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^{7}Be decay scheme and the solar neutrino problem

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The decay scheme of ^{7}Be has been reinvestigated. Known numbers of ^{7}Be nuclei were produced in targets via the ^{7}Li(p,n) reaction. Following activation, the yields of 478-keV γ rays from the targets were measured. From three such measurements, performed at different bombarding energies, the ^{7}Be decay branching ratio to the first excited state of ^{7}Li has been determined to be $10.8\pm0.4\,\%$. The implications of this result for the solar neutrino problem are discussed.

[RADIOACTIVITY ^{7}Be: measured I_γ; deduced branching ratio to first excited state in ^{7}Li. Neutron detector. Ge(Li) detector.]

The long-standing discrepancy between the experimental and theoretical values for the solar neutrino flux is one of the outstanding problems in physics. The combined results of nearly ten years of observations by Davis and collaborators[1] have established that the mean capture rate for the ^{37}Cl detector is 1.8 ± 0.9 SNU (3σ uncertainty), where 1 SNU $=10^{-36}$ neutrino captures per target atom per second. Over an even longer period of time, numerous theoretical estimates of the solar neutrino flux have been performed. The most recent calculations by Bahcall *et al.*[2] and Filippone and Schramm[3] yield values of 7.6 ± 3.3 SNU and 7.0 ± 3.0 SNU, respectively, for the ^{37}Cl detector. The cause for this disagreement between experiment and theory continues to be a subject of great interest.

Because of its relatively high threshold energy (0.81 MeV), the ^{37}Cl detector is mainly sensitive to the high energy neutrinos produced by the beta decay of ^{8}B. The production of ^{8}B in the sun is the result of a very small branch of the proton-proton chain, the last four reactions of which are

$$^3\mathrm{He}+{}^4\mathrm{He}\rightarrow{}^7\mathrm{Be}+\gamma\ , \qquad (1)$$

$$^7\mathrm{Be}+p\rightarrow{}^8\mathrm{B}+\gamma\ , \qquad (2)$$

$$^8\mathrm{B}\rightarrow{}^8\mathrm{Be}+e^{+}+\nu\ , \qquad (3)$$

$$^8\mathrm{Be}\rightarrow{}^4\mathrm{He}+{}^4\mathrm{He}\ . \qquad (4)$$

Hence, the ^{37}Cl solar neutrino capture rate is nearly linearly dependent upon the rates for the ^{3}He$(^4$He$,\gamma)^7$Be and ^{7}Be$(p,\gamma)^8$B reactions.[4] The ^{7}Be decay scheme plays a role in some experimental determinations of the cross sections for both of these reactions.

The ^{3}He$(^4$He$,\gamma)^7$Be reaction was studied experimentally in the 1960's by Parker and Kavanagh[5] and by Nagatani, Dwarakanath, and Ashery[6] and was reinvestigated recently by Kräwinkel *et al.*[7] and by Osborne *et al.*[8] In all of these studies, the yields of the capture γ rays were measured in beam. The results of the two early measurements agree reasonably well with each other. However, the recent work of Kräwinkel *et al.*[7] suggests that the cross section factor, $S_{34}(0)$, may be 30—50 % lower than the previous values. If this result were correct, it would substantially reduce the discrepancy between the ex-

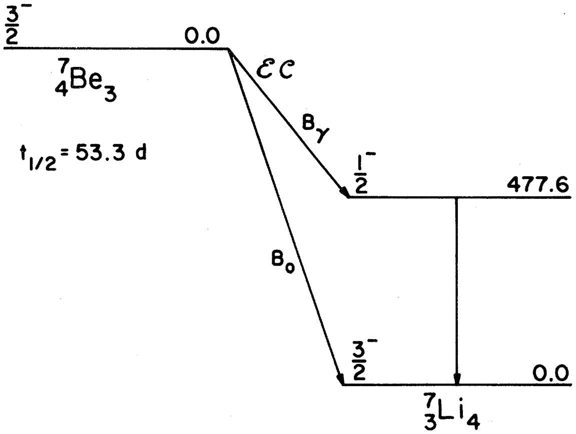

FIG. 1. Decay scheme of ^{7}Be. B_0 and B_γ are the ^{7}Be electron-capture decay percentages to the ^{7}Li ground state and to the 477.6 keV first excited state, respectively.

perimental and theoretical values of the solar neutrino flux. The results of the subsequent measurement by Osborne *et al.*[8] again agree with the early results.

