

## Direct Measurement of Resonances in ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$ Relevant to $\nu p$ -Process Nucleosynthesis

A. Psaltis<sup>1,2,\*</sup>, A. A. Chen<sup>1,2</sup>, R. Longland<sup>3,4</sup>, D. S. Connolly<sup>5,‡</sup>, C. R. Brune<sup>6</sup>, B. Davids<sup>5,7</sup>, J. Fallis<sup>8</sup>, R. Giri<sup>6</sup>, U. Greife<sup>9</sup>, D. A. Hutcheon<sup>5</sup>, L. Kroll<sup>1,2</sup>, A. Lennarz<sup>5</sup>, J. Liang<sup>1,§</sup>, M. Lovely<sup>9</sup>, M. Luo<sup>10</sup>, C. Marshall<sup>3,4,||</sup>, S. N. Paneru<sup>6,¶</sup>, A. Parikh<sup>11</sup>, C. Ruiz<sup>5,12</sup>, A. C. Shotter<sup>13</sup> and M. Williams<sup>5,14</sup>

<sup>1</sup>Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada

<sup>2</sup>The NuGrid Collaboration

<sup>3</sup>Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA

<sup>4</sup>Triangle Universities Nuclear Laboratory, Duke University, Durham, North Carolina 27710, USA

<sup>5</sup>TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

<sup>6</sup>Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA

<sup>7</sup>Department of Physics, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada

<sup>8</sup>North Island College, 2300 Ryan Road, Courtenay, British Columbia V9N 8N6, Canada

<sup>9</sup>Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA

<sup>10</sup>Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada

<sup>11</sup>Department de Física, Universitat Politècnica de Catalunya, E-08036 Barcelona, Spain

<sup>12</sup>Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8W 2Y2, Canada

<sup>13</sup>School of Physics, University of Edinburgh EH9 3JZ Edinburgh, United Kingdom

<sup>14</sup>Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom



(Received 31 December 2021; revised 1 July 2022; accepted 24 August 2022; published 14 October 2022)

We have performed the first direct measurement of two resonances of the  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  reaction with unknown strengths using an intense radioactive  ${}^7\text{Be}$  beam and the DRAGON recoil separator. We report on the first measurement of the 1155 and 1110 keV resonance strengths of  $1.73 \pm 0.25(\text{stat}) \pm 0.40(\text{syst})$  eV and  $125^{+27}_{-25}(\text{stat}) \pm 15(\text{syst})$  meV, respectively. The present results have reduced the uncertainty in the  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  reaction rate to  $\sim 9.4\%$ – $10.7\%$  over  $T = 1.5$ – $3$  GK, which is relevant for nucleosynthesis in the neutrino-driven outflows of core-collapse supernovae ( $\nu p$  process). We find no effect of the new, constrained reaction rate on  $\nu p$ -process nucleosynthesis.

DOI: [10.1103/PhysRevLett.129.162701](https://doi.org/10.1103/PhysRevLett.129.162701)

Nucleosynthesis in the neutrino-driven winds of core-collapse supernovae has gained attention in recent years. The most recent multidimensional hydrodynamic studies of neutrino-driven explosions with an energy-dependent neutrino transport mechanism suggest that the early supernova ejecta are proton rich [with electron fraction  $Y_e \equiv n_p/(n_p + n_n) > 0.5$ , where  $n_p$  and  $n_n$  are the number densities of protons and neutrons, respectively] [1–4]. At later times, the wind becomes slightly neutron rich ( $Y_e \sim 0.40$ – $0.49$ ), and in these conditions the weak  $r$  process produces nuclei up to  $A \approx 90$ – $110$ , below the second  $r$ -process peak [5–7].

