PHYSICAL REVIEW C VOLUME 27, NUMBER 4 APRIL 1983

Final state branching ratio in the ^{7}Be decay

D. P. Balamuth, L. Brown,* T. E. Chapuran, J. Klein, R. Middleton, and R. W. Zurmühle
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 13 December 1982)

The fractional decay branch in the EC decay of ^{7}Be leading to the first excited state of ^{7}Li has been measured. ^{7}Be ions from a beam produced by a tandem Van de Graaff accelerator were implanted into a surface-barrier detector; the decay γ rays were then counted using a well-shielded Ge(Li) detector of known absolute efficiency. The resulting decay branch, $(10.10\pm0.45)\%$, is in good agreement with previously published values and in strong disagreement with a recent measurement.

[RADIOACTIVITY ^{7}Be; measured I_γ; deduced branching ratio to first excited state in ^{7}Li.]

I. INTRODUCTION

The fraction of ^{7}Be decays resulting in a 478 keV γ ray from the first excited to the ground state of ^{7}Li is of interest because of its relevance to the determination of the cross section for the reaction

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

at energies low enough to permit reliable extrapolation to solar temperatures. This reaction is directly involved in the production of ^{8}B, which is responsible for practically all of the solar neutrinos detected in the Davis experiment.[1] The accurate determination of this cross section is thus important as a potential means of resolving the well-known solar neutrino puzzle. Despite its importance, two measurements of the capture cross section reported within the past year[2,3] differ by more than 70%, well outside the quoted errors.

The direct measurement of the capture γ rays poses severe technical difficulties because of the very small cross sections, as can be surmised from the severe disagreement between the results obtained in Refs. 2 and 3. An alternative method of measuring the capture cross section (1) is to count the residual ^{7}Be activity using the 478 keV γ ray from the branch to the first excited state of ^{7}Li. Two recent measurements of the capture cross section using this method[2,4] give essentially the same result; if the branching ratio in the EC decay is taken as the currently accepted[5] value of $(10.37\pm0.12)\%$, these measurements agree with the Caltech results (Ref. 2) and disagree with those of the Münster group (Ref. 3).

Knowledge of the branching ratio is clearly critical for interpreting measurements of the capture cross section using the ^{7}Be decay. Consequently recent reports of a measurement[6] by Rolfs *et al.* implying a significantly higher decay branch $[(15.4\pm0.8)\%]$ to the first excited state of ^{7}Li have generated a good deal of interest. Revision of the branching ratio upward would of course reduce the deduced value of the capture cross section and tend to favor the results of Ref. 3.

Previous measurements of the branching ratio have involved more or less indirect determinations of the source strength, either by detecting the neutrons in a 4π detector following the ^{7}Li(p,n) reaction[7] or by detecting low-energy Auger electrons[8] following the electron capture itself. In contrast, in Ref. 6 the ^{7}Be ions were produced in a nuclear reaction and implanted into a silicon surface-barrier detector, which was then removed to a shielded environment where the 478 keV γ rays were counted. In the present study we have adopted an approach similar to that used in Ref. 6; however, instead of using a nuclear reaction (which produces copious amounts of particles other than ^{7}Be, thereby requiring the subtraction of a non-negligible background) we have produced a monoenergetic beam of ^{7}Be ions in a tandem Van de Graaff accelerator. This method has the advantage that the high energies and low backgrounds involved make identification of the ^{7}Be ions quite straightforward and the counting very accurate.

The experimental techniques used in the present study are described in Sec. II, including the method of calibrating the efficiency of the Ge(Li) detector used for counting the γ rays. The results of the measurements are given in Sec. III, including a comparison with previous work.

II. EXPERIMENTAL PROCEDURE

The apparatus used to produce and accelerate a beam of ^{7}Be ions is identical to that used for the neighboring long-lived isotope ^{10}Be and has been previously described.[9] In the present measurements charge state +4 was selected for momentum analysis by the 90° magnet to reduce background associated with trace impurities of ^{7}Li in the source material. Examination of an E-ΔE plot using an ionization-chamber—solid-state counter telescope showed that all particles passing through the magnetic analysis were ^{7}Be ions; background levels were less than 0.1%. Once the purity of the beam was established, the counter telescope was replaced by a 200 mm^2 silicon surface barrier detector which was collimated by a stainless-steel aperture of diameter 6.35 mm. At this point 1.009×10^8 ions were implanted into the detector. The energy spectrum of the implanted ions was continuously monitored, and was observed to be essentially constant at all times during the implantation. The number of ions was counted by differentiating the output of a charge-sensitive preamplifier (time constant 20 ns) using a fast timing filter amplifier and sending the resulting pulses into a fast integral discriminator. The electronic circuitry was independently determined to have a dead time of approximately 350 ns per event using pulses from a ^{241}Am α source at a rate of approximately 20000 Hz. The actual count rate during the implantation of the ^{7}Be ions was approximately 6000 Hz, resulting in a (negligible) dead time of 0.2%.

