

β -decay measurements of ^{12}B with Gammasphere

M. Alcorta^{1,a}, H. O. U. Fynbo², M. Albers¹, S. Almaraz-Calderon¹, P. F. Bertone^{1,b}, P. F. F. Carnelli³, M. P. Carpenter¹, C. J. Chiara^{1,4}, B. DiGiovine¹, J. P. Greene¹, C. R. Hoffman¹, R. V. F. Janssens¹, T. Lauritsen¹, K. L. Laursen², S. T. Marley^{1,5,c}, C. Nair¹, O. Nusair¹, K. E. Rehm¹, D. Seweryniak¹, C. Ugalde^{1,6,7}, and S. Zhu¹

¹Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

²Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark

³Laboratorio Tandar, Comisión Nacional de Energía Atómica, B1650KNA Buenos Aires, Argentina

⁴Department of Chemistry and Biochemistry, University of Maryland, College Park, MD 20742, USA

⁵Physics Department, Western Michigan University, Kalamazoo, MI 49008, USA

⁶Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA

⁷Joint Institute for Nuclear Astrophysics, Chicago, IL 60637, USA

Abstract.

The β -decay branching ratio of ^{12}B to the Hoyle state in ^{12}C was measured by detection of γ rays. ^{12}B nuclei were produced via the $^{11}\text{B}(\text{d,p})^{12}\text{B}$ reaction in inverse kinematics on a TiD_2 target. The present results corroborate those obtained recently for the β branch by implantation. The value from both experiments is inconsistent with that accepted in the literature.

1 Introduction

Recent measurements of the β branch of ^{12}B to the Hoyle state in ^{12}C give a value of 0.58(2)% [1], about half that found in the literature (although in ref. [2] the value given is 1.5(3)%, in ref. [3] an argument is given for updating the literature value to 1.2(3)%). This branching ratio is important for understanding the R-Matrix fits of excitation energies in ^{12}C between 9 and 13 MeV. Accurate fits to the data are necessary in order to fully disentangle the different states of natural spin and parity in the region, which is key in the search for the 2^+ excitation built on the Hoyle state [4].

The method used to determine the β branch of ^{12}B to the Hoyle state in ref. [1] consisted of directly implanting the ^{12}B nuclei into a highly-segmented Si detector, thus measuring the sum of the three α energies emitted in the subsequent decay. It is important to verify this result using an independent method. This manuscript reports on a coincidence measurement of the γ branch of the Hoyle state (a cascade going through the 4.44 MeV, 2^+ state) using Gammasphere (GS) at ATLAS. By accurately measuring the γ cascade, the β branch to the Hoyle state can be determined using the following relation:

^ae-mail: malcorta@gmail.com

^bPresent address: Marshall Space Flight Center, Huntsville, Alabama 35811, USA

^cPresent address: Physics Department, University of Notre Dame, Notre Dame, Illinois 46556, USA

$$\text{BR}(7.65) = \text{BR}(4.44) \cdot \frac{N_{\gamma\gamma}}{N_{4.44} \cdot \epsilon_{3.21}} \frac{1}{C_{\theta} \cdot \Gamma_{\gamma}/\Gamma} \quad (1)$$

where BR(4.44) is the branching ratio of 1.28(4)% [2] to the 4.44 MeV state in ^{12}C . The efficiency of the 3.21-MeV γ ray, $\epsilon_{3.21}$, was determined for this experiment. C_{θ} , a correction factor allowing for the angular correlation in the $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascade, is assumed to be 1 due to the 4π coverage of GS. The gamma width of the Hoyle state, Γ_{γ}/Γ , is well known with a value $\Gamma_{\gamma}/\Gamma = 4.12(11) \times 10^{-4}$ [6]. The major inhibiting factor in obtaining a precise measurement of the branching ratio is the large amount of bremsstrahlung radiation from the high-energy beta particles (up to 13 MeV), as described in ref. [5].

2 Experiment

The experiment was carried out at the ATLAS facility at Argonne National Laboratory, using the GS array [7]. A pulsed ^{11}B beam (40 ms on, 40 ms off) with an intensity of 1 pnA and an energy of 40 MeV impinged on a 22 mg/cm² TiD₂ target (1.5 mg/cm² D₂ on a thick Ti foil). The GS array was operated in singles mode, and the γ rays from excited ^{12}C states populated in the β decay of ^{12}B ($T_{1/2}=20.2$ ms) were measured during the beam-off period.

As mentioned in the previous section, the difficulty in measuring the weak $0^+ \rightarrow 2^+ \rightarrow 0^+$ cascade is due to the large background induced by bremsstrahlung radiation of the high-energy beta particles. In order to reduce this radiation, a low-Z chamber was designed from a Bonner sphere (Fig. 1) that surrounded the target and greatly reduced the bremsstrahlung yield in GS.

