The branching ratio in the decay of ^{7}Be

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A measurement of the branching ratio for electron capture (EC) decay of ^{7}Be to the 478-keV level in ^{7}Li is reported. The reaction ^{10}B(p, α)^{7}Be was used and the ^{7}Be recoils were detected and stopped in a particle detector thin enough to transmit the protons. The absolute γ-ray emission rate of 478-keV γ rays from the implanted detector was determined with a well-shielded intrinsic Ge detector. The absolute efficiency of the Ge detector was established with ^{22}Na, ^{137}Cs, and ^{88}Y standard sources. A value of 11.4 ± 0.7% was obtained for the EC branch to the 478-keV state. Calculations suggest that the axial vector coupling constant G_A must be reduced by a factor of 0.94 ± 0.02 to obtain agreement with the experimental result.

On rapporte les résultats d'une mesure du rapport d'embranchement de conversion interne dans la désintégration de ^{7}Be vers le niveau de 478 keV dans ^{7}Li. La réaction ^{10}B(p, α)^{7}Be a été utilisée, et les ^{7}Be de recul ont été détectés et arrêtés dans un détecteur de particules assez mince pour transmettre les protons. Le taux absolu d'émission des rayons gamma de 478 keV par les atomes implantés dans le détecteur a été déterminé avec un détecteur Ge intrinsèque bien protégé. On a déterminé l'efficacité absolue de ce détecteur avec des sources étalons de ^{22}Na, ^{137}Cs et ^{88}Y. La valeur obtenue pour le rapport d'embranchement de conversion interne dans la transition à l'état de 478 keV est 11,4 ± 0,7%. On a calculé que la constante de couplage de veteur axial G_A doit être réduite par un facteur de 0,94 ± 0,02 pour obtenir un accord avec le résultat expérimental.

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Introduction

The branching ratio for the electron capture (EC) decay of ^{7}Be to the 478-keV first excited state in ^{7}Li is important to the analysis of data connected with the solar neutrino problem. The solar neutrino flux measured by the ^{37}Cl detector is 1.8 ± 0.3 SNU (1 SNU = 10^{-36} captures per ^{37}Cl atom per second) (1). The standard solar model predicts 7.6 ± 3.3 SNU (3σ error) (2). The ^{3}He(^{4}He, γ)^{7}Be cross section is an important parameter (2) in the predicted value since the Brookhaven solar neutrino detector is sensitive to neutrinos that arise from a series of reactions involving this reaction. The ^{7}Be branching ratio to the 478-keV level in ^{7}Li can be used in the determination of the ^{3}He(^{4}He, γ)^{7}Be cross section by an activation technique. The cross section can also be determined by directly measuring the capture γ rays, and results from both techniques have been reported (3−8).

The yield of capture γ rays from the ^{3}He(^{4}He, γ)^{7}Be reaction has been measured in beam, and the cross section, extrapolated to low energies, has been reported by Parker and Kavanagh (3), Nagatani *et al.* (4), Kräwinkel *et al.* (5), and Osborne *et al.* (6). Three of these measurements are in reasonable agreement; however, Kräwinkel's value of the cross-section factor $S_{34}(0)$, where $S(E_{CM}) = E_{CM}\cdot\sigma(E_{CM})$ exp $(164.12/\sqrt{E_{CM}})$, is 40% lower than the others. The discrepancy between measured and predicted neutrino capture rates would be substantially reduced if the lower result were correct, yet a recent new measurement (24) of the absolute cross section has reaffirmed the larger values and a weighted average of $S_{34}(0) = 0.50 \pm 0.05$ keV·b is recommended. Osborne *et al.* (6), Roberston *et al.* (7), and Volk *et al.* (8) have recently measured the capture cross section by the alternative method of measuring the ^{7}Be activity produced by ^{3}He(^{4}He, γ)^{7}Be by counting off-line the 478-keV γ rays following electron capture decay of ^{7}Be to the first excited state of ^{7}Li. Their results depend on the pre-1974 measured value for the electron capture branch to the 478-keV state of ^{7}Li, B_γ = 10.35 ± 0.07% (9). The average of these activation-type measurements is $S_{34}(0) = 0.57 \pm 0.02$ keV·b, a value 3.5 standard deviations different from the average $S_{34}(0) = 0.50 \pm 0.02$ keV·b of the direct-capture γ-ray measurements. To confuse the issue further, a value of B_γ = 15.4 ± 0.8% has recently been reported by Trautvetter *et al.* (10); this result, if correct, would bring the activation measurements into agreement with the lowest value (5) of $S_{34}(0)$, but not into agreement with the recommended value. Because of the importance of this branching ratio to the solar neutrino