Immediately following the implantation the silicon wafer was removed from its case and accurately located in front of a 65 cm^3 Ge(Li) detector. The detector was surrounded by approximately 5 cm of Pb shielding. A γ spectrum showing the 478 keV line is shown in Fig. 1; this spectrum is the result of counting for 44 hours. The background was determined to be essentially flat by counting for a 24 hour period with an unirradiated silicon detector substituted for the irradiated one. In the actual data reduction a linear background subtraction was employed.

In order to deduce the branching ratio from the number of counts in the γ spectrum of Fig. 1 it is necessary to know the absolute efficiency of the Ge(Li) detector for 478 keV photons. This quantity was measured using a ^{207}Bi source mounted in the same geometry as the silicon detector and with the radioactive material confined to a spot approximately 6 mm in diameter (designed to simulate the actual conditions for counting the ^{7}Be γ rays). The decay scheme of ^{207}Bi involves a cascade in which a 1.064 MeV γ ray is always followed by a 0.5697 MeV transition.[10] The apparatus used to determine the efficiency is illustrated schematically in Fig. 2. Briefly, the total number of counts in the 1.06 MeV full energy peak in detector 1 (N_s) was compared to the number of coincidences (N_c) with a 1.06 MeV photopeak count in detector 1 and a 0.57 MeV photopeak count in detector 2. The absolute photopeak efficiency of detector 2 at E_γ = 570 keV is then given by

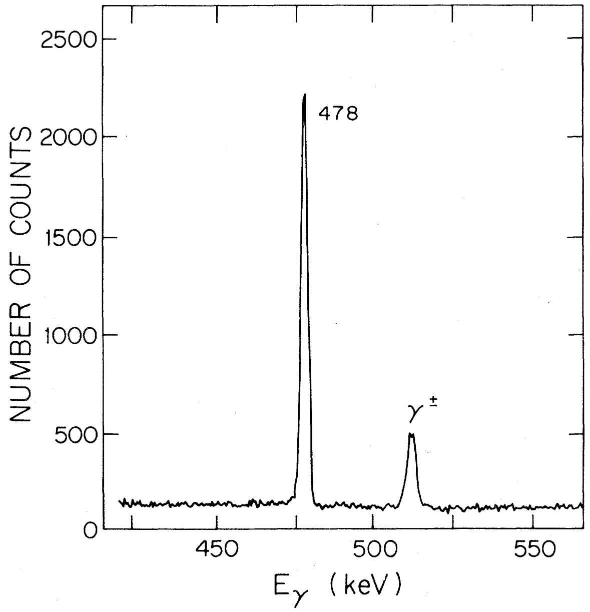

FIG. 1. Spectrum of 478 keV γ rays from the decay of ^{7}Be ions implanted into a silicon detector.

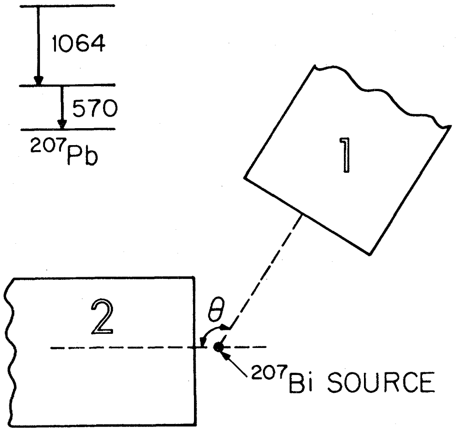

FIG. 2. Schematic diagram of apparatus used in the determination of the efficiency of the counting arrangement used to obtain the spectrum of Fig. 1.

$$\epsilon = \frac{N_c f_{\text{pu}} f_{\text{ic}}}{N_s f_{\text{sum}}} \tag{2}$$

where f_{pu}, f_{ic}, and f_{sum} are small corrections which are described below.

Coincidence losses resulting from pulse pileup in detector 2 were measured by sending artificial coincidences from a pulser into the test inputs of both preamplifiers simultaneously; these losses were approximately 2.5%; the shaping times for the linear signals digitized by the computer were deliberately shortened to 0.5 μs to reduce the effects of pileup. The factor f_{pu} is the appropriate correction for pileup effects.

The angular correlation of the two γ rays is known to have only the $k = 2$ term appreciably different from zero.[11] The effect of the angular correlation on the efficiency measurement can therefore be minimized by setting $\vartheta = 125°$ (see Fig. 2). This was done in the present study; in addition, the angular correlation was checked experimentally by making measurements at $\vartheta = 180°$. The results were in good agreement with the known[11] angular correlation.

