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Direct Measurement of Resonances in $^{7}Be(\alpha,\gamma)^{11}C$ With DRAGON

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Direct Reactions with Exotic Beams

Matsue, Japan

5th June 2018



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- Motivation
- Experimental technique
- Analysis and Preliminary results
- Future plans

Heavy Element Nucleosynthesis

10^{2} 10Abundances [Si=106] 10^{4} 10 10^{-2} 10^{-3} 130 10^{-4} 152Gd/ 10'5 ⁸⁰Ta^m 10.0 20080 100120140160180А

 Isotopic abundances of elements heavier than Fe explained by *s* process, *r* - process and *p* - process nucleosynthesis

M. Arnould and S. Goriely, Phys. Rep. 384, 1 (2003)

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Heavy Element Nucleosynthesis

⁹²Pd ⁹³Pd ⁹⁵Pd 96 Pd ⁹⁷Pd ⁹⁹Pd s-process path ¹Pd ⁹⁴Pd ^{98}Pd 100 Pd ^{02}Pd *r*-process decays ³⁹Rh ⁹¹Rh 92 Rh ⁹⁷Rh ⁹⁸Rh ⁹⁹Rh ⁰⁰Rh ^{.02}Rh 90 Rh ⁹³Rh ⁹⁴Rh ⁹⁵Rh ⁹⁶Rh p-nucleus ⁸⁸Ru ⁹²Ru ⁸⁹Ru 96 Ru ⁸⁷Ru 90 Ru ⁹¹Ru 93 Ru ⁹⁴Ru 95 Ru ⁸⁶Ru 85 Ru ⁹Ru ¹⁰⁰Ru not produced in 87 Tc ⁸⁸Tc ⁸⁹Tc ⁸⁶Tc $^{90}\mathrm{Tc}$ ⁹²Tc ⁹¹Tc ⁹³Tc ^{94}Tc s-process, r-process ⁸⁴Mo ^{85}Mo ⁸⁶Mo ⁸⁷Mo ⁸⁸Mo ⁸⁹Mo ⁹⁰Mo ⁹¹Mo $^{92}\mathrm{Mo}$ ⁴Mo ⁸³Mo ¹¹Mo ²Mo ⁸¹Nb ⁸³Nb ⁸⁴Nb ⁸⁵Nb ⁸⁶Nb ⁸⁷Nb ⁸⁸Nb ⁸⁹Nb ⁹³Nb ³²Nb ⁹⁰Nb ^{91}Nb ³⁰Nb ⁸⁴Zr 85 Zr 86 Zr $^{87}\mathrm{Zr}$ 79 Zr 80 Zr 81 Zr ⁸²Zr 83 Zr 88 Zr ⁸Zr ^{82}Y ^{83}Y ^{77}Y 78 V ^{79}Y ^{80}Y 81 V ^{84}Y ^{85}Y ^{86}Y ^{87}Y ^{95}Y 84 Sr ^{82}Sr ^{83}Sr ^{85}Sr 76 Sr 77 Sr ⁷⁸Sr ⁷⁹Sr 80 Sr $^{81}\mathrm{Sr}$ ⁸²Bb ⁸⁴Rb Rb 75 Rb ⁷⁶Rb ⁷⁷Bb ⁷⁸Bb ⁷⁹Rb ⁸⁰Bb 81 Bb ⁸³Bb ⁹⁰Bb ⁹¹Bb ^{92}Bb ⁹³Bb ⁹⁴Bb ⁹⁵Bb ³⁹Bb ⁷⁹Kr 74 Kr $^{75}\mathrm{Kr}$ ⁷⁶Kr $^{90}\mathrm{Kr}$ $^{91}\mathrm{Kr}$ 92 Kr $^{94}\mathrm{Kr}$ $^{95}\mathrm{Kr}$ 77 Kr ⁸⁹Kr $^{93}\mathrm{Kr}$ ⁸Kr ^{73}Br ^{74}Br ^{75}Br ^{76}Br ^{77}Br $^{78}\mathrm{Br}$ ^{84}Br ^{85}Br ^{89}Br $^{90}\mathrm{Br}$ ^{91}Br ^{92}Br ^{93}Br ^{94}Br 74 Se 84 As ⁹⁰As ⁷²As ⁷⁹As ^{83}As 85 As 86 As ⁸⁷As ^{88}As 91 As ^{'1}As ^{80}As ⁸¹As ⁸⁹ As ^{92}As ⁷⁸Ge ⁷⁹Ge ^{32}Ge 84 Ge 85 Ge 86 Ge 87 Ge 88 Ge 89 Ge 30 Ge ³¹Ge ⁸³Ge ⁹⁰Ge -eGa 82Ga ⁷⁷Ga ⁸³Ga 84 Ga 85 Ga 74 Ga ⁷⁸Ga ⁷⁹Ga 80 Ga ⁸¹Ga 86 Ga 87 Ga ³Zn 74 Zn ⁶Zn ⁷⁷Zn ⁷⁸Zn ⁷⁹Zn 2 Zn ⁸³Zn 84 Zn ⁷⁵Zn 80 Zn 1 Zn

