RAPID COMMUNICATIONS

PHYSICAL REVIEW C

NUCLEAR PHYSICS

THIRD SERIES, VOLUME 51, NUMBER 2 FEBRUARY 1995

RAPID COMMUNICATIONS

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β-delayed γ-ray emission in ^{37}Ca decay

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(Received 14 October 1994)

We detect β-delayed γ rays emitted in ^{37}Ca decay and use these results plus our previous work on β-delayed proton yields to calculate B(GT) values for the $^{37}\mathrm{Ca}\rightarrow{}^{37}\mathrm{K}$ transitions. We compare these results to the isospin-analog B(GT) values inferred from a high-resolution $^{37}\mathrm{Cl}(p,n)$ study. Although the new β decay and (p,n) results remove some of the previously noted discrepancies between B(GT) values measured in ^{37}Ca decay and those inferred from $^{37}\mathrm{Cl}(p,n)$ cross sections, significant discrepancies remain.

PACS number(s): 23.40.Hc, 21.60.Cs, 25.40.Ep, 27.30.+t

There are a variety of circumstances where we need to know Gamow-Teller (GT) strengths that cannot be obtained directly from β-decay measurements simply because the transitions are energetically forbidden. Such cases occur, for example, in stellar evolution and nucleosynthesis, where electron capture rates play a crucial role, in efficiency calibrations of radiochemical neutrino detectors, and in nuclear structure studies of giant GT resonances. In these circumstances one has to deduce the squared matrix element of the $\sigma\tau$ operator from hadronic charge-exchange reactions. Deducing these B(GT) values from the forward-angle cross sections of, for example, intermediate-energy (p,n) reactions, is necessarily model dependent. It is therefore important to test the validity of the extraction procedure as extensively as possible. However, such tests are not easy to find. Suppose B is a β emitter that decays to a stable nucleus A. Although one can use the $A(p,n)B$ reaction to estimate B(GT) values for transitions to many states of B, only one of these values (for the ground-state transition) can be calibrated against a β-decay value. This limitation can be sidestepped by using isospin symmetry to relate mirror β decay and (p,n) transitions. A particularly favorable case for such a comparison occurs in the $A=37$ system where the large Q value for ^{37}Ca β decay ($Q_{\mathrm{EC}}=11.696$ MeV) allows the $^{37}\mathrm{Cl}(p,n)^{37}\mathrm{Ar}$ cross sections for final states with energies up to $E_x\approx 8$ MeV to be compared to the corresponding $^{37}\mathrm{Ca}\rightarrow{}^{37}\mathrm{K}$ decays.

A recent study [1] of ^{37}Ca β^+-decay covering ^{37}K excitation energies up to 8 MeV revealed unexpected discrepancies with $^{37}\mathrm{Cl}(p,n)$ results of Rapaport *et al.* [2]. Especially prominent problems were found at low excitation energies, in the region of the superallowed transition, and at excitation energies above 7 MeV. These results motivated a Seattle IUCF-OSU-LANL Collaboration [3] to make new $^{37}\mathrm{Cl}(p,n)$ and $^{37}\mathrm{Cl}(\vec{p},\vec{n})$ studies with improved energy resolution. A preliminary analysis [4] of the polarization-transfer results shows that the discrepancy in the region of the superallowed transition was due to an oversubtraction of Fermi strength in the earlier (p,n) experiment of Rapaport *et al.* On the other hand, the high-resolution (p,n) data revealed new anomalies at low excitation energies, particularly for the transitions feeding the ^{37}Ar and ^{37}K levels at $E_x=1.37$ and 3.24 MeV (see Fig. 1).