In the proton-rich environment of the neutrino-driven ejecta, the  $\nu p$  process operates, synthesizing heavy nuclei with  $A > 74$  [8–10]. At first, the ejected material from the protoneutron star (PNS) is very hot and consists mainly of protons and neutrons, with an excess of the former, since  $Y_e > 0.5$ . Expansion causes the ejecta to cool down, and  $Z = N$  nuclei are assembled—mainly  ${}^{56}\text{Ni}$  and  ${}^4\text{He}$ —via nuclear statistical equilibrium. At  $T \sim 3$  GK, the excess of protons interacts with the electron antineutrinos that are streaming from the PNS, producing a small amount of

neutrons, which can be immediately captured by  ${}^{56}\text{Ni}$ . By a series of  $(n, p)$  and  $(p, \gamma)$  reactions, the reaction flow proceeds to heavier nuclei, until the ejecta temperature falls to  $T \sim 1.5$  GK, where the  $(p, \gamma)$  reactions freeze out due to the Coulomb barrier.

The aforementioned scenario has been proposed as a possible production mechanism for the light  $p$  nuclei, a subset of the around 35 neutron-deficient nuclei with  $A \geq 74$ , which cannot be synthesized by either the  $s$  or the  $r$  process [11,12]. In particular,  ${}^{92,94}\text{Mo}$  and  ${}^{96,98}\text{Ru}$ , that are underproduced in the astrophysical  $\gamma$  process [13], could be synthesized via the  $\nu p$  process. Furthermore, the  $\nu p$  process could also explain the high abundance of Sr, Y, and Zr relative to Ba in metal-poor stars and has been proposed as a candidate of the light-element primary process [6,14].

Despite its successes, the  $\nu p$  process exhibits many uncertainties that have already been identified since it was first proposed. Its efficiency strongly depends on the characteristics of the neutrino-driven wind (e.g., electron fraction  $Y_e$  and entropy  $s$ ) and the underlying nuclear physics input (e.g., reaction rates and  $Q$  values) [6,15,16].

One of the most important reactions affecting the nucleosynthesis output of the  $\nu p$  process is the triple- $\alpha$  reaction, which controls the relative abundances of protons,  $\alpha$  particles, and  $^{56}\text{Ni}$  seed nuclei before the onset and during the  $\nu p$  processing [16]. In particular, a high rate of the triple- $\alpha$  reaction decreases the efficiency of the  $\nu p$  process, since it creates more seed nuclei, acting as a “proton poison” by decreasing the ratio of neutrons to seed nuclei,  $\Delta_n$ . However, Wanajo *et al.* [15] identified a couple of two-body breakout reaction sequences between  $A < 12$  ( $pp$ -chain region) and  $A \geq 12$  (CNO region) that can have a similar effect to the triple- $\alpha$  reaction and compete with it in the temperature range of the  $\nu p$  process, namely,  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}(\alpha, p)^{14}\text{N}$  and  $^7\text{Be}(\alpha, p)^{10}\text{B}(\alpha, p)^{13}\text{C}$ . The most important reaction for each sequence is  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  and  $^7\text{Be}(\alpha, p)^{13}\text{C}$ , respectively, and for this reason they were included in a nucleosynthesis sensitivity study by Wanajo *et al.* [15]. Their results suggest that species with  $90 < A < 110$  are sensitive to variations of the  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  reaction rate. Their abundances can vary up to an order of magnitude when varying the  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  reaction rate by factors between 0.1 and 10, and for this reason it needs to be well constrained experimentally.

In the relevant energy region for  $\nu p$ -process nucleosynthesis, there are three experimental studies of the  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  reaction [17–19]. The two low-lying resonances at  $E_r = 561$  and  $876$  keV were studied by Hardie *et al.* [17] in forward kinematics using a radioactive  $^7\text{Be}$  target, and their strengths were measured. For the  $E_r = 1110$  and  $1155$  keV resonances, Wiescher *et al.* [18] used the  $^{10}\text{Be}(p, \gamma)^{11}\text{C}$  reaction and calculated their  $\Gamma_\gamma/\Gamma$  from the cross section ratio  $\sigma_{(p, \gamma)}/\sigma_{(p, \alpha)}$ , but their strengths remain unknown. The most recent relevant study was performed by Yamaguchi *et al.* [19]. The authors performed a  $^7\text{Be} + \alpha$  resonant scattering and  $^7\text{Be}(\alpha, p)$  reaction measurement using the thick-target method in inverse kinematics and measured the excitation functions for  $E_x = 8.7$ – $13.0$  MeV on  $^{11}\text{C}$ . Their  $R$ -matrix analysis revealed a new state at  $E_x = 8.9$  MeV ( $E_r = 1356$  keV) which could have a 10% contribution to the total  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  reaction rate in the relevant energy region. However, the authors argue that, due to their large uncertainty in the low-energy region, this level might be the  $E_x = 8.699$  MeV ( $E_r = 1155$  keV) state.

