV level contains some Fermi strength. We therefore take the conservative position that half the observed strength to this state is Fermi with an error that allows all or none of this strength to arise from isospin mixing.

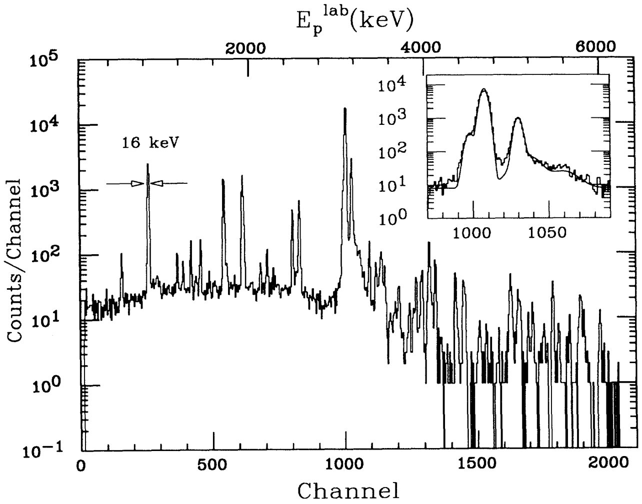

FIG. 2. Spectrum of delayed p's from ^{37}Ca β^+ decay. The continuum in the left half of the spectrum is due to a "tail" on the intense superallowed peak occurring near channel 1000. Inset: Expansion of the region about the superallowed group, showing the data and the fit.

This fixes the absolute β^+ branching ratios to the proton-unbound levels, and (because the sum of all β^+ branching ratios must be unity) leads to $B(\mathrm{GT};\frac{1}{2}{}_1^+) = (6.5\pm1.0)\times10^{-2}$, which strongly disagrees with the value $B(\mathrm{GT};\frac{1}{2}{}_1^+)\leq 1.4\times10^{-2}$ inferred from the ^{37}Cl(p,n) work.

^{37}Ca decays to unbound levels of ^{37}K could also fail to produce delayed protons if γ decay competes successfully with p decay. This effect should be largest for the 2750-keV level (it lies only 893 keV above the proton threshold) and for the first $T=\frac{3}{2}$ level (its p decay violates isospin conservation). A proton width $\Gamma_p(2750)=3.4$ eV is expected from the known [16] spectroscopic factor $S=0.31 \pm 0.07$ of the analog level in ^{37}Ar. The ^{37}Ar

TABLE I. Reduced transition strengths in ^{37}Ca β^+ decay.

