Measurement of the electron capture branching ratio of ^{7}Be

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The value of the electron capture branching ratio of ^{7}Be to the 478 keV state in ^{7}Li has been measured using sources of determinable intensity fabricated by capturing in silicon surface barrier detectors ^{7}Be recoils from the ^{10}B(p,α)^{7}Be reaction at $E_p=1.5$ MeV and 4.5 MeV. Results from independent measurements utilizing detectors implanted in a scattering chamber and in the focal plane of a magnetic spectrograph are in good agreement. An absolute determination of the rate at which the 478 keV gamma rays were emitted from each source yielded a weighted average value of $10.6\pm0.5\%$ for the branching ratio. This result is in agreement with the previously accepted value of $10.37\pm0.12\%$ and does not support the recent suggestion that the branching ratio is appreciably larger.

[RADIOACTIVITY ^{10}B(p,α)^{7}Be, $E=1.5,4.5$ MeV; enriched target; measured $I_{^7\mathrm{Be}}$; silicon surface barrier detector; measured E_γ, I_γ; Ge(Li) detector; deduced branching ratio of ^{7}Be to 478 keV state in ^{7}Li.]

The results of many investigations depend on the magnitude of the electron capture branching ratio of ^{7}Be in the determination of absolute cross sections. Recently, Rolfs *et al.*[1] questioned the magnitude of this branching ratio, suggesting that it could be appreciably larger than the previously accepted value[2] of $10.37\pm0.12\%$. Because significant measurements relying on this branching ratio disagree with results obtained by other methods, there is renewed interest in determining this quantity by new techniques. One such disagreement exists in the magnitude of the cross section for the ^{3}He(α,γ)^{7}Be reaction at low energies, a key reaction in the production of the neutrinos to which the ^{37}Cl detection experiment[3,4] is especially sensitive. While some of the ^{3}He(α,γ) cross section determinations depend on direct measurement of the total gamma ray yield, others are normalized using the ^{7}Be yield determined through the decay of the 478 keV state in ^{7}Li produced by electron capture of ^{7}Be ($T_{1/2}=53.3$ d). The latter technique relies on the ^{7}Be branching ratio, which if different, would affect the corresponding ^{3}He(α,γ)^{7}Be reaction cross section measurement. This branching ratio is also of importance for reactions of astrophysical interest involving a ^{7}Be target and in the determination of the absolute efficiency of neutron detectors at low and intermediate energies. This paper reports a new measurement of this branching ratio using a modification of the basic technique proposed by Rolfs *et al.*[1] to circumvent many of the difficulties that could have influenced the earlier determinations.

We used the ^{10}B(p,α)^{7}Be reaction to fabricate a ^{7}Be radioactive source of determinable strength, taking advantage of the reaction kinetics to liberate the ^{7}Be recoil ions from a thin ($20-30$ μg/cm^2) self-supporting enriched ^{10}B target. To determine the intensity of the radioactive source, the ^{7}Be recoils associated with the ground state (^{7}Be$_0$) and first excited state (^{7}Be$_1$) were implanted in silicon surface barrier detectors and pulse height spectra acquired during the entire bombardment. The measurement of the strength of the 478 keV gamma rays emitted in the decay of ^{7}Li produced by the electron capture decay of the ^{7}Be implanted in the detector then leads to a determination of the electron capture branching ratio. We have used this general technique in a scattering chamber at the Ohio State accelerator at $E_p=1.5$ MeV, $\theta=75°$ to replicate the Rolfs *et al.*[1] conditions. At this energy, however, the ^{7}Be ion energy is low (<1 MeV) so that the recoils are implanted near the surface of the material (<5 μm). If these recoils later diffuse out of the material, one obtains a branching ratio that is too low. To increase the implantation depth, we repeated the measurements at $E_p=4.5$ MeV, where the reaction cross section reaches another maximum.[5] Further, in an independent measurement, the broad range magnetic spectrograph at the Notre Dame tandem accelerator was used to implant ^{7}Be nuclei in a silicon detector located at the focal plane.