The current rate for the  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  reaction is adopted from NACRE (I and II) [20,21] and includes contributions only from the two low-lying (561 and 876 keV) narrow resonances, for which experimentally measured strengths exist. In the Letter of Angulo *et al.* [20] (NACRE I), whose rate was used as a baseline in the sensitivity study of Wanajo *et al.* [15], Hauser-Feshbach contributions were added for  $T > 2$  GK. In the most recent evaluation of the rate by Xu *et al.* [21] (NACRE II), the authors included contributions from four broad resonances at higher energies. Descouvemont [22] also suggests that the

TABLE I. Beam and gas target properties for the two independent measurements of the present study. (The 1110 keV resonance was studied in two independent measurements, due to a low recoil yield in the first measurement. We quote the weighted average values for the presented quantities.)

$E_{\text{beam}}$ (A keV)	$E_{\text{lab}}$ (MeV)	$P_{\text{target}}$ (Torr)	$E_{\text{c.m.}}$ (MeV)	$t_{\text{irrad}}$ (h)	$N_{^7\text{Be}}$ ( $\times 10^{13}$ )
464.2(3)	3.249(2)	7.9(1)	$1157 \pm 24$	25.4	1.07(2)
442.2(2)	3.098(1)	4.92(7)	$1111 \pm 13$	34.2	3.29(5)
351.8(3)	2.463(2)	5.75(4)	$878 \pm 17$	27.8	2.12(4)

subthreshold resonance at  $E_x = 7.4997$  MeV ( $E_r = -43.9$  keV) can dominate the reaction rate at low temperatures, below  $T \approx 0.3$  GK, which could impact the destruction of the important radionuclide  $^7\text{Be}$  in astrophysical sites such as classical novae and PopIII stars. The NACRE-II thermonuclear reaction rate is uncertain by factors of 1.76–1.91 for  $T = 1.5$ – $3$  GK [21]. In addition to that, contributions from higher-energy resonances with unknown strengths are expected to influence the reaction rate for  $T > 1.5$  GK [15].

In this Letter, we present the first experimental study of the  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  reaction in inverse kinematics utilizing an intense  $^7\text{Be}$  radioactive ion beam (RIB) to measure two key resonances at  $E_r = 1110$  and  $1155$  keV, with unknown strengths, and determine their contribution to the reaction rate at  $\nu p$ -process nucleosynthesis energies. In addition, we remeasured the  $E_r = 876$  keV resonance strength.

The measurements were performed using the DRAGON (Detector of Recoils and Gammas of Nuclear Reactions) recoil separator [23] at the ISAC-I (isotope separator and accelerator) experimental hall of TRIUMF, Canada’s particle accelerator center in Vancouver, British Columbia, Canada. Intense beams of  $^7\text{Be}$  ( $I \sim 1.3$ – $5.8 \times 10^8$  pps) were produced using the ISOL technique, by bombarding thick ZrC and graphite targets with  $55 \mu\text{A}$  500 MeV protons from the TRIUMF cyclotron. The  $^7\text{Be}$  content of the beam was enhanced compared to the main  $A = 7$  isobar  $^7\text{Li}$  using the TRIUMF resonant ionization laser ion source (TRILIS) [24]. The radioactive beams were then accelerated through the ISAC-I radio-frequency quadrupole (RFQ) and drift-tube linac (DTL) to energies, so that each resonance was centered in the gas target. To ensure a pure RIB, an additional  $20 \mu\text{g}/\text{cm}^2$  carbon stripping foil was placed upstream of the DTL to select a specific charge state ( $4^+$ ) to completely eliminate the main isobaric contaminant  $^7\text{Li}$ . Finally,  $^7\text{Be}^{4+}$  was delivered to the helium-filled DRAGON windowless gas target with effective length of  $12.3(1)$  cm [23]. In Table I, we present an overview of the beam and gas target parameters for our measurements.