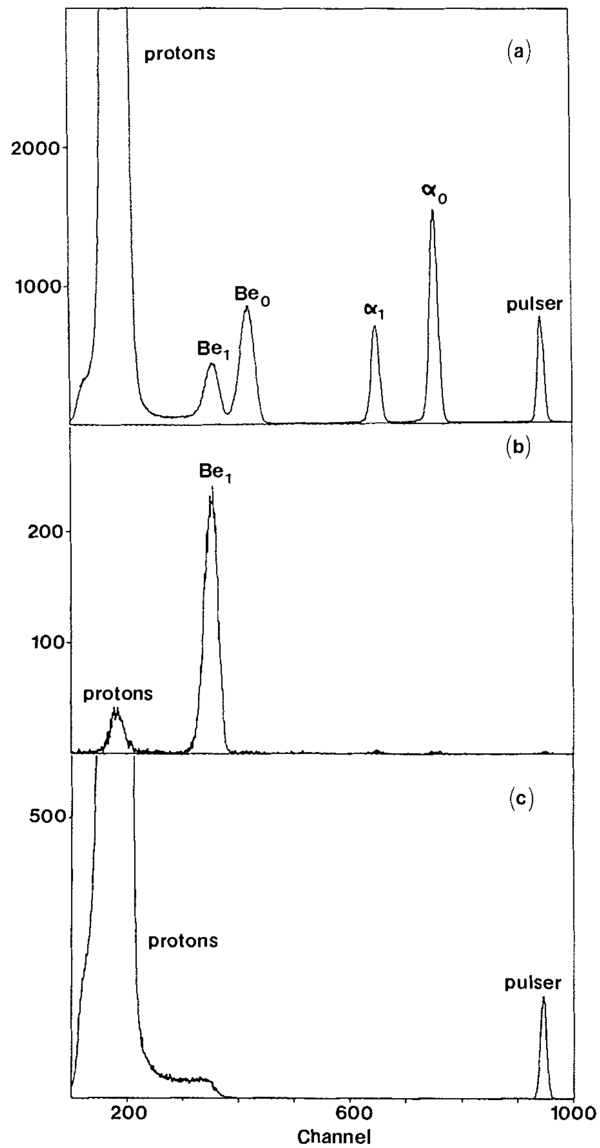

FIG. 1. (*a*) The spectrum observed in the thin transmission detector during implantation of ^{7}Be produced by 2-MeV protons in the ^{10}B(p, α) reaction. The reaction populates both the ground state and the first excited state of ^{7}Be. The various peaks are identified; the large low-energy peak is due to protons, which deposit only a small fraction of their energy when passing through the detector. (*b*) The spectrum of particles observed in coincidence with the α_1 particle group in a detector at 90°. The line shape of the Be_1 peak indicates that tailing is not significant in this detector. The small proton peak is due to random coincidences. (*c*) The spectrum of proton scattered in a thin gold target, deposited on a carbon foil, observed by the 17-μm transmission detector. The toe on the high-energy side of the proton peak is due to backscattering off the gold on the surface of the detector. The gold surface was turned away from the target during implantation to reduce straggling of the ^{7}Be peaks.

problem, we have remeasured it using a technique similar to that of Trautvetter *et al.* Since the present measurement was initiated, many other laboratories have remeasured the ^{7}Be branching ratio. Their results are summarized in the discussion in a later section.