To achieve ^{7}Be source strengths approaching 2×10^8 nuclei while using ^{10}B targets sufficiently thin to permit comparatively easy egress of the recoils from the target, beam currents of a few μA are needed to restrict the implantation period to a few days. However, at such currents, other reaction products, mainly the elastic protons from the ^{10}B and contaminant nuclei in the target, produce detector count rates that result in appreciable pileup effects in the detector electronics and dead time effects in the pulse height analyzer [here, a LeCroy 3500 system with fast 3511 analog-to-digital converters

(ADC's)]. Those effects make difficult the determination of the ^{7}Be integrated flux from the raw pulse height spectrum of the implanted detector. To circumvent this, two 500 μm detectors were used simultaneously during each of our four scattering chamber implantations: an implanted detector located at 75° with a 3.6 msr solid angle and a monitor detector located at 105° or 60° with a smaller ($\sim\frac{1}{40}$) solid angle. We determined the normalization factor between the two detectors at low beam currents (typically 50 nA) immediately prior to the actual implantation, by using the ratio of yields for both the well isolated ground state alpha group (α_0) and the two overlapping ^{7}Be peaks.

Figures 1(a) and (b) document the quality of the data at 1.5 MeV characteristic of the low count rate normalization runs in the implanted and monitor detectors, respectively. Electronic pileup and dead time effects for both detectors were monitored continuously by using a pulser signal, which was both scaled and fed to each preamplifier at amplitudes appreciably higher than those of any of the reaction products. During the detector normalization runs, the effects due to pileup and dead time totaled $<2\%$ for the implantation detector and were negligible for the monitor detector. The corresponding effects during the implantation made at beam currents of 1 to 4.5 μA were 25–60 % for the implanted detector and 2–6 % for the monitor detector. In Fig. 1(c), the pulse height spectrum for the monitor detector, recorded for the entire implantation, illustrates that the quality of the original normalization spectrum [Fig. 1(b)] was preserved throughout the bombardment. The number of ^{7}Be nuclei deposited in the monitor detector was determined using the laboratory computer by subtracting a smooth background from under the peaks. This number, normalized as above, yielded the total number of ^{7}Be nuclei implanted in the 75° detector. The final data taken at Ohio State are based on two detectors implanted at $E_p=1.5$ MeV, and two additional detectors implanted at $E_p=4.5$ MeV, all using this monitor detector normalization procedure. For these, implantation times ranged from 24 to 48 h.

To explore the sensitivity of this measurement to electronic pileup, we show in Fig. 2 several additional spectra for the implanted detector, recorded at 1.5 MeV. Figure 2(a) shows the spectrum for a detector implanted with 1.56×10^8 ^{7}Be nuclei at $I_p\approx1.3$ μA; Fig. 2(b) shows another with 1.6×10^8 ^{7}Be nuclei but acquired at about triple the count rate ($I_p\approx4.5$ μA). Comparison of these spectra, which have comparable integrated flux, illustrates well the deterioration in the quality of the pulse height spectrum with respect to beam current due to electronic pileup effects. Figure 2(c) shows the spectrum of the latter detector after being implanted with an additional 6.4×10^8 ^{7}Be nuclei at $I_p\approx4.5$ μA. There is little further deterioration in the quality of the spectrum even with a fivefold increase in the integrated particle flux. What is significant, however, is that without compensation for pileup effects, all spectra in Fig. 2 would yield an underdetermination of the actual number of ^{7}Be nuclei implanted in the detector. Even the spectrum in Fig. 2(a), that might appear to be of reasonable quality from which to extract the number of ^{7}Be nuclei, yields without correction about 30% fewer ^{7}Be nuclei than obtained using the above normalization technique.