An array of 30 highly efficient bismuth germanate (BGO) detectors surrounding the gas target detected the prompt  $\gamma$  rays of the  $^{11}\text{C}$  recoil deexcitation and provided  $\gamma$

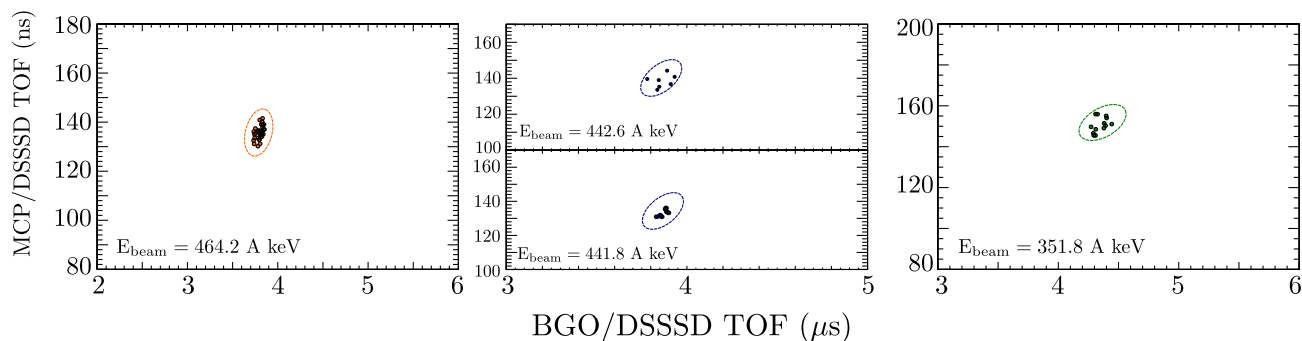


FIG. 1. MCP/DSSSD versus BGO/DSSSD (separator) time of flight for the recoil events for each of the resonances we studied in the present Letter. For the 1110 keV resonance, we show the two independent measurements in separate panels. Positively identified  $^{11}\text{C}$  recoils for each resonance are shown. The ovals are used to help the reader's eye.

tagging for the coincidence analysis. The most intense charge state of the recoils ( $^{11}\text{C}^{2+}$ ) was tuned through the separator to a 66- $\mu\text{m}$ -thick, gridded double-sided silicon strip detector (DSSSD)—Micron W1(G) model—placed near the focal plane of DRAGON, with a typical rate of 5–15 Hz. The  $^{11}\text{C}$  recoils were detected both in single and coincidence modes. In the former, we employed time-of-flight (TOF) measurements between a microchannel plate detector (MCP) close to the DRAGON focal plane and the DSSSD, and in the latter we used the detected  $\gamma$  rays in the BGO array and hits on the DSSSD (see the particle identification plot in Fig. 1).

According to the reaction kinematics for the  $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$  reaction in the energy range of interest, the recoil angular distribution greatly exceeds the nominal DRAGON acceptance ( $\theta_{r,\text{max}} \sim 43\text{--}47$  mrad compared to  $\theta_{\text{DRAGON}} = 21$  mrad). For this reason, we performed detailed simulations using the standard DRAGON GEANT package [25,26] to calculate the efficiency of the BGO array ( $\eta_{\text{BGO}}$ ) and the transmission of the recoils through the separator ( $\eta_{\text{separator}}$ ), which are used in the data analysis and the calculation of the resonance strengths. This procedure has already been employed successfully in DRAGON experiments and more recently with a benchmark measurement of a resonance with a known strength of the  $^6\text{Li}(\alpha, \gamma)^{10}\text{B}$  reaction, whose products also had a maximum angular cone larger than DRAGON nominal acceptance [27,28]. A more detailed discussion about these simulations can be found in the accompanying publication [29]. We observe a very good agreement between the Geant simulations and the experimental data. In particular, Fig. 2 shows a spectrum of the highest-energy  $\gamma$  ray per coincident event versus the position along the beam axis for the 1155 keV resonance.