Experimental procedure

The reaction ^{10}B(p, α)^{7}Be was used to produce energetic ^{7}Be ions that were implanted into a 17-μm transmission-type Si surface-barrier particle detector placed at a 60° angle to the beam. The detector was behind a 4.8-mm diameter aperture, 10 cm from the target. A 300-nA beam of 2.0-MeV protons was obtained from the Queen's University 4-MV Van de Graaff accelerator. The 80-μg/cm^2 self-supporting ^{10}B target was enriched to 94%.

A typical spectrum from the particle detector, obtained during implantation, is shown in Fig. 1*a*. The reaction populated both the ground state and the first excited state of ^{7}Be, and the corresponding α particles and Be ions are indicated. The line shape for the Be_1 peak was obtained by requiring a coincidence between the α_1 group in another particle detector at 90° and the 17-μm transmission detector at 60°. The coincidence spectrum is shown in Fig. 1*b*; there is no evidence of significant tailing in this spectrum. The gold surface on the Si detector was turned away from the target during the implantation to reduce scattering at the surface of the detector. The background between the Be_1 and proton peaks is due to protons that are backscattered from the gold surface. This toe effect on the upper edge, illustrated in Fig. 1*c*, was observed and quantitatively measured by replacing the ^{10}B target with a thin gold target evaporated onto a carbon foil. The proton line shape obtained from this measurement was used to subtract the contribution from protons under the Be_1 peak. The total counting rate was 1500–2000 counts/s and corrections applied for dead time losses were typically 1–2%.

The problem created by broken self-supporting targets was carefully monitored. When breakage occurred, the resolution of the Be peaks deteriorated substantially, even though the α peaks were not changed significantly. The implantation proceeded in a series of $\frac{1}{2}$-h runs; after each, the spectra were recorded and then cleared to maintain high sensitivity to the effects of target damage. On the few occasions when the target broke, the areas of the α_0 and α_1 peaks and the previously constant ratios of these peaks to the Be_0 and Be_1 peaks were used to obtain a reliable value for the number of implanted beryllium nuclei. The total implantation time was 13 h, during which (3.03 ± 0.06) × 10^6 ^{7}Be atoms were implanted in the transmission detector.