At Notre Dame, we implanted at $E_p=4.5$ MeV a 300 μm silicon detector placed in the focal plane of the Notre Dame spectrograph with ^{7}Be recoils in the $q=3$ charge

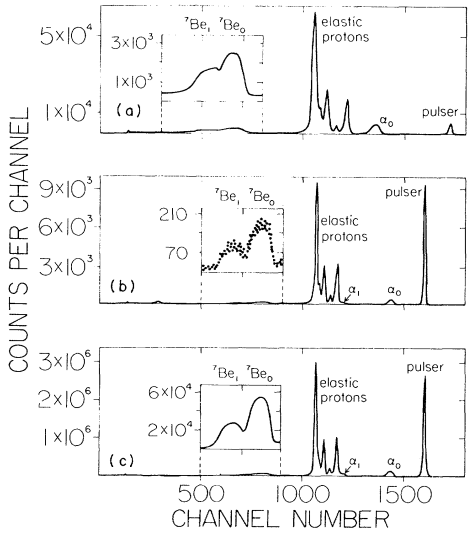

FIG. 1. Sample spectra of the ^{10}B(p,α)^{7}Be reaction at 1.5 MeV obtained with detectors in a scattering chamber. The inserts show an expanded view of the ^{7}Be recoil peaks. (a) and (b) are examples of the low count rate spectra for the implanted and monitor detectors, respectively, used to determine the normalization factor between the two detectors. (c) shows the spectrum for the monitor detector recorded over an entire implantation run.

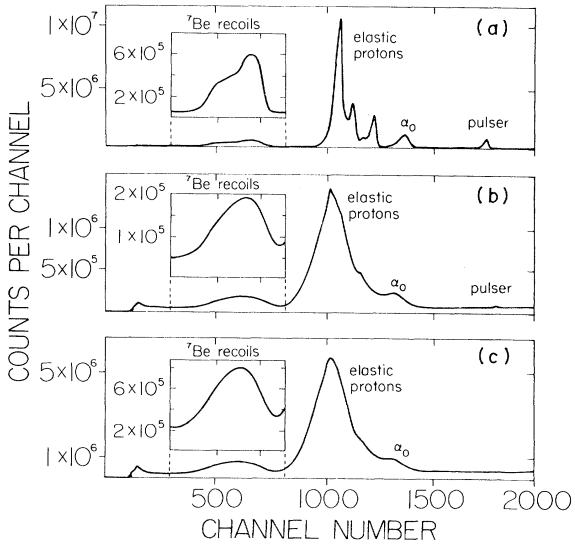

FIG. 2. Spectra for the ^{10}B(p,α)^{7}Be reaction at 1.5 MeV from implanted detectors. (a) Detector implanted with 1.56×10^8 ^{7}Be nuclei at $I_p\approx1.3$ μA. (b) Detector implanted with 1.6×10^8 ^{7}Be nuclei at $I_p\approx4.5$ μA. (c) Detector in (b) with a total of 8×10^8 ^{7}Be nuclei implanted at $I_p\approx4.5$ μA. Note that the quality of the spectrum is primarily a function of beam current, not the total integrated flux.

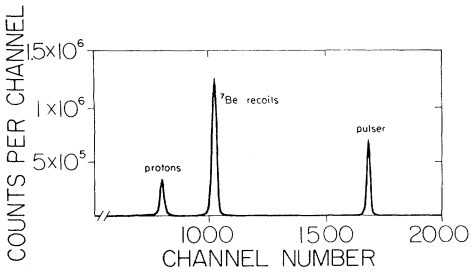

FIG. 3. The spectrum obtained at $E_p = 4.5$ MeV for the $^{10}B(p,\alpha)^7Be$ reaction using a magnetic spectrograph, set such that ^7Be in the $q = 3$ charge state would be implanted in the detector. The proton peak is due to slit-scattered protons (see the text).