The number of the incident beam particles was determined by using the elastically scattered target particles, using two silicon surface barrier detectors placed at well-defined lab angles of  $30^\circ$  and  $57^\circ$  with respect to the beam axis. The beam stopping power through helium gas and the

recoil charge state distribution, which are used for the calculation of the experimental resonance strength, were measured using  $^7\text{Be}$  and  $^{12}\text{C}$  beams, respectively.

Figure 1 shows the MCP-DSSSD versus separator TOF for the three resonances studied in the present Letter. Clusters of 33, 9/7, and 13 coincidence events were recorded for the 1155, 1110, and 876 keV resonances, respectively. For all the resonance strength measurements, a very high beam suppression is demonstrated, consistent with the reported  $10^{13}$  in Ref. [30].

The main sources of systematic uncertainty in the final result arise from the  $\gamma$  decay branching ratio uncertainties and the  $\gamma$  ray angular distributions which both affect the BGO efficiency and, subsequently, the recoil transmission through the separator [31]. The relative uncertainties of the product of  $\eta_{\text{BGO}}$  and  $\eta_{\text{separator}}$  uncertainty for the three resonances are the following: 19.9% ( $E_r = 1155$  keV), 11.0% ( $E_r = 1110$  keV), and 29.3% ( $E_r = 876$  keV). Smaller contributions to the systematic uncertainty arise

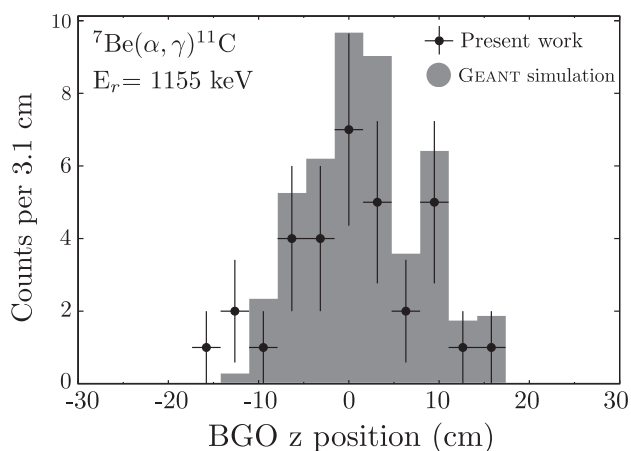


FIG. 2. BGO position profile spectrum for the  $E_r = 1155$  keV resonance. The black points indicate the experimental data and the gray histogram a *scaled* Geant simulation. The centroid of the experimental peak is at  $z_r = +0.47$  cm with respect to the center of the gas target.

from the MCP detection efficiency (5.5%–10.7%) and the stopping power measurements (3.7%–4.3%) (see also the discussion and Table VIII in Ref. [29]). The statistical uncertainties, in turn, are due to the low detection yield, caused by the very low transmission of the recoils through the separator. However, even though the transmission is small, it is a parameter that is well understood and quantified [27]. The detected recoil uncertainties for the 1110 and 876 keV resonances were determined using the prescription of Feldman and Cousins [32] for a Poissonian signal with zero background, as is evident in Fig. 1.

We determined the resonance strengths of the 1155, 1110, and 876 keV resonances to be  $1.73 \pm 0.25(\text{stat}) \pm 0.40(\text{syst})$  eV,  $125_{-25}^{+27}(\text{stat}) \pm 15(\text{syst})$  meV, and  $3.00_{-0.72}^{+0.81}(\text{stat}) \pm 0.61(\text{syst})$  eV, respectively. For the 1110 keV resonance strength, since we performed two independent measurements, we created a combined statistical uncertainty distribution, accounting for the asymmetric statistical uncertainties from the prescription of Feldman and Cousins [32]. We provide a detailed discussion of this procedure in Psaltis *et al.* [29].

Using the results from the present experiment, we evaluated the  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  reaction rate using the RatesMC code [33,34]. Figure 3 shows the new reaction rate in comparison with both the NACRE rates [20,21] and the compilation of Caughlan and Fowler [35] (CF88). The new  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  reaction rate differs less than  $\sim 2\%$  at temperatures between  $T = 1.5$  and 3 GK with the NACRE-II rate, but it is now constrained to  $\sim 9.4\%$ – $10.7\%$ , which is sufficient for astrophysical applications. It is worth noting that the decrease in the rate uncertainty mainly originates from properly propagating the relevant errors within the RatesMC framework, and the newly measured resonance strengths contribute  $\lesssim 10\%$  to the total rate in  $\nu p$ -process temperatures (see the discussion in Ref. [29], Sec. E).