- Isotopic abundances of elements heavier than Fe explained by *s* process, *r* - process and *p* - process nucleosynthesis
- Origin of *p* nuclei still not fully understood

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Heavy Element Nucleosynthesis



W. Rapp et al., Astrophys. J. 653, 474 (2006)

- Isotopic abundances of elements heavier than Fe explained by s process, r - process and p - process nucleosynthesis
- Origin of *p* nuclei still not fully understood
- p and y processes underpredict abundances of several p – nuclei

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vp-process

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- Isotopic abundances of elements heavier than Fe explained by s process, r - process and p - process nucleosynthesis
- Origin of *p* nuclei still not fully understood
- *p* and *γ* processes underpredict abundances of several *p* – nuclei
- vp process thought to occur in ejecta of CCSN, probable site of synthesis of p - nuclei

J. José and C. Iliadis, Rep. Prog. Phys. 74, 096901 (2011)

⁷Be(α, γ)¹¹C and the vp-process



S. Wanajo, H.-T. Janka and S. Kubono, Astrophys. J. 729, 46 (2011)



⁷Be(α, γ)¹¹C and the *vp*-process



- ⁷Be(α, γ)¹¹C competes with 3α in breakout from *p-p* chain
- Recent sensitivity study found that altering ⁷Be(α, γ)¹¹C rate significantly alters *p*-nuclei abundances

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⁷Be(α, γ)¹¹C and the νp -process

[′]Be(α,γ)¹¹C Reaction Rate (cm[°] mol⁻s⁻10¹ 0¹ 0¹ NACRE II Adopted NACRE II Low NACRE II High ----- Caughlan (1988) ----- TALYS 1.8 2.0 2.5 3.0 1.5 0.0 0.5 1.0 7 [10⁹ K]

S. Goriely, S. Hilaire and A. J. Koning, Astron. Astro. **487**, 767 (2008) Y. Xu et al., Nucl. Phys. A **918**, 61 (2013)

- ${}^{7}\text{Be}(\alpha, \gamma){}^{11}\text{C}$ competes with 3α in breakout from *p-p* chain
- Recent sensitivity study found that altering ${}^{7}\text{Be}(\alpha, \gamma){}^{11}\text{C}$ rate significantly alters *p*-nuclei abundances
- ${}^{7}\text{Be}(\alpha,\gamma){}^{11}\text{C}$ reaction rate poorly known over temperature range of interest (1.5 – 3 GK)

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Previous Measurements

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| | | | | | | $E_{\rm r} [{\rm MeV}]$ | $E_x [{\rm MeV}]$ | J^{π} | |
|--|-------------|------------------|------------------------|-----------------|----------------|--|--|--|--------|
| | | | | | | 1.355 1.154 1.109 | $\begin{array}{r} 9.645 \\ \hline 9.200 \\ \hline 8.900 \\ \hline 8.699 \\ \hline 8.654 \\ \hline 8.420 \\ \hline 8.105 \end{array}$ | $3/2^{-1}$ $(9/2^{+})$ $(9/2^$ | |
| | | | | | | $\frac{7.545}{^{7}\text{Be}+\alpha}3/2^{-7}$ | 7.500 | $\frac{3/2^+}{3/2^+}$ | |
| E_{x} [MeV] | E_r [MeV] | J^{π} | Γ_{α} [eV] | Γ_n [eV] | <i>ωγ</i> [eV] | | 6.904 6.478 | $\frac{7/2}{7/2}$ | |
| 8.900 ³ | 1.355 | (9/2+) | 8 keV | - | - | | 6.339 | $\frac{1/2}{1/2^+}$ | |
| 8.699(2) ^{2,3} | 1.154 | 5/2+ | 15(1) keV | - | - | | | | |
| 8.654(4) ^{2,3} | 1.109 | 7/2+ | ≤5 keV | - | - | | 4.804 | 3/2- | |
| 8.420(2) ¹ | 0.877 | 5/2 ⁻ | 12.6(3.8) | 3.1(1.3) | 3.80 | | 4.139 | 5/2 | |
| 8.105(17) ¹ | 0.560 | 3/2- | 6^{+12}_{-2} | 0.350(56) | 0.331 | | | | |
| | | | | | | - | | | |
| | | | | | | | 2.000 | 1/2- | |
| | | | | | | | | | |
| 10 | | | | | | | | | |
| ¹ G. Hardie et al., Phys. Rev. C 29 , 1199 (1984) ² M. Wiescher et al., Phys. Rev. C 28 , 1431 (1983) | | | | | | | 0 | 3/2 20 | 018-06 |