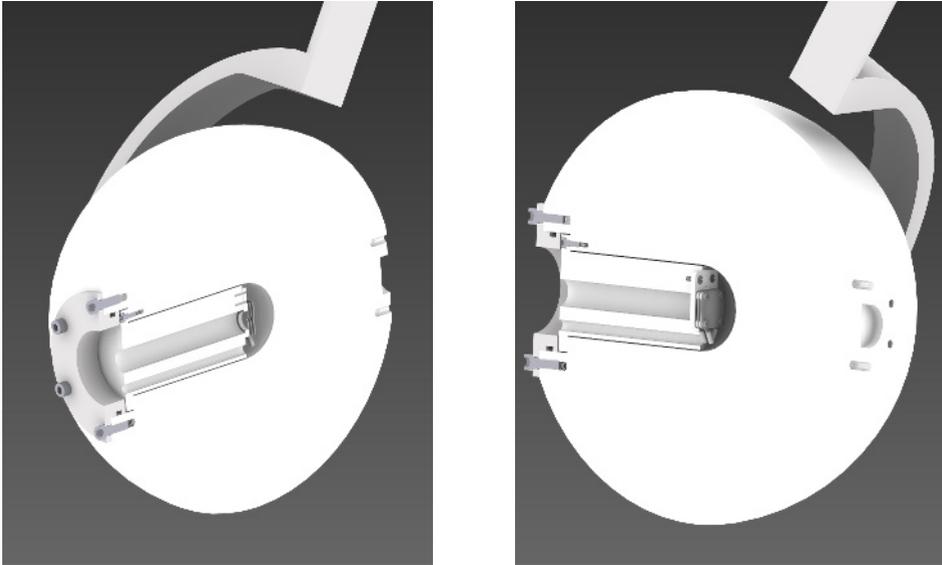


Figure 1. Schematic drawing of a low-Z chamber made from a Bonner sphere. This sphere was designed to maximize the coverage with a low-Z material while minimizing the attenuation of γ rays. The beam enters for the left side, and impinges on the target, located in the middle. The target is removable and is easily slid in and out. The sources used for efficiency calibrations were placed in the target position before and after the run was completed.

3 Analysis

The branching ratio given in Eq. 1 is determined from two values given by the literature, with the following obtained from experiment: $N_{\gamma\gamma}$, $N_{4.44}$, $\epsilon_{3.21}$, and C_{θ} . As stated above, the correction factor is assumed to be 1 given the symmetric 4π coverage of GS. $N_{\gamma\gamma}$ and $N_{4.44}$ were determined by fitting the peaks displayed in Fig. 2. The difficulty in the analysis arises from the determination of $\epsilon_{3.21}$, the detection efficiency for a γ ray of 3.21 MeV.

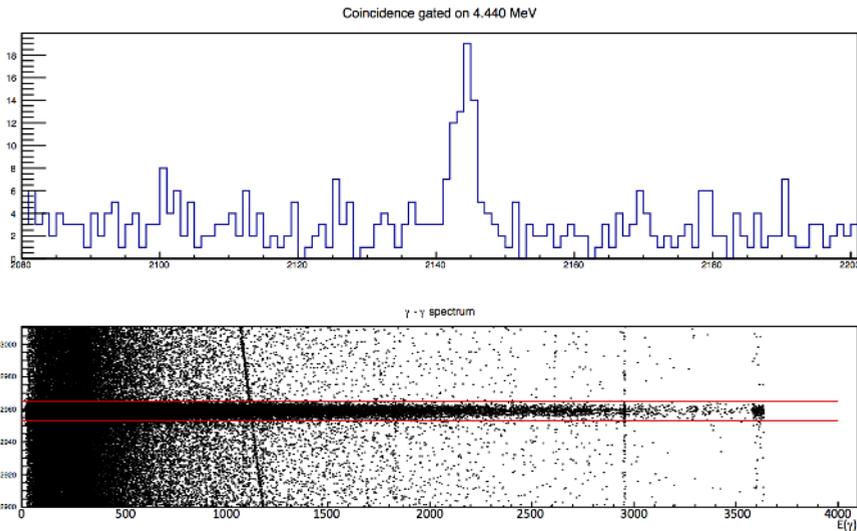


Figure 2. Coincidence spectrum accumulated from the TiD_2 target displayed together with the projection from the gated 4.44-MeV peak on top; the energies are binned in 0.666 keV/channel. The 4.44 MeV (ch. 2961) gated spectrum clearly shows a peak at 3.21 MeV (ch. 2142).