The activity implanted in the transmission detector

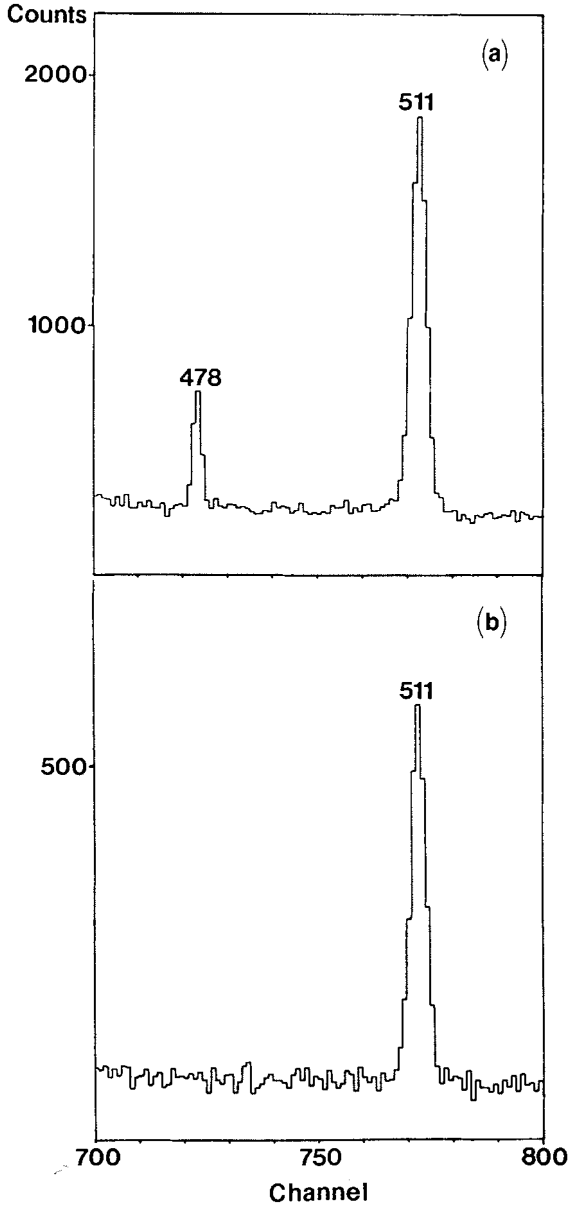

FIG. 2. (a) A portion of the total spectrum of γ rays observed over a period of 7 d when the implanted particle detector was located 15 mm in front of the shielded germanium counter. The 478-keV γ ray, which follows electron capture of ^{7}Be to the first excited state of ^{7}Li, and the 511-keV annihilation radiation lines are indicated. (b) The background observed in the shielded germanium detector over a time of 62 h. The average background between 450 and 500 keV was 1.9 counts/h/keV.

was observed by an 18%-efficient, high-purity germanium detector inside a 100-mm-thick lead shield. The implanted detector was placed in a lucite holder and positioned in front of the germanium detector; two

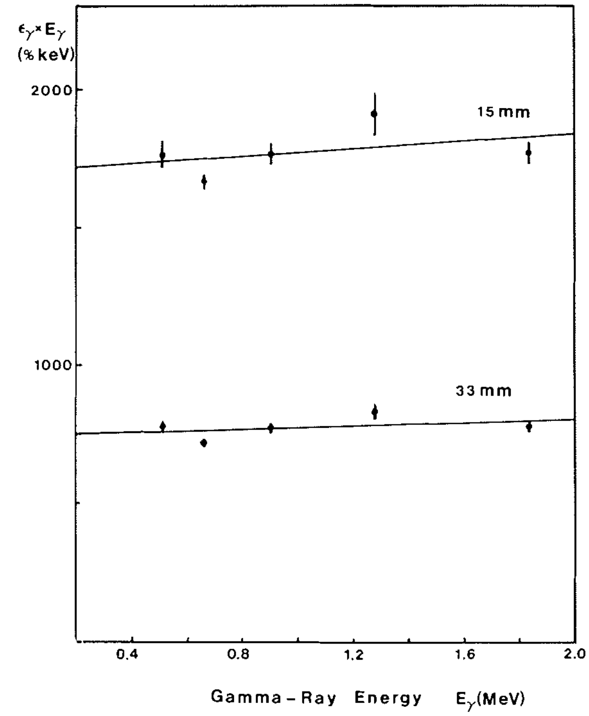

FIG. 3. The absolute efficiency calibration of the high-purity germanium detector was obtained with ^{22}Na, ^{137}Cs, and ^{88}Y standard sources. The product of efficiency times γ-ray energy is plotted for sources 15 and 33 mm from the detector. The straight lines represent least squares fits to the data.

source-to-detector distances were used, 15 and 33 mm, measured to the front face of the Ge detector vacuum enclosure.

A portion of the γ-ray spectrum, obtained over a period of 7 d in the closer geometry, is shown in Fig. 2a. The background, accumulated over 62 h with the shielded germanium detector, is shown in Fig. 2b. The background is flat in the region near 478 keV, where the average counting rate was 1.9 counts/h/keV. Earlier background tests of a Ge(Li) detector inside the lead shield had revealed a very small peak at 478 keV, and experiments performed with an Am–Be neutron source placed outside the shield suggest this peak was associated with neutrons. Neutrons at very low intensity were probably produced by the Van de Graaff generator, which was located some 30 m away behind substantial additional concrete shielding. With the intrinsic germanium detector, no background peak at 478 keV was observed during extensive observations.