Goodman *et al.* [5] suggested that the $E_x=1.37$ and 3.24 MeV discrepancies arose because of a shortcoming in the β-decay work, namely that the B(GT) values of Ref. [1] were deduced from delayed proton yields under the assumption that essentially all β^+ decays feeding unbound levels of ^{37}K produced delayed protons. If the 3.24 MeV level of ^{37}K, which is unbound to proton decay by 1.38 MeV, decayed primarily by γ emission with $\Gamma_\gamma/\Gamma_p\approx 40$, the delayed proton and (p,n) results for the transition to that level would

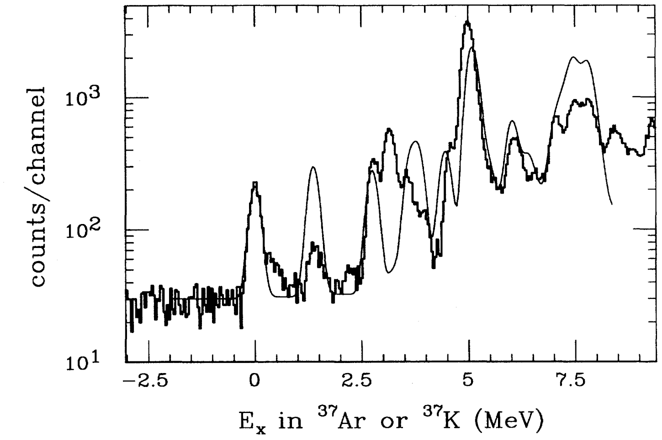

FIG. 1. Comparison of results from recent ^{37}Cl(p,n) and ^{37}Ca β-decay experiments, showing the zero-degree neutron spectrum taken at $E_p \approx 100$ MeV [4] (histogram), together with the B(GT)'s deduced from the β-decay experiment [1] (continuous line). The data were normalized so that the transition to the ground state has the same area in both spectra. The β-decay results were smeared so that the energy resolution appears similar in both cases. We added an exponential tail with 10% of the area of the peak to simulate the neutron spectrum, and corrected the B(GT)'s with a line with 14% change between 0 and 10 MeV, to account for the form factor. The discrepancy at $E_x \approx 5$ MeV (superallowed transition) is not significant and arises because of the Fermi component in the (p,n) yield.

be reconciled. Furthermore, because the strength to the bound first-excited state at 1.37 MeV was not directly measured in Ref. [1] but deduced from the requirement that the sum of all branching ratios be unity, the increased B(GT) of the 3.24 MeV level would reduce the B(GT) of the 1.37 MeV level bringing it into agreement with the (p,n) value as well [6].

Illiadis *et al.* [7] recently measured the ^{36}Ar(p,γ) resonance strength corresponding to the $E_x = 3.24$ MeV level and obtained $\omega\Gamma_p\Gamma_\gamma/\Gamma = (0.60 \pm 0.15)$ meV. They estimated $\Gamma_\gamma = 8.2$ meV from the lifetime of the analog ^{37}Ar level and concluded that $\Gamma_\gamma/\Gamma_p \approx 40$ so that the discrepancies between the β decay and (p,n) B(GT) values had been resolved.

In this Rapid Communication we present a direct measurement of β-delayed γ emission in ^{37}Ca decay and show that, contrary to previous claims [7,8], the discrepancies between the (p,n) and β-decay work are not resolved. Although the largest anomalies have been eliminated, problems remain at the factor-of-2 level. Our results for the β-delayed protons will be presented elsewhere.

Our ^{37}Ca source was produced using a ^{37}CaF beam from the ISOLDE general-purpose on-line isotope separator at the CERN PS/Booster. The fluorinated $A=56$ beam had very little radioactive contamination. In particular, it had virtually no ^{37}K activity that in an $A=37$ beam is typically 5 orders of magnitude more intense than ^{37}Ca, producing an annihilation radiation background that would have made it impossible to do our experiment. The fluorination process was very efficient; the $A=56$ beam had about 30 ^{37}CaF ions per second, 50% of the ^{37}Ca intensity observed in the $A=37$ beam.