this work			previous[a]
E_x(keV)	$B(GT)$	decay	E_x(keV)
0	$(4.83 \pm 0.14)\times10^{-2}$ [b]		0
1371	$(7.4 \pm 1.0)\times10^{-2}$ [c]		1370.85
2750.1 ± 0.8	$(6.7 \pm 0.4)\times10^{-2}$	p_0	2750.27
3239.4 ± 1.8	$(3.9 \pm 0.9)\times10^{-3}$	p_0	3240 ± 10
3622.2 ± 2.5	$(7.5 \pm 0.4)\times10^{-2}$	p_0	3617 ± 8
3840.2 ± 3.1	$(9.4 \pm 0.5)\times10^{-2}$	p_0	3841 ± 7
4190.8 ± 9.0	$(2.0 \pm 0.7)\times10^{-3}$	p_0	
4412.8 ± 1.3	$(4.3 \pm 0.2)\times10^{-2}$	p_0,p_1	$4413.2 \pm .4$
4495.5 ± 3.9	$(6.0 \pm 0.3)\times10^{-2}$	p_0	4496 ± 10[d]
5016.1 ± 4.3	$(6.4 \pm 6.4)\times10^{-2}$	p_0	$5018.5 \pm .6$
5050.6 ± 1.3	0.10 ± 0.10[c]	p_0,p_1	5049.2 ± 1.0
5120.2 ± 1.6	$(4.7 \pm 0.2)\times10^{-1}$	p_0,p_1	5116 ± 5[e]
5323.0 ± 1.8	$(4.8 \pm 0.3)\times10^{-2}$	p_0,p_1	5320 ± 5
5357.0 ± 6.6	$(4.7 \pm 0.6)\times10^{-3}$	p_0	
5423.7 ± 3.0	$(5.4 \pm 1.2)\times10^{-3}$	p_1	5417 ± 5
5445.9 ± 4.7	$(1.3 \pm 0.1)\times10^{-2}$	p_0	5450 ± 5
5464.8 ± 4.6	$(2.2 \pm 0.2)\times10^{-2}$	p_0	5469 ± 5
5569.3 ± 4.5	$(4.2 \pm 0.7)\times10^{-3}$	p_0	5568 ± 5
5623.4 ± 2.4	$(1.7 \pm 0.2)\times10^{-2}$	p_0,p_1	5624 ± 15
5788.2 ± 4.9	$(7.0 \pm 1.0)\times10^{-3}$	p_0	5789 ± 10
5931.6 ± 4.6	$(2.6 \pm 0.3)\times10^{-2}$	p_0	5935 ± 10
6014.2 ± 2.8	$(9.4 \pm 0.7)\times10^{-2}$	p_0,p_1	6017 ± 10
6091.5 ± 2.8	$(6.6 \pm 0.5)\times10^{-2}$	p_0,p_1	6090 ± 10[d]
6322.8 ± 4.8	$(3.0 \pm 0.3)\times10^{-2}$	p_0	6325 ± 10[d]
6414.4 ± 4.8	$(1.9 \pm 0.3)\times10^{-2}$	p_0	6411 ± 10[d]
6431.3 ± 3.3	$(3.4 \pm 0.6)\times10^{-2}$	p_0,p_1	6430 ± 10[d]
6604.0 ± 4.7	$(1.8 \pm 0.9)\times10^{-2}$	p_0,p_3	6606 ± 10[d]
6682.7 ± 4.7	$(6.4 \pm 1.4)\times10^{-3}$	p_0	6689 ± 10[d]
6738.9 ± 4.7	$(5.5 \pm 1.4)\times10^{-3}$	p_0	6726 ± 10[d]
			6747 ± 10[d]
6822.9 ± 4.7	$(5.7 \pm 1.6)\times10^{-3}$	p_0	6821 ± 10[d]
6972.9 ± 4.7	$(7.1 \pm 0.7)\times10^{-2}$	p_0	6976 ± 10[d]
7072.7 ± 4.7	$(5.7 \pm 0.6)\times10^{-2}$	p_0	
7182.3 ± 3.5	$(1.3 \pm 0.3)\times10^{-1}$	p_0	
7238.0 ± 4.7	$(3.1 \pm 0.5)\times10^{-2}$	p_0,p_1	
7368.5 ± 3.3	$(1.7 \pm 0.1)\times10^{-1}$	p_0,p_1	
7473.3 ± 3.3	$(3.2 \pm 0.4)\times10^{-1}$	p_0,p_1,p_2	
7542.3 ± 4.7	$(2.1 \pm 0.4)\times10^{-2}$	p_0	
7631.5 ± 4.7	$(1.2 \pm 0.1)\times10^{-1}$	p_1	
7659.8 ± 4.9	$(4.1 \pm 0.8)\times10^{-2}$	p_0	
7805.3 ± 3.7	$(2.5 \pm 0.3)\times10^{-1}$	p_0,p_1	
7834.3 ± 4.6	$(1.7 \pm 0.2)\times10^{-1}$	p_1	
8027.3 ± 5.3	$(8.5 \pm 1.5)\times10^{-2}$	p_0	

[a] From Ref. [14] unless otherwise noted.

[b] Inferred from ^{37}Ar decay.

[c] Inferred as discussed in text.

[d] Reference [11].

[e] Reference [12].

TABLE II. Solar ν cross sections for the ^{37}Cl detector (calculated only for neutrino sources whose cross sections are affected by our measurement).

ν source	σ_{standard}[a] (10^{-42} cm^2)	σ_{Sextro}[b] (10^{-42} cm^2)	$\sigma_{\text{this work}}$[c] ($10^{-42}$ cm^2)
^{8}B	1.06 ± 0.10	1.03	1.09 ± 0.03
Hep	3.9	3.74	4.26 ± 0.15

[a] Reference [2].

[b] Our calculation using the results of Sextro, Gough, and Cerny [4].

[c] Our calculation using B(GT) values and errors shown in Table I.

analog level has an $M1$ width of ≈ 33 meV so that γ decay of the 2750-keV level of ^{37}K is expected to be negligible. The lowest $T=\frac{3}{2}$ level is known [13] to have $\Gamma_\gamma/\Gamma_{p'} = (7\pm2)\times10^{-2}$, while our delayed-$p$ work gives $\Gamma_{p'}/\Gamma_p = (3.4\pm0.3)\times10^{-3}$. Combining these results we find $\Gamma_\gamma/\Gamma_p = (2.4\pm0.7)\times10^{-4}$, so that γ decays of the $T=\frac{3}{2}$ level can be neglected as well. We therefore assumed that each β^+ decay to an unbound level of ^{37}K produced a delayed p.