Furthermore, we performed nucleosynthesis calculations using the new  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  reaction rate and parametric

neutrino-driven wind trajectories from Ref. [36] to study the impact on the production of heavy elements. Despite the fact that the new  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  thermonuclear reaction rate is more constrained compared to NACRE II, we did not observe any differences in the production of heavy elements via the  $\nu p$  process. For completeness, and to note the sensitivity of  $\nu p$ -process nucleosynthesis to this rate, we did find that a  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  reaction rate  $\sim 2$  times lower than the NACRE II increased the production of  $A = 55$ – $130$  nuclei by as much as a factor of 100 in specific astrophysical conditions of the neutrino-driven wind [36], which is significantly larger than the typical abundance changes observed by Wanajo *et al.* [15]. Such a rate reduction is beyond our determined rate uncertainty, however. That said, a future detailed study of this nucleosynthesis scenario will examine if such discrepancies also exist for other important  $\nu p$ -process rates and include the results from recent measurements of such reactions [37–39].

In addition to the nuclear physics uncertainties, the  $\nu p$  process is strongly dependent on the local astrophysical conditions of the neutrino-driven wind and, more specifically, on the combination of  $Y_e$ ,  $s$ , and expansion timescale  $\tau$ . Given that the state-of-the-art multidimensional simulations of core-collapse supernovae support proton-rich outflows [1–4], the  $\nu p$  process should be a very common nucleosynthesis scenario, and its yields need to be included in galactical chemical evolution models. Nevertheless, as Kobayashi *et al.* [40] have argued, the inclusion of such yields leads to an overproduction for elements between strontium (Sr) and tin (Sn), compared to observations. For this reason, we argue for a coordinated effort between experimental nuclear physicists, stellar modelers, and observational astronomers to constrain the most common conditions for the  $\nu p$  process and its role in the origin of the heavy elements in the Universe.

To recapitulate, in this Letter, we presented the first inverse kinematics study of the  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  reaction using the DRAGON recoil separator and an intense  ${}^7\text{Be}$  beam from ISAC. We successfully measured for the first time the strength of two resonances at 1155 and 1110 keV [ $\omega\gamma = 1.73 \pm 0.25(\text{stat}) \pm 0.40(\text{syst})$  eV and  $125_{-25}^{+27}(\text{stat}) \pm 15(\text{syst})$  meV] and remeasured one at 876 keV [ $\omega\gamma = 3.00_{-0.72}^{+0.81}(\text{stat}) \pm 0.61(\text{syst})$  eV], which agrees within uncertainty with the measurement of Hardie *et al.* [17] [ $\omega\gamma = 3.80(57)$  eV]. The uncertainty of the  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  reaction rate is now reduced to  $\sim 9.4\%$ – $10.7\%$  at the temperature region relevant to  $\nu p$ -process nucleosynthesis,  $T = 1.5$ – $3$  GK. According to our results, the new reaction rate is well constrained for astrophysical calculations, and our initial nucleosynthesis calculations suggest that it does not affect the production of neutron-deficient heavy elements ( $p$  nuclei). This experiment is a major technical achievement, being the first radiative capture reaction measurement using a RIB and a recoil separator, in which the angular distribution of the reaction products exceeds the

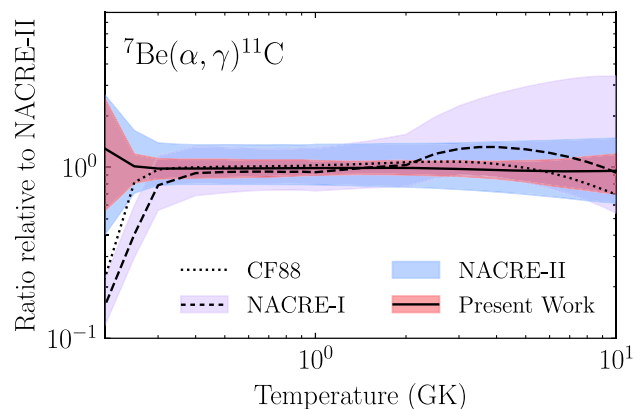


FIG. 3. Comparison between the NACRE-I [20] and NACRE-II [21]  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$  thermonuclear reaction rate and that of Caughlan and Fowler [35] (CF88) and the present Letter for the same temperature region.