Another technique to determine the ^{3}He(^{4}He,γ)^{7}Be cross section is to measure the ^{7}Be activity following the bombardment. As can be seen in Fig. 1, ^{7}Be electron capture decays with a 53.3 d half-life to the ground state and first excited state of ^{7}Li. Thus by measuring the yield of the 478-keV γ rays from an activated target cell, the ^{7}Be production cross section can be determined. This method was used by Osborne *et al.*[8] and recently by Robertson *et al.*,[9] and both experiments yielded results consistent with those obtained from the early in-beam measurements. Obviously, a parameter which enters the calculation of the ^{3}He(^{4}He,γ) cross section from the 478-keV γ-ray yield is B_γ, the ^{7}Be decay branching ratio to the $J^{\pi}=\frac{1}{2}^{-}$ first excited state of ^{7}Li.

This same branching ratio also plays a role in some measurements of the ^{7}Be(p,γ)^{8}B cross sections. One of the methods that has been used to determine the thicknesses of ^{7}Be targets used in such experiments is to measure the yield of 478-keV γ rays from the targets.[10,11] Again, in order to calculate the number of ^{7}Be nuclei contained in the target from the γ-ray yield, B_γ must be known.

Over the years, B_γ has been measured a number of times by both direct and indirect techniques.[12–22] In the direct B_γ determinations, electron-capture decays to both the ground state and 478-keV excited state of ^{7}Li were observed in measurements of the Auger electron and γ-ray yields. The indirect methods rely on a measurement of the number of ^{7}Be nuclei produced in a target and a separate measurement of the γ-ray yield. The results of these experiments agree remarkably well with one another and yield a mean value of 10.4%.[23] However, Rolfs *et al.*[24] recently reported a value of 15.4±0.8% based upon an indirect measurement. If this result were correct, it would cause the ^{3}He(^{4}He,γ) cross sections obtained by Osborne *et al.*[8] and by Robertson *et al.*[9] in their activation experiments to be reduced by approximately 33%, thus bringing them into closer agreement with the result of Kräwinkel *et al.*[7] On the other hand, if B_γ were 15.4%, then the thicknesses of ^{7}Be targets inferred from γ-ray measurements would have to be reduced, and hence the ^{7}Be(p,γ) reaction rates determined from such measurements would have to be increased by approximately 50%.

Because of its importance in both of these aspects of the solar neutrino problem, we have reinvestigated the decay scheme of ^{7}Be using an indirect activation method. The number of ^{7}Be nuclei produced in a target via the ^{7}Li(p,n) reaction was determined by measuring the neutron yield. Following activation, the target was counted and the yield of the 478-keV γ ray was determined. From three such measurements performed at different proton bombarding energies B_γ was determined.

Targets consisting of approximately 700 μg/cm^{2} ^{7}LiF evaporated onto thick Au backings were bombarded with proton beams of a few nanoamperes from the University of Washington's FN tandem accelerator. At the bombarding energies used in the present experiment, 1.90, 2.10, and 3.50 MeV, the only neutron-producing reaction possible is the ^{7}Li(p,n)^{7}Be reaction. The neutron yield (and hence the number of ^{7}Be nuclei produced in each target) was measured with a large neutron detection system, the details of which will be described elsewhere.[25] Briefly, the system consists of ten ^{3}He-filled proportional counters that are imbedded in a 1.5-m diameter graphite moderator which surrounds the target area. The detectors are oriented perpendicular to the beam direction and are positioned around the surface of a half-cylinder. The beam is stopped in the target assembly and the outgoing neutrons are moderated in a 15-cm diameter iron sphere immediately surrounding the target and in the large graphite pile.

Four different techniques were used to measure the detection efficiency of this system. Three of these methods measured the absolute efficiency averaged over three different energy intervals while the fourth method determined the relative efficiency as a function of neutron energy. Two of the measurements involved the use of calibrated neutron sources, a ^{252}Cf fission source calibrated to ±3% and a ^{238}Pu-^{13}C source calibrated to ±10%. We emphasize that both of these sources had been calibrated by techniques independent of the ^{7}Be decay scheme. Each source was placed at the normal target position and counting was done for a measured period of time. The third absolute efficiency determination was obtained by placing a thick PbF$_2$ target in the target position and bombarding it with a beam of 2 nA of 10.0-MeV alpha particles. At this bombarding energy, the only significant neutron

TABLE I. Results of neutron detector efficiency measurements.

Neutron source		Efficiency (%)
^{238}Pu-^{13}C		5.69±0.57
^{19}F(α,n)^{22}Na		5.32±0.29
^{252}Cf		5.49±0.27
	Weighted mean	5.45±0.18

TABLE II. Results of the present measurements of B_γ using the ^{7}Li(p,n) reaction.