The ^{37}CaF beam was focused onto a particle telescope that was surrounded by an annular eight-segment NaI detector that covered $\Delta\Omega/4\pi \approx 0.9$. The NaI photomultiplier gains were stabilized by a computer feedback system that adjusted the bias voltage in each segment to keep the 0.511 MeV positron annihilation peak in a fixed channel. The telescope consisted of a ΔE gas proportional counter similar to that used in Ref. [1], a fully-depleted silicon E1 counter (300 mm^2 area, 500 μm thick) that stopped the delayed protons, followed by a silicon E2 counter (450 mm^2 area, 1000 μm thick) that identified β's.

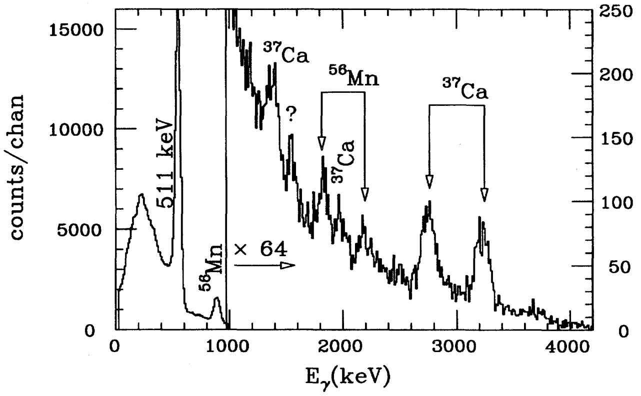

FIG. 2. Spectrum of events satisfying trigger 2 in three of the NaI segments. The 1.37, 2.75, and 3.24 MeV γ rays are from ^{37}Ca decay. The 0.85, 1.81, and 2.11 MeV peaks are from a ^{56}Mn contamination in our $A=56$ beam.

We used three triggers for the computer data acquisition: (1) Any event in the E1 counter; this trigger plus the requirements of no signal in E2 and an appropriate signal in ΔE identified "proton" events. (2) Any coincidence between the E2 counter and the NaI's; this trigger plus the requirement of an appropriate E1 signal identified "positron-followed-by-γ-ray" events. (3) A prescaled trigger from any event in any NaI segment; this was used for the gain stabilization mentioned above.

Figure 2 shows a spectrum of events taken in three of the eight NaI segments using trigger 2 and requiring in addition a signal in the E1 counter. We summed the events in only three of the NaI's because the energy resolution was significantly worse in the other segments. We obtained absolute β-delayed γ-ray branching ratios from the γ-ray spectrum in Fig. 2 and the simultaneously accumulated delayed proton spectrum in the E1 counter using the expression

$$R_\gamma(i) = \frac{N_\gamma(i)}{N_p} \frac{\epsilon_{p1}}{\epsilon_\gamma(i)\ \epsilon_{\beta1}\ \epsilon_{\beta2}} R_p , \tag{1}$$

where $R_\gamma(i)$ is the β-delayed γ-ray branching ratio to the ith level, $N_\gamma(i)$ is the number of counts in the appropriate γ-ray photopeak, and N_p is the number of counts in the superallowed delayed proton peak whose absolute branching fraction, $R_p = 0.46 \pm 0.01$, can be computed reliably (see Ref. [1]). ϵ_γ is the absolute efficiency for counting γ's in the NaI detector, ϵ_{p1} and $\epsilon_{\beta1}$ are the absolute efficiencies for detecting protons and positrons in the E1 counter, and $\epsilon_{\beta2}$ is the efficiency for detecting a positron in the E2 counter given that it was already detected in the E1 counter.

TABLE I. β-delayed γ rays from ^{37}Ca decay.

E_γ (MeV)	Peak area	ϵ_γ (%)	R_γ (%)
1.37	418 ± 64	19 ± 3	1.5 ± 0.4
2.75	650 ± 50	12 ± 2	3.6 ± 0.8
3.24	660 ± 40	10 ± 1	4.4 ± 0.6
3.62	$\leqslant50$	9 ± 1	$\leqslant0.4$
3.84	$\leqslant50$	9 ± 1	$\leqslant0.4$