The absolute efficiency of the intrinsic germanium detector was calibrated as a function of γ-ray energy with standard ^{22}Na, ^{137}Cs, and ^{88}Y sources. Each source was placed in the same position in front of the germanium detector as the implanted ^{7}Be source. Figure 3 shows the product of absolute efficiency times γ-ray

TABLE 1. Summary of measurements

Source–detector distance (mm)	N_0 ($\times 10^6$)	n_γ	ϵ_γ (%)	B_γ (%)
15	3.03±0.06	1251±66	3.64±0.09	11.1±0.7
33	3.03±0.06	778±54	1.63±0.04	12.3±1.1
		weighted average for B_γ =		11.4±0.7

TABLE 2. Recent measurements of the ^{7}Be EC branching ratio

Authors	Refs.	B(%)	Method
Trautvetter *et al.*	10	15.4±0.8	*a*
Balamuth *et al.*	11	10.10±0.45	*b*
Norman *et al.*	12	9.8±0.5	*c*
Davids *et al.*	13	10.61±0.23	*d*
Donoghue *et al.*	14	10.6±0.5	*a*
Mathews *et al.*	15	10.7±0.2	*d*
Fisher and Hershberger	16	10.7±0.3	*c*
Knapp *et al.*	17	10.9±1.1	*e*
Taddeuci *et al.*	18	10.3±1.1	*f*
Skelton and Kavanagh	19	10.49±0.07	*c*
Present		11.4±0.7	*a*
Weighted average of modern results not including ref. 10		10.52±0.06	

[a] ^{7}Be implanted in Si detector from ^{10}B(p, α)^{7}Be reaction; γ yield measured.
[b] ^{7}Be beam implanted in Si detector; γ yield measured.
[c] ^{7}Li(p, n)^{7}Be reaction used; neutron yield measured; γ yield measured.
[d] ^{1}H(^{7}Li, ^{7}Be)n reaction used; ^{7}Be implanted in Si detector in focal plane of magnetic spectrograph; γ yield measured.
[e] Inner bremsstrahlung.
[f] Transition strengths of ^{7}Li(p, n)^{7}Be measured at 0° from 60 to 200 MeV.

energy as a function of γ-ray energy. A weighted linear least squares fit to the data is represented by the straight lines for the two source–detector distances.

The branching ratio was obtained from the equation

$$n_\gamma = \lambda N_0 B_\gamma \epsilon_\gamma \int_{t_1}^{t_2} e^{-\lambda t}\, dt = N_0 B_\gamma \epsilon_\gamma e^{-\lambda t_1}(1 - e^{-\lambda(t_1 - t_2)})$$

where n_γ is the number of counts in the 478-keV peak, N_0 is the number of ^{7}Be atoms implanted, B_γ is the required branching ratio, ϵ_γ is the absolute efficiency for detecting 478-keV γ rays, λ is the constant for ^{7}Be decay, and t_1 and t_2 are the beginning and end of the counting period measured from the end of the bombardment. The time required to produce the activity (13 h) was negligible compared with the ^{7}Be half-life (53.3 d).

The numerical values obtained in the two geometries are summarized in Table 1. The weighted average for B_γ in the two geometries is 11.4 ± 0.7%.

A summary of recent measurements of the ^{7}Be electron capture branching ratio to the first excited state of ^{7}Li is given in Table 2. The present measurement agrees with most of these recent results, but disagrees strongly with the value of B_γ reported by Trautvetter *et al.* (10), which was obtained by a method very similar to the one used in this work. Our value for B_γ agrees within 1.5 standard deviations with the much more precise weighted average of all precise measurements, 1962 to 1974, B_γ = 10.38 ± 0.06 (ref. 9 and references therein) and suggests there is no reason to question its use in deducing the cross section for the ^{3}He + ^{4}He reaction from activation measurements.

Theoretical considerations

The low-lying states of ^{7}Be and ^{7}Li should arise predominantly from the $(1p)^3$ configuration. Using wave functions generated by Kumar's interaction (20), we calculate that the doubly reduced matrix element $\langle \boldsymbol{\tau\sigma} \rangle$ between the lowest T = 1/2, J^π = 3/2$^-$ and 1/2$^-$ $(1p)^3$ states has a value of 5.45, leading to $|M_{GT}|^2$ = 1.24 for the Gamow–Teller (GT) strength in electron capture. If the axial-vector coupling constant G_A appropriate to free neutron decay is used, this leads to an ft value of 3270 s and a 3/2$^-$ → 1/2$^-$ EC branch of 10.3% when the half-life of ^{7}Be is set equal to the known 53.3 d (9).