state emitted at $\theta = 20°$. The measurement was made possible by running the spectrograph in the high solid angle (QQD) mode.[6] Here, because the elastically scattered protons cannot strike the detector, electronic pileup and dead time effects were reduced to $<4\%$ in the implanted detector. This technique also permitted us to explore the characteristics of the detector response to low energy ^7Be nuclei, in particular, to determine the shape of the ^7Be peak and assess whether straggling or pulse height tails occur which could result in an underestimation of the total ^7Be yield in our scattering chamber implantations. The pulse height spectrum taken with the spectrograph is shown in Fig. 3. Although the ^7Be peak is quite isolated with negligible tails, a second peak is present. The latter was determined to be slit scattered protons by comparison with measurements on a carbon target and from a later bombardment on a ^{10}B target using nuclear emulsions. The ^7Be nuclei formed well defined groups at the calculated positions, whereas the protons were a continuous background along the entire plate. Because the ^7Be ions leave the ^{10}B target in primarily three charge states (the $q = 3$ charge state is about 50% of the total[7] at 4.5 MeV) and the spectrograph selects a single ^7Be group, the total implanted yield for this bombardment was only 4.9×10^7 ^7Be nuclei using the available beam current ($\sim 1\ \mu A$).

Immediately following each bombardment, the implanted ^7Be detector was placed inside a totally shielded lead house. The 478 keV gamma rays resulting from the decay of the first excited state of ^7Li were detected with a nominal 25% efficient Ge(Li) detector. For this, the implanted detector was generally placed at a separation distance of 10 cm from the front face of the Ge(Li) detector, except in the case of the spectrograph implanted detector, where the lower source strength necessitated a 5 cm separation distance. The absolute efficiency of the Ge(Li) detector was determined using calibrated (5% absolute) sources of ^{133}Ba, ^{137}Cs, and ^{22}Na obtained from Amersham Searle. The calibration of our γ detection system was made for each of the five independent branching ratio determinations reported in this paper. The internal consistency of these sources was better than the stated absolute accuracy. Since ^7Be might diffuse out of the silicon, the plastic cap provided with each detector was placed over it after implantation. Furthermore, from the intermediate γ spectra recorded and stored on a magnetic disk during the gamma counting phase, there was no evidence for ^7Be diffusion losses over a period of two weeks. Finally, to assess possible gamma ray contaminant lines, the lead house was counted with the implanted detectors removed. No evidence for a gamma peak in the region of interest was observed.

TABLE I. Results of ^7Be electron capture branching ratio measurements.

Method	E_p (MeV)	Total ^7Be yield	Branching ratio (%)
Scattering chamber	1.5	8.9×10^{8a}	9.3±0.9
	1.5	1.56×10^{8a}	11.1±0.8
	4.5	4.0×10^{8a}	11.5±0.7
	4.5	4.8×10^{8a}	10.3±0.7
Weighted average			10.9±0.7
Spectrograph	4.5	4.9×10^7	10.5±0.6
Total weighted average			10.6±0.5

[a]Normalized (see the text).

Each source (implanted detector) was counted independently two to four times over a two week period with corrections made for the half-life of the ^7Be. The final results for each of the five separate implanted detectors are presented in Table I. Typical contributions to the quoted uncertainties, which were combined in quadrature, are (where applicable): the ^7Be normalization procedures (6%), the uncertainty in the analysis of the ^7Be spectrum (5%), the statistical accuracy associated with the gamma detection (2–5%), and the absolute efficiency of the Ge(Li) detector (6%). The weighted average (calculated considering the systematic errors separately) of the four values of the branching ratio using the scattering chamber technique is 10.9±0.7%. This is in quite good agreement with the 10.5±0.6% value obtained in the independent spectrograph determination. The final weighted average of both techniques is 10.6±0.5%, consistent with the accepted value[2] of 10.37±0.12%. Since submission of our paper, other measurements[8–11] of this branching ratio have been reported, all of which are in agreement with our results. Thus, it would appear that the source of the discrepancy[12–14] in the $^3He(\alpha,\gamma)^7Be$ cross section at astrophysical energies must lie elsewhere.

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