We found ϵ_γ using calibrated γ-ray sources to obtain the energy dependence of the efficiency, and delayed γ's from ^{37}K decay to obtain the absolute efficiency at $E_\gamma=2.796$ MeV. The latter measurement was made using an $A=37$ beam (that contained mainly ^{37}K) to obtain the ratio of counts at $E_\gamma=2.796+0.511$ MeV to those at $E_\gamma=0.511$ MeV. Because the origin of 0.511 MeV γ rays can be questionable, we chopped the $A=37$ beam so that the activity was accumulated for 10 ms and then counted for ≈8 s. For each event we recorded the reading of a clock that was zeroed at the beginning of every beam burst. In this way we were able to check that the half-life for the 0.511 MeV γ rays agreed within 4% with that of ^{37}K. We checked the energy dependence of the efficiency using the code GEANT and obtained good agreement with our measurements. GEANT was then used to extrapolate the absolute calibration at $E_\gamma=2.796$ MeV to the energies needed for the ^{37}Ca work.

The known solid angle of the E1 counter gave $\epsilon_{p1}=0.064\pm0.002$. $\epsilon_{\beta1}$ was found using events in which a proton and a positron from the same decay passed through the E1 detector. These events could be clearly identified because they produced "satellite" peaks in the E1 proton spectrum that lay about 150 keV (the β^+ energy loss in the E1 detector) higher than the "pure" proton peak. These contained a fraction of the counts in the "pure" peak about equal to the efficiency of the E1 counter for positrons. The observed fraction, 0.064 ± 0.004, was then corrected for the low-energy threshold in the E1-counter ADC, which eliminated about 7% of the events in the "Landau distribution." The E2 detector can also detect the positrons going through the E1 counter, and $\epsilon_{\beta2}$ was determined as the efficiency to veto events in the "satellite" peaks. We thus obtained $\epsilon_{\beta2}=(0.85\pm0.06)$. We finally obtained

$$\frac{\epsilon_{p1}}{\epsilon_{\beta1}\ \epsilon_{\beta2}}=1.21\pm0.11 \qquad (2)$$

for the combination of all of the particle efficiencies.

Table I presents the measured photopeak areas, the corresponding γ-ray efficiencies, and the resulting absolute β-delayed γ-ray branches inferred from the known ground-state γ-ray branching ratios for the 1.37 MeV (100%) and the 2.75 MeV (98.2% [10]) levels. We assumed that the 3.24, 3.62, and 3.84 MeV levels had ground-state γ-ray branches of 100%, 100%, and 84%, respectively, the values observed for the decays of the analog levels in ^{37}Ar [10]. The areas were corrected using GEANT to account for escapes of 0.511 MeV γ's from the detector—the photopeak of the 2.75 MeV γ ray contained a 10% contribution from the unresolved first-escape peak of the 3.24 MeV γ ray.

TABLE II. ^{37}Ca β^+ branches studied in this work.

E_x (MeV)	R_p (%)[a]	R_γ (%)[b]	R_{tot} (%)	$\Gamma_\gamma/\Gamma_p(^{37}\text{K})$
1.37		1.5 ± 0.4	1.5 ± 0.4	
2.75	5.2 ± 0.1	3.6 ± 0.8	8.8 ± 0.8	0.69 ± 0.15
3.24	0.22 ± 0.01	4.4 ± 0.6	4.6 ± 0.6	20 ± 3
3.62	3.2 ± 0.1	$\leqslant 0.4$	$3.2^{+0.5}_{-0.1}$	$\leqslant 0.1$
3.84	3.6 ± 0.2	$\leqslant 0.5$	$3.6^{+0.5}_{-0.2}$	$\leqslant 0.1$

[a] From Ref. [1].

[b] This work.

Combining our β-delayed γ-ray branching ratios with the β-delayed proton branches from Ref. [1], we obtain the total β branches and corresponding GT strengths shown in Table II.