Our resulting B(GT) values are listed in Table I. Our new decay scheme, in which $(2.68\pm0.09)\%$ of the ^{37}Ca decays end up feeding $^{36}\text{Ar}(2^+)+p$, is consistent with the results of our first attempt [17] to remeasure the ^{37}Ca decays which gave a $(2.9\pm0.8)\%$ ratio. For $E_x \le 5.5$ MeV, our B(GT)'s are in fair agreement with those of Sextro, Gough, and Cerny [4], except that we see no evidence for feeding of a 4679-keV level in ^{37}K. However, we find much more strength at $E_x \ge 5.5$ MeV, so that our integrated GT strength is roughly twice that of Sextro, Gough, and Cerny. We also observe $(52\pm10)\%$ more GT strength below $E_x = 8.0$ MeV than was inferred from the $^{37}\text{Cl}(p,n)$ work [7].

Our revised ^{37}Ca decay scheme can be used to compute the production of ^{37}Ar by the $^{37}\text{Cl}(\nu_e,e^-)$ reaction. We assume that the B(GT) values are isospin symmetric, but use (when known) the actual excitation energies of the ^{37}Ar analogs of the ^{37}K levels. Our revised cross sections [18] using the ν spectra of Ref. [3] are shown in Table II. For the ^{8}B solar neutrino spectrum (neglecting possible ν oscillations) the efficiency of the ^{37}Cl detector should be increased by 6% compared to the value deduced from the results of Sextro, Gough, and Cerny. Bahcall's recommended cross sections [2,3] are 3% higher than those deduced solely from Sextro, Gough, and Cerny's data and are in remarkably good agreement with our values. Our results have a considerably larger impact on the efficiency for detecting higher-energy ν_e's such as those generated in supernova explosions [19] or solar flares [20]. For example, the cross section should be increased by 25% for supernova ν_e's with a Fermi-Dirac distribution characterized by a temperature of 4.5 MeV.

In conclusion, our results provide a secure basis for calculating the ^{37}Cl(ν_e,e^-) cross sections that govern the efficiency of the Homestake Mine solar neutrino detector. With our corrected efficiency, the standard-solar-model prediction [2] for the counting rate of the ^{37}Cl detector [21] becomes 8.1 ± 1.1 solar neutrino units. In addition, our results (that extend nearly to excitation energies where ^{37}Ar becomes unbound) should improve significantly the accuracy of a proposed [22] direct test of the ^{37}Cl detection scheme using μ^+-decay neutrinos (which have energies up to ~50 MeV).

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(a)Present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720.

[1] J. N. Bahcall and R. Davis, Jr., in *Essays in Nuclear Astrophysics*, edited by C. A. Barnes, D. D. Clayton, and D. Schramm (Cambridge Univ. Press, Cambridge, 1982).

[2] J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. **60**, 297 (1988).

[3] J. N. Bahcall and B. R. Holstein, Phys. Rev. C **33**, 2121 (1986).

[4] R. G. Sextro, R. A. Gough, and J. Cerny, Nucl. Phys. **A234**, 130 (1974).

[5] B. A. Brown and B. H. Wildenthal, At. Data Nucl. Data Tables **33**, 347 (1985).

[6] D. H. Wilkinson and B. E. F. Macefield, Nucl. Phys. **A232**, 58 (1974).

[7] J. Rapaport *et al.*, Phys. Rev. Lett. **47**, 1518 (1981).

[8] E. G. Adelberger and W. C. Haxton, Phys. Rev. C **36**, 879 (1987).

[9] H. L. Ravn and B. W. Allardyce, in *Nuclei Far from Stability*, edited by D. A. Bromley, Treatise on Heavy Ion Science Vol. 8 (Plenum, New York, 1989), p. 363.

[10] Using α and p beams of the same magnetic rigidity, we found that 5.486-MeV α's produced the same pulse height as 5.535-MeV p's.

[11] T. T. Thwaites, Nucl. Phys. **A150**, 531 (1970).

[12] D. R. Goosman and R. W. Kavanagh, Phys. Rev. **161**, 1156 (1967).

[13] H. P. L. de Esch and C. Van der Leun, Nucl. Phys. **A476**, 316 (1988).

[14] P. M. Endt, Nucl. Phys. **A521**, 1 (1990).

[15] W. E. Ormand and B. A. Brown, Nucl. Phys. **A491**, 1 (1989); B. A. Brown (private communication).

[16] P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978).

[17] A. García *et al.*, Phys. Rev. C **42**, 765 (1990).

[18] We neglect forbidden corrections to both ^{37}Ca β decay and ^{37}Cl(ν,e).

[19] A. Burrows, Astrophys. J. **283**, 848 (1984).

[20] J. N. Bahcall, Phys. Rev. Lett. **61**, 2650 (1988); T. Kuramoto *et al.*, Nucl. Phys. **A512**, 711 (1990).

[21] R. Davis, A. K. Mann, and L. Wolfenstein, Annu. Rev. Nucl. Part. Sci. **39**, 467 (1989).

[22] LAMPF experiment E1213, Ken Lande and Ray Davis, spokesmen.