The determination of $\epsilon_{3.21}$ was carried out in two steps. The first was to determine the relative efficiency of GS. This was done by using ^{152}Eu and ^{56}Co calibration sources, placed in the center of the GS chamber. The absolute efficiency can then be determined from the following. In the case of a $\gamma - \gamma$ cascade where all of the flux in the intermediate level proceeds via the second γ ray, the ratio of the areas of the peaks in a $\gamma - \gamma$ coincidence matrix will give the efficiency of a detector at the energy of the second transition. By summing over all detectors, one can then determine the absolute efficiency of GS. For this reaction, it was found that ^{24}Mg was an ideal candidate since it was produced throughout the irradiation and so the decay was measured in the same conditions as the decay of the ^{12}B nuclei. The ^{24}Mg was likely produced from background reactions with the ^{13}C in the Bonner sphere. The $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade was used, so that the absolute efficiency was determined for $E_\gamma=1.369$ MeV. The absolute efficiency for a 3.21 MeV γ was subsequently deduced to be 2.94(9)%.

4 Conclusions

The preliminary value for the β -decay branching ratio of ^{12}B to the Hoyle state is $\text{BR}(7.65)=0.68(11)\%$, in agreement with the 0.58(2)% branch determined using β decay [1]. These findings support the view that the literature value of 1.2(3)% should be revised. In this experiment, the error is dominated by statistics ($\pm 0.09\%$) rather than by systematics ($\pm 0.02\%$). The large amount

of background reactions on the Ti backing greatly limited the usable beam current. Changing to a higher-Z backing, such as Hf, would enable the use of higher beam intensities and, therefore, result in a significant increase in statistics.

With the verification of the β -decay result presented here, it is possible to use the same method to then determine the radiative branching ratio, Γ_γ/Γ from Eq. 1:

$$\Gamma_\gamma/\Gamma = \frac{\text{BR}(4.44)}{\text{BR}(7.65)} \cdot \frac{N_{\gamma\gamma}}{N_{4.44} \cdot \epsilon_{3.21}} \frac{1}{C_\theta} \quad (2)$$

Reducing the error estimate on the radiative branching ratio is important for lowering the error on the radiative width, which dominates the uncertainty of the triple- α reaction rate, $R(3\alpha)$:

$$R(3\alpha) \propto T^{-3/2} \frac{\Gamma(^8\text{Be})\Gamma_{\text{rad}}}{\Gamma_{\text{tot}}} \exp\left(-\frac{Q_{3\alpha}}{kT}\right), \Gamma_{\text{rad}} = \frac{\Gamma_{\text{rad}}}{\Gamma_{\text{tot}}} \cdot \frac{\Gamma_{\text{tot}}}{\Gamma_\pi} \cdot \Gamma_\pi \quad (3)$$

Currently, the literature gives the following values and uncertainties for those quantities:

Quantity	Value	Error(%)	Reference
$\frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma_{\text{tot}}}$	$4.12(11) \times 10^{-4}$	2.7	[6]
$\frac{\Gamma_\pi}{\Gamma_{\text{tot}}}$	$6.7(6) \times 10^{-6}$	9.2	[8]
Γ_π	$59.6(1.5) \mu\text{eV}$	2.5	[9]

While the main source of error for $R(3\alpha)$ is the pair decay partial width, the current value for the radiative branching ratio is determined from a weighted average of various measurements, mostly comprised of inelastic scattering data. Using the method described in this manuscript would give a value of $\frac{\Gamma_{\text{rad}}}{\Gamma_{\text{tot}}}$ with different systematics. With an increase in statistics, it may be possible in a future experiment to obtain a value with a similar error to the literature value for $\frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma_{\text{tot}}}$.

5 Acknowledgements

This work is supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contracts No. DE-AC02-06CH11357 and No. DE-FG02-04ER41320 and Grant No. DE-FG02-94ER40834. We also acknowledge financial support from the European Research Council under ERC starting grant ‘‘LOBENA’’, No. 307447.

References

- [1] S. Hyldegaard et al., Phys. Lett. B **678**, 459 (2009).
- [2] F. Ajzenberg-Selove, Nucl. Phys. **A506**, 1 (1990).
- [3] S. Hyldegaard et al., Phys. Rev. C **80**, 044304 (2009).
- [4] H. O. U. Fynbo and M. Freer, Physics **4**, 94 (2011).
- [5] D. E. Alburger, Phys. Rev. **131**, 1624 (1963).
- [6] R. G. Markham, S. M. Austin, and M. A. M. Shahabuddin, Nucl. Phys. **A270**, 489 (1976).
- [7] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
- [8] D. E. Alburger, Phys. Rev. C **16**, 2394 (1977).
- [9] M. Chernykh et al., Phys. Rev. Lett. **105**, 022501 (2010).