nominal acceptance of the separator by more than a factor of 2. In addition, the intense  ${}^7\text{Be}$  radioactive beams produced with the use of graphite targets can be employed for other challenging measurements, such as the  ${}^7\text{Be}(p, \gamma){}^8\text{B}$  and  ${}^7\text{Be}(\alpha, \alpha){}^7\text{Be}$  reactions.

The authors gratefully acknowledge the beam delivery and ISAC operations groups at TRIUMF. In particular, we thank F. Ames, T. Angus, A. Gottberg, S. Kiy, J. Lassen, and O. Shelbaya for all their help during the experiment. The core operations of TRIUMF are supported via a contribution from the federal government through the National Research Council of Canada and the Government of British Columbia provides building capital funds. Authors from McMaster University are supported by the National Sciences and Engineering Research Council of Canada (NSERC). DRAGON is funded through NSERC Grant No. SAPPJ-2019-00039. A. P. also acknowledges support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project No. 279384907-SFB 1245 and the State of Hesse within the Research Cluster ELEMENTS (Project ID No. 500/10.006). R. L. and C. M. acknowledge support from the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Grants No. DE-SC0017799 and No. DE-FG02-97ER41042. C. R. B., R. G., and S. P. acknowledge support from the U.S. Department of Energy, under Grants No. DE-FG02-88ER40387 and No. DE-NA0003883. Authors from the Colorado School of Mines acknowledge support from U.S. Department of Energy Office of Science Grant No. DE-FG02-93ER40789. This work benefited from discussions at the "Nuclear Astrophysics at Rings and Recoil Separators" Workshop supported by the National Science Foundation under Grant No. PHY-1430152 (JINA Center for the Evolution of the Elements).

\*psaltisa@mcmaster.ca

<sup>†</sup>Present address: Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany.

<sup>‡</sup>Present address: Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA.

<sup>§</sup>Present address: TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada.

<sup>||</sup>Present address: Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA.

<sup>¶</sup>Present address: Facility for Rare Isotope Beams, East Lansing, Michigan 48824, USA.