The fourth column in Table II shows the ratio Γ_γ/Γ_p for the ^{37}K daughter levels. These values are surprisingly large. The $E_x=2.75$ MeV $J^\pi=5/2^+$ level, which is unbound by 0.89 MeV, decays by γ-ray emission with a significant probability: $\Gamma_\gamma/\Gamma_p\approx0.7$. This was not expected from information available for the assigned isospin analog in ^{37}Ar, where a spectroscopic factor $S\approx0.3$ and a $\Gamma_\gamma\approx33$ meV predict a negligible γ branch for the ^{37}K level if one assumes isospin symmetry of the spectroscopic factors and γ-ray widths. However, the measured $^{36}\text{Ar}(p,\gamma)$ [9,10] resonance strength of this level, $\Gamma_p\Gamma_\gamma/(\Gamma_p+\Gamma_\gamma)=(69.1\pm0.1)$ meV together our result for Γ_γ/Γ_p yield $\Gamma_\gamma=(117\pm20)$ meV [$B(M1)=0.27$ W.u.] and $\Gamma_p=(169\pm33)$ meV (which corresponds to $\approx10^{-2}$ of a single-particle unit). Our widths imply a half-life $\tau=2.3\pm0.3$ fs which agrees well with a previous limit [9,10] of $\tau\lesssim3$ fs.

The 3.24 MeV $J_\pi=5/2^+$ [11] level, which is unbound by 1.38 MeV, has $\Gamma_\gamma/\Gamma_p\approx20$. Combining our result with the $\Gamma_\gamma\Gamma_p/(\Gamma_\gamma+\Gamma_p)$ value from Ref. [7], we find that $\Gamma_\gamma=4.2\pm1.0$ meV [$B(M1)=6.0\times10^{-3}$ W.u.] and $\Gamma_p=0.21\pm0.05$ meV (a proton width that is only 4×10^{-6} of a single-particle value). Our measured Γ_γ differs by a factor of about 2 from the estimate of Illiadis *et al.* [7] based on the known lifetime of the analog state in ^{37}Ar. Such differences are not unexpected.

Finally, the measured absolute branch to the 1.37 MeV level, (1.5 ± 0.4)%, is consistent with the condition that the

TABLE III. Analog B(GT) values obtained from ^{37}Ca β decay and $^{37}\text{Cl}(p,n)$.

$E_x(^{37}\text{ K})$	$B(\text{GT};\ \beta^+)$[a]	$E_x(^{37}\text{ Ar})$	$B(\text{GT};\ p,n)$[b]
0.00	$(4.8\pm0.1)\times10^{-2}$	0.00	$(4.8\pm0.1)\times10^{-2}$
1.37	$(9.2\pm2.5)\times10^{-3}$	1.41	$(1.4\pm0.1)\times10^{-2}$
2.75	$(1.2\pm0.1)\times10^{-1}$	2.80	$(7.0\pm0.2)\times10^{-2}$
3.24	$(8.2\pm1.6)\times10^{-2}$	3.17	$(1.28\pm0.04)\times10^{-1}$
3.62	$(7.5\pm0.4)\times10^{-2}$	3.60	$(5.8\pm0.3)\times10^{-2}$
3.84	$(9.4\pm0.5)\times10^{-2}$	3.94	$(1.9\pm0.1)\times10^{-2}$
4.19	$(2.0\pm0.7)\times10^{-3}$	4.41	$(4.3\pm0.2)\times10^{-2}$
4.50	$(6.0\pm0.3)\times10^{-2}$	4.57	$(8.5\pm0.2)\times10^{-2}$

[a] From this work.

[b] From the $E_p\approx100$ MeV $^{37}\text{Cl}(p,n)$ data of Ref. [14]. Data are normalized so that the ground-state transition has the correct value determined by the ^{37}Ar lifetime.