A small correction (2.2%) is also necessary for internal conversion of the 570 keV $E2$ transition; this was taken from Ref 10. f_{ic} is the appropriate correction to the efficiency. Finally, the factor f_{sum} corrects for the counts (about 2.3%) which are lost from the singles because of coincident detection of both γ rays in detector 1;

$$f_{\text{sum}} = \frac{1}{1-\epsilon_{\text{tot}} W(0°)}, \tag{3}$$

where ϵ_{tot} is the total efficiency of detector 1 for 570 keV photons and $W(0°)$ is the normalized γ-γ angular correlation function evaluated at 0°. This correction was calculated from the known[12] total absorption coefficients of Ge and the nominal detector geometry. As an additional check, the sum peak at $E_\gamma = 0.57 + 1.064$ MeV was examined and gave consistent results. Once the efficiency at 570 keV is known, the value at a γ ray energy of 478 keV can be obtained by measuring the detector response as a function of energy. This quantity was determined using a ^{154}Eu source in the actual counting geometry. The required relative intensities were taken from the work of Roney and Seale.[13] The data were fitted to an efficiency function of the form

$$\epsilon(E_\gamma) = A E_\gamma^{-B}. \tag{4}$$

Only the five strongest lines above $E_\gamma = 200$ keV known (from the decay scheme) to be free from significant summing contributions were used in the calibration. Summing effects were also checked by varying the source-to-detector distance; only small changes (1–2%) in the exponential parameter were found, consistent with previous measurements[14] using single γ-ray sources and a similar detector geometry. The correction to the efficiency resulting from the difference in γ ray energies is found to be

$$\frac{\epsilon(E_\gamma = 478\ \text{keV})}{\epsilon(E_\gamma = 570\ \text{keV})} = 1.20 \pm 0.02. \tag{5}$$

It should be emphasized that the aim of the present study was not to improve on the precision of previous measurements,[7,8] but rather to investigate the (spectacular) disagreement of the results of Ref. 6 with earlier work. The principal advantage of the present technique is the relatively easy preparation of a source with a very accurately known number of atoms. Clearly the errors associated with counting the decay γ rays dominate the resulting experimental errors, and could be reduced by improving the experimental arrangement, e.g., by using a large well detector.

III. RESULTS

The efficiency of the Ge(Li) detector for the full energy peak at $E_\gamma = 478$ keV obtained using the above procedure is $(4.64 \pm 0.19)\%$. The quoted experimental errors include counting statistics, uncertainties in extracting the relevant peak areas, and an estimated ±0.5 mm uncertainty in the geometrical positioning of the radioactive source. (The effect of positional uncertainty was checked directly by varying the source-to-detector distance.) The average counting rate from the ^{7}Be source, corrected for decay, was found to be $7.12 \pm 0.15 \times 10^{-2}$ counts per second. The branching ratio then follows from the relationship

$$f = \frac{dN}{dt}(t=0) \Big/ \lambda N_0 \epsilon, \tag{6}$$

where f is the branching ratio to the excited state, $(dN/dt)(t=0)$ is the count rate corrected for decay, λ is the usual decay constant, N_0 is the number of atoms present at $t = 0$, and ϵ is the detector efficiency. This leads to a branching ratio $f = (10.10 \pm 0.45)\%$, where statistical and systematic errors have been combined in quadrature. This is in good agreement with the more precise values of $(10.42 \pm 0.18)\%$ (Ref. 7) and $(10.35 \pm 0.08)\%$ (Ref. 8) obtained in two recent measurements.

The results of the present measurements thus strongly contradict the suggestion[6] in the work of Rolfs *et al.* that the previously measured branching ratio is in error, and thus indirectly support the larger value of the ^{3}He + ^{4}He capture cross section as measured in Ref. 2.

This work was supported by the National Science Foundation.

---

[*] Permanent address: Department of Terrestrial Magnetism, Carnegie Institution, Washington, D.C.

[1] For a review of the relevance of the ^{3}He + ^{4}He capture cross section see Refs. 2 and 3 below and additional references therein.

[2] J. L. Osborne *et al.*, Phys. Rev. Lett. 48, 1664 (1982).

[3] H. Kräwinkel *et al.*, Z. Phys. A304, 307 (1982).

[4] R. G. H. Robertson *et al.*, Phys. Rev. C 27, 11 (1983).

[5] F. Ajzenberg-Selove, Nucl. Phys. A320, 1 (1979); and (unpublished).

[6] C. Rolfs *et al.* (unpublished).

[7] Ian W. Goodier *et al.*, Int. J. Appl. Rad. Isotopes 25, 373 (1974).

[8] W. P. Poenitz and A. Devolpi, Int. J. Appl. Rad. Isotopes 24, 471 (1973).

[9] J. Klein *et al.*, Nucl. Instrum. Methods 193, 601 (1982).

[10] *Table of Isotopes,* 7th ed., edited by C. Michael Lederer and Virginia S. Shirley (Wiley, New York, 1978).

[11] F. T. Avignonne and T. A. Girard, Phys. Rev. C 23, 2067 (1976).

[12] J. B. Marion and F. C. Young, *Nuclear Reaction Analysis* (North-Holland, Amsterdam, 1968), p. 65.

[13] W. M. Roney, Jr. and W. A. Seale, Nucl. Instrum. Methods 171, 389 (1980).

[14] Kiyrshi Kawade *et al.*, Nucl. Instrum. Methods 190, 101 (1981).