- [1] A. Burrows and D. Vartanyan, *Nature (London)* **589**, 29 (2021).
- [2] B. Müller, *Pub. Astron. Soc. Aust.* **33**, e048 (2016).
- [3] S. Wanajo, B. Müller, H.-T. Janka, and A. Heger, *Astrophys. J.* **852**, 40 (2018).
- [4] D. Vartanyan, A. Burrows, D. Radice, M. A. Skinner, and J. Dolence, *Mon. Not. R. Astron. Soc.* **482**, 351 (2019).
- [5] Y.-Z. Qian and G. Wasserburg, *Phys. Rep.* **442**, 237 (2007).
- [6] A. Arcones and F. Montes, *Astrophys. J.* **731**, 5 (2011).
- [7] S. Wanajo, *Astrophys. J. Lett.* **770**, L22 (2013).
- [8] C. Fröhlich, G. Martínez-Pinedo, M. Liebendörfer, F.-K. Thielemann, E. Bravo, W. R. Hix, K. Langanke, and N. T. Zinner, *Phys. Rev. Lett.* **96**, 142502 (2006).
- [9] J. Pruet, R. D. Hoffman, S. E. Woosley, H.-T. Janka, and R. Buras, *Astrophys. J.* **644**, 1028 (2006).
- [10] S. Wanajo, *Astrophys. J.* **647**, 1323 (2006).
- [11] M. Arnould and S. Goriely, *Phys. Rep.* **384**, 1 (2003).
- [12] T. Rauscher, N. Dauphas, I. Dillmann, C. Fröhlich, Zs Fülöp, and Gy Gyürky, *Rep. Prog. Phys.* **76**, 066201 (2013).
- [13] M. Pignatari, K. Göbel, R. Reifarth, and C. Travaglio, *Int. J. Mod. Phys. E* **25**, 1630003 (2016).
- [14] F. Montes, T. C. Beers, J. Cowan, T. Elliot, K. Farouqi, R. Gallino, M. Heil, K.-L. Kratz, B. Pfeiffer, M. Pignatari, and H. Schatz, *Astrophys. J.* **671**, 1685 (2007).
- [15] S. Wanajo, H.-T. Janka, and S. Kubono, *Astrophys. J.* **729**, 46 (2011).
- [16] N. Nishimura, T. Rauscher, R. Hirschi, G. Cescutti, A. St J. Murphy, and C. Fröhlich, *Mon. Not. R. Astron. Soc.* **489**, 1379 (2019).
- [17] G. Hardie, B. W. Filippone, A. J. Elwyn, M. Wiescher, and R. E. Segel, *Phys. Rev. C* **29**, 1199 (1984).
- [18] M. Wiescher, R. N. Boyd, S. L. Blatt, L. J. Rybarczyk, J. A. Spizuoco, R. E. Azuma, E. T. H. Clifford, J. D. King, J. Görres, C. Rolfs, and A. Vlieks, *Phys. Rev. C* **28**, 1431 (1983).
- [19] H. Yamaguchi *et al.*, *Phys. Rev. C* **87**, 034303 (2013).
- [20] C. Angulo *et al.*, *Nucl. Phys.* **A656**, 3 (1999).
- [21] Y. Xu, K. Takahashi, S. Goriely, M. Arnould, M. Ohta, and H. Utsunomiya, *Nucl. Phys.* **A918**, 61 (2013).
- [22] P. Descouvemont, *Nucl. Phys.* **A584**, 532 (1995).
- [23] D. Hutcheon *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **498**, 190 (2003).
- [24] J. Lassen, P. Bricault, M. Domsbky, J. P. Lavoie, Ch. Geppert, and K. Wendt, *Hyperfine Interact.* **162**, 69 (2005).
- [25] The Geant simulation package of DRAGON can be found at [https://github.com/DRAGON-Collaboration/G3\\_DRAGON](https://github.com/DRAGON-Collaboration/G3_DRAGON).
- [26] D. G. Gigliotti *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **204**, 671 (2003).
- [27] A. Psaltis *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **987**, 164828 (2021).
- [28] A. Psaltis, Radiative alpha capture on  ${}^7\text{Be}$  with DRAGON at  $\nu p$ -process nucleosynthesis energies, Ph.D. thesis, McMaster University, 2020.
- [29] A. Psaltis *et al.*, companion paper, *Phys. Rev. C* **106**, 045805 (2022).
- [30] S. Sjuve *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **700**, 179 (2013).
- [31] C. Ruiz, U. Greife, and U. Hager, *Eur. Phys. J. A* **50**, 99 (2014).
- [32] G. J. Feldman and R. D. Cousins, *Phys. Rev. D* **57**, 3873 (1998).
- [33] The RatesMC code to calculate thermonuclear reaction rates can be found at <https://github.com/rlongland/RatesMC>.
- [34] R. Longland *et al.*, *Nucl. Phys.* **A841**, 1 (2010).
- [35] G. R. Caughlan and W. A. Fowler, *At. Data Nucl. Data Tables* **40**, 283 (1988).
- [36] M. Jacobi, Influence of astrophysical and nuclear physics uncertainties on the nucleosynthesis in proton-rich

neutrino-driven winds, Master's thesis, Technische Universität Darmstadt, 2018.

- [37] Q. Liu *et al.*, *Phys. Rev. C* **101**, 025808 (2020).  
[38] T. Kibédi *et al.*, *Phys. Rev. Lett.* **125**, 182701 (2020).  
[39] J. S. Randhawa *et al.*, *Phys. Rev. C* **104**, L042801 (2021).  
[40] C. Kobayashi, A. I. Karakas, and M. Lugaro, *Astrophys. J.* **900**, 179 (2020).