Such excellent agreement with experiment is probably fortuitous, because neglected wavefunction components lying outside the $(1p)^3$ model space are likely to modify $\langle \boldsymbol{\tau\sigma} \rangle$, and the axial-vector coupling constant in nuclei is believed to be quenched compared with its value in neutron decay. Various authors (21) have obtained estimates of this quenching in a semi-empirical manner by combining the known magnetic moments of mirror pairs with shell-model calculations of the diagonal matrix element $\langle (1 - \boldsymbol{\tau})\boldsymbol{\sigma} \rangle$. Similarly, the effect of uncertainties in calculated quantities for mass 7 can be greatly reduced by making use of the experimental M1 transition strengths between the $1/2^-$ and $3/2^-$ states. The strength depends on $\langle \tau\sigma \rangle$ and, to a much lesser degree, the matrix elements $\langle \boldsymbol{\sigma} \rangle$ and $\langle \boldsymbol{\tau L} \rangle$, since the magnetic moment operator with free-nucleon g factors can be expressed as

$$\boldsymbol{\mu} = 0.5\boldsymbol{J} - 2.355\tau_z\boldsymbol{\sigma} - 0.5\tau_z\boldsymbol{L} + 0.19\boldsymbol{\sigma}$$

and $B(\mathrm{M1}: 1/2^- \rightarrow 3/2^-)$ is given by

$$B(\mathrm{M1}) = \frac{3}{8\pi}(0.96\langle \boldsymbol{\tau\sigma} \rangle + 0.20\langle \boldsymbol{\tau L} \rangle \pm 0.19\langle \boldsymbol{\sigma} \rangle)^2$$

with the plus sign applying to ^{7}Be and the minus sign to ^{7}Li. Hence, assuming a positive phase for $\langle \boldsymbol{\tau\sigma} \rangle$,

$$[B_{\mathrm{Li}}(\mathrm{M1})]^{1/2} - [B_{\mathrm{Be}}(\mathrm{M1})]^{1/2} = \pm 0.13\langle \boldsymbol{\sigma} \rangle$$

and

$$[B_{\mathrm{Li}}(\mathrm{M1})]^{1/2} + [B_{\mathrm{Be}}(\mathrm{M1})]^{1/2} = 0.66\langle \boldsymbol{\tau\sigma} \rangle + 0.14\langle \boldsymbol{\tau L} \rangle$$

The experimental mean lifetimes of the $1/2^-$ states in ^{7}Li and ^{7}Be are 105 ± 5 fs (22, 23) and 196 ± 15 fs (23), giving $B(\mathrm{M1}) = 4.97 \pm 0.24\ \mu_N^2$ and $3.67 \pm 0.26\ \mu_N^2$, respectively. The first equation above, therefore, gives

$$|\langle \boldsymbol{\sigma} \rangle| = 2.4 \pm 0.7$$

if the experimental errors are combined in quadrature. The Kumar interaction gives $\langle \boldsymbol{\sigma} \rangle = -2.25$. The estimate of $\langle \boldsymbol{\tau L} \rangle = 1.85$ provided by this interaction, used in conjunction with the second equation, leads to

$$\langle \boldsymbol{\tau\sigma} \rangle = 5.85 \pm 0.13$$

requiring that G_A be reduced by a factor of $\rho = 0.94 \pm 0.02$ to reproduce the experimental EC branch of 10.4%. The quoted uncertainty does not reflect possible error in the calculated matrix element, but even a 50% change in $\langle \boldsymbol{\tau L} \rangle$ would lead to a change in ρ of only 0.03; if the calculated value of $\langle \boldsymbol{\sigma\tau} \rangle$ were used to determine ρ without making use of the M1 transition rates, even a 3% error in the calculation would give rise to an error of this magnitude in ρ. Therefore, it appears that the observed EC branch implies an axial-vector strength quenching of only a few percent in mass 7, much smaller than that found for many heavier nuclei in the investigations of ref. 21.

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