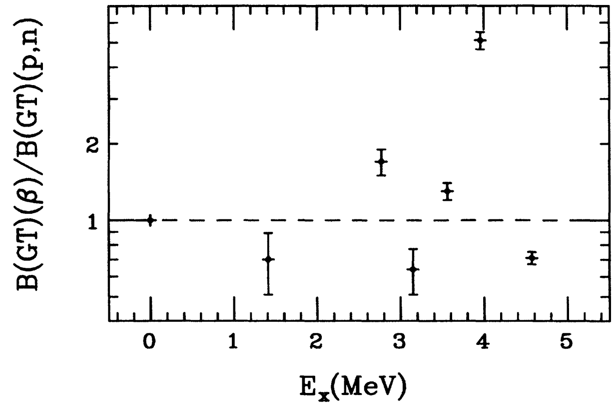

FIG. 3. Ratio of B(GT)'s obtained from ^{37}Ca decay (this work) to those inferred from the ^{37}Cl(p,n) data of Ref. [4]. The latter were normalized so that the ground-state transition had the β-decay value.

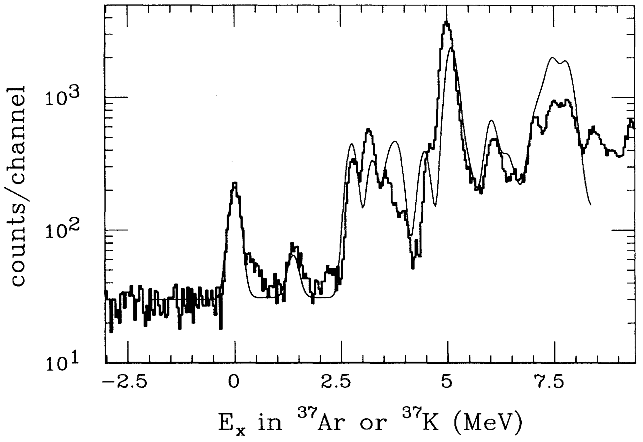

FIG. 4. Same as Fig. 1 after including the findings of this work.

sum of all branches must be unity, which requires that the branching ratio fall within the interval (3.8±2.5)%.

Table III compares the ^{37}Ca B(GT) values from this experiment to the analog B(GT) values found in the recent ^{37}Cl(p,n) work. The (p,n) B(GT)'s were normalized so that the ground-state transition had the "correct" value given by the ^{37}Ar lifetime and the q dependence of the form factor was taken from Ref. [12]. [We explored the effect on the B(GT)'s if the q dependence was approximated by a straight line with 14% change between $E_x = 0.0$ and 10.0 MeV, and found changes smaller than 4%.] Figure 3 shows the ratio of the analog B(GT)'s from the ^{37}Cl(p,n) and the ^{37}Ca β-decay work. Figure 4 shows a comparison with the ^{37}Cl(p,n) data after the present work.

We call attention to the fact that the ratio between the (p,n) and β-decay results is far from being a constant, and varies by amounts that can be as large as a factor of 2. To what extent can the observed variations result from isospin-breaking effects? Ormand and Brown [13] have calculated the expected B(GT) asymmetries using a (2s1d) shell model with empirically determined charge-dependent single-particle energies and two-body matrix elements. They predict effects much smaller than the factor of about 2 that we observe [14]. Ormand and Brown did not include effects of charge-dependent radial wave-function overlaps but these are expected to be small; the Coulomb barrier causes protons and neutrons to have very similar radial functions. Therefore, we argue that the differences shown in Fig. 3 reflect problems in extracting B(GT) values from charge-exchange cross sections. Discrepancies of this magnitude are not necessarily surprising. For weak transitions such as those considered here, where $B(\mathrm{GT}) \ll 1$, one can expect inadequacies in the simple reaction model customarily used to extract B(GT) values from forward-angle charge-exchange cross sections (see Ref. [15] for one possible mechanism for such discrepancies).

We conclude that important discrepancies remain between the GT strengths measured in ^{37}Cl(p,n) and in ^{37}Ca β decay, and argue that these indicate the need for improved techniques for extracting Gamow-Teller strengths from charge-exchange data.

We thank the entire ISOLDE team, especially Helge Ravn, for helping to make this measurement a success; and Teng-Lek Khoo for lending us the segmented NaI detector. A.G. wishes to thank M. Wiescher for helpful comments, and the Warren Foundation and NSF for support.

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