*0*5 10

³H. Yamaguchi et al., Phys. Rev. C **87**, 034303 (2013)

Experiment



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ISAC-I

 50 μA 500 MeV p+ from main cyclotron

- Ta target
- A = 7 extracted from target using TRIUMF Resonant Ionization Laser Ion Source (TRILIS)
- Transported to high resolution mass separator
- Reaccelerated to 454 A keV by ISAC-I accelerators (RFQ & DTL)
- Delivered to DRAGON gas target
- $I_{avg} = 2.0(1.4) \times 10^7 \text{ pps}$
 - 2018-06-05 11

Experiment





• 3 main parts:

- Head
 - Differentially-pumped windowless gas target
 - High geometric efficiency BGO γ-ray array
 - Detects prompt γ emissions of excited recoil nuclei
- Body
 - High-suppression
 electromagnetic mass separator
 - 2 stages of separation (MD, ED, MD, ED)
- Tail
 - Suite of heavy ion detectors
 - Dual MCP for TOF
 - DSSSD, IC, or Hybrid for E-loss / deposition

Experiment

- Performed ^{6,7Li}(α, γ)^{10,11}B yield measurements for background / acceptance characterization
- Performed Yield measurements of $E_r = 1.155$ MeV and $E_r = 1.109$ MeV resonances



Analysis





- *E_r* = 1.155 MeV
- Candidate recoils identified via TOF between coincident γ and heavy ion signals

Analysis





Analysis





- *E_r* = 1.155 MeV
- Candidate recoils identified via TOF between coincident γ and heavy ion signals
- Gating on TRILIS signal provides further discrimination of ¹¹C / ¹¹B
- 8 candidate ¹¹C recoils pass gates on Separator TOF, TRILIS, E_{BGO} , E_{DSSSD}

⁷Li Contamination



- $\frac{(m_{\tau_{Be}} m_{\tau_{Li}})}{m_{\tau_{Be}}} = 0.00013 \rightarrow \text{expect significant } ^7\text{Li contamination}$
- Average 7 Li / 7 Be ratio = 520:1
- Observed total of 172 candidate recoil events (signal + bg region)
- Given detection efficiencies, number or signal / bg events and ratio of signal / bg regions yields an upper limit¹ of 15 detected ¹¹C recoils (given detection efficiencies and ratio of signal / bg regions)

$$Y = \frac{N_{rec}}{N_b \eta_{DRA}} = 6.39 \times 10^{-11}$$

 \rightarrow Preliminary (1 – σ) upper limit (E_r = 1.155 MeV resonance)

$$\omega \gamma = \frac{2 Y_{\infty}}{\lambda_r^2} \frac{m_{^7Be}}{m_{^7Be} + m_{\alpha}} \epsilon_{lab} = 0.64 \text{ eV}$$

¹W. A. Rolke et al., Nucl. Instrum. Meth. A **551**, 493 (2005)

Future Plans



• Further analysis of current data

 \rightarrow upper limits on E_r = 1.155 MeV and E_r = 1.109 MeV resonances

- Post-experiment ⁷Be beam development on UC_x target yielded intensities as high as 2.4×10⁸ pps
 - Suggests use of pure SiC target could yield intensities ~10⁹ pps
 - Possible to post-strip in HEBT beamline at these intensities
 → pure ⁷Be on target by selecting q = 4
 - Reperform previous measurements of E_r = 1.109 MeV and E_r = 1.155 MeV resonances with pure ⁷Be on target
 - Probe possible existence of $E_r = 1.355$ MeV resonance





- ${}^{7}\text{Be}(\alpha,\gamma){}^{11}\text{C}$ reaction rate impacts isotopic abundances of *p*-nuclei in *vp*-process nucleosynthesis
- 2 resonances in ⁷Be(α, γ)¹¹C were directly measured with DRAGON E_r = 1.155 MeV and E_r = 1.109 MeV
 - Preliminary (1σ) upper limit 0.64 eV(E_r = 1.155 MeV resonance)
- Beam Development suggests use of pure SiC target could yield a background-free measurement



Thank You!

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Discovery, accelerated

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