E_p (MeV)	Mean E_n (MeV)	B_γ (%)
1.90	0.05	11.2±0.5
2.10	0.20	10.8±0.4
3.50	1.29	10.6±0.4
	Weighted mean[a]	10.8±0.4

[a] Uncertainty in mean value includes systematic 3.3% uncertainty in ^{7}Be reference source calibration.

production mechanism is the ^{19}F$(\alpha,n)^{22}$Na reaction. The neutron yield from a Pb target was measured and was found to be negligible at 10 MeV. The neutron yield from the PbF$_2$ was measured and following the bombardment, the ^{22}Na activity in the target was determined by measuring the yield of 1275-keV γ rays with a well-shielded Ge(Li) detector. The efficiency of the Ge(Li) detector at this energy was determined with two calibrated (±5%) ^{22}Na sources obtained from New England Nuclear. Finally, by dividing the observed neutron yield by the number of ^{22}Na nuclei produced in the target, the neutron detection efficiency was obtained. The results of these three measurements are summarized in Table I.

Each of the above-mentioned efficiency measurements involved neutrons with continuous energy spectra, from a few keV up to several MeV. To measure the dependence of the efficiency on the neutron energy, we bombarded a tritium target with 2–6 MeV protons. At low bombarding energies, the neutrons produced by the ^{3}H(p,n) reaction are emitted in a fairly narrow energy range. Thus, as the proton energy was varied, the mean neutron energy was varied from approximately 0.7 to 3 MeV. The observed neutron yields were divided by the known ^{3}H(p,n) cross sections[26] to obtain the detector efficiency. The results of these measurements showed that the efficiency varies by less than 15% over this energy range. Furthermore, a Monte Carlo calculation of the efficiency was performed utilizing a three-dimensional model of the detector. These calculations suggest that the efficiency varies by no more than 10% over the range of neutron energy 1–3 MeV.

Following the ^{7}Li(p,n) activations, each target was counted with a well-shielded 79 cm^3 Ge(Li) detector and the yield of the 478-keV ^{7}Be γ ray was measured. The efficiency of the Ge(Li) detector at this energy was determined with a ^{7}Be source from Isotope Products Laboratories whose γ-ray emission rate had been calibrated to ±3.3%. Additional checks on the γ-ray detection efficiency were made with a number of standard calibrated sources. Dividing the observed γ-ray yield by the inferred number of ^{7}Be nuclei in each target thus yields the ^{7}Be decay branching percentage to the 477.6-keV level in ^{7}Li. The results of this procedure are summarized in Table II. The mean value obtained from the three measurements of B_γ is 10.8±0.4%. The uncertainty in the mean value includes both statistical and systematic errors.

In Table III, the results of the present experiment are compared with previous measurements of B_γ. As can be seen, the present results are in good agreement with the early measurements, but definitely do not agree with the recent measurement of Rolfs *et al.*[24] We do not have an explanation for this discrepancy. However, we feel that the combined

TABLE III. Results of present and previous measurements of B_γ.

Author	Year	Method[a]	B_γ (%)
Rumbough *et al.* (Ref. 12)	1938	*A*	10^{+20}_{-7}
Williamson and Richards (Ref. 13)	1949	*B*	10.7 ±2.0
Turner (Ref. 14)	1949	*B*	11.8 ±1.2
Dickson and Randle (Ref. 15) (reevaluation of Turner)	1951		12.3 ±0.6
Taylor and Merritt (Ref. 16)	1962	*C*	10.32±0.16
Poenitz (Refs. 17 and 18)	1966	*B*	10.5 ±0.2
Mutterer (Ref. 19)	1970	*C*	10.47±0.20
Szabo *et al.* (Ref. 20)	1972	*D*	10.4 ±0.3
Poenitz and DeVolpi (Ref. 21)	1973	*B*	10.42±0.18
Goodier *et al.* (Ref. 22)	1974	*C*	10.35±0.08
Rolfs *et al.* (Ref. 24)	1982	*D*	15.4 ±0.8
Present work	1982	*B*	10.8 ±0.4

[a] Indirect: (*A*) Measured neutron yield from ^{6}Li(d,n) and γ yield; (*B*) measured neutron yield from ^{7}Li(p,n) and γ yield; (*D*) measured α yield [and ^{7}Be yield (Ref. 24)] from ^{10}B(p,α) and γ yield. Direct: (*C*) Measured Auger-electron yield and γ yield.

results of ten independent experiments, using several different techniques, support a value of B_γ of approximately 10.4%. This was the value used by Osborne *et al.*[8] and by Robertson *et al.*[9] in the analysis of their activation experiments. Thus the ^{3}He(^{4}He,γ) cross section factors determined in their two experiments are in good agreement with each other and with the results of Parker and Kavanagh[5] and Nagatani *et al.*[6] This same value of B_γ was used in the ^{7}Be target thickness measurements of Wiezorek *et al.*[10] and Filippone *et al.*[11] Thus, no changes are required in the results they obtained for the ^{7}Be(p,γ) cross sections. The discrepancy between the experimental and theoretical values for the solar neutrino flux, therefore, remains a tantalizing puzzle.

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