Breakout reactions from the *pp*-chain and the νp-process: Measurement of the ^{7}Be$(\alpha, \gamma)^{11}$C reaction rate in inverse kinematics

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Nuclear Astrophysics Group
Department of Physics & Astronomy, McMaster University

SAP-EEC Meeting
Vancouver, July 22nd, 2016

Introduction & Motivation

Introduction: How heavy elements are formed?

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are synthesized by *s*-process & *r*-process.

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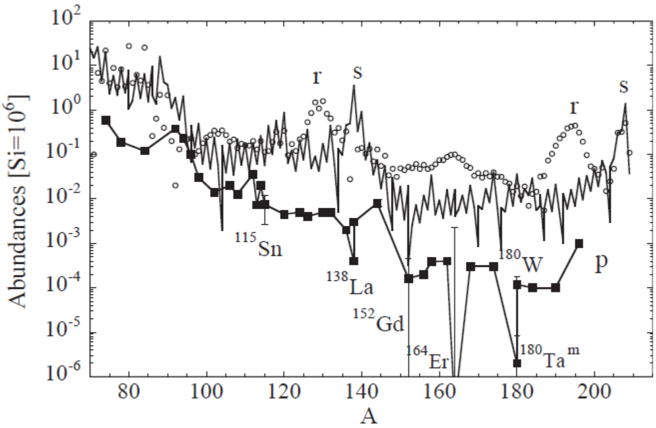
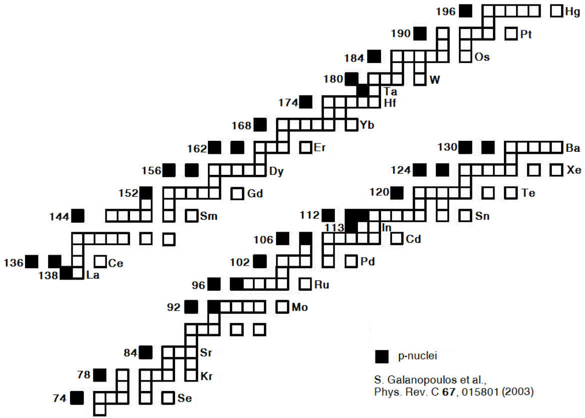


[M. Arnould and S. Goriely, Phys. Rep. **384**, 1 (2003)] *Review Article*

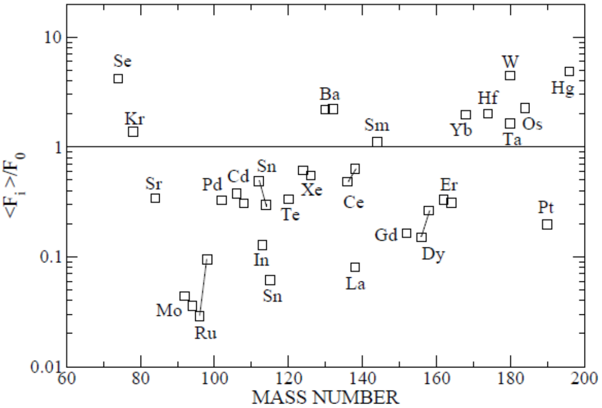
Introduction: p-nuclei & γ-process



S. Galanopoulos et al., Phys. Rev. C **67**, 015801 (2003)

There are about 35 neutron deficient stable isotopes with $A \geq 74$ that cannot be synthesized by any of the known neutron capture processes.

Introduction: *p*-nuclei & γ-process



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

Their most promising nucleosynthetic scenario is the γ-process.
Abundances of some species cannot be reproduced.


Image Credit: Bob Franke

Introduction: νp-process as the origin of *p*-nuclei

Occurs in core-collapse supernovae when intense neutrino fluxes create proton-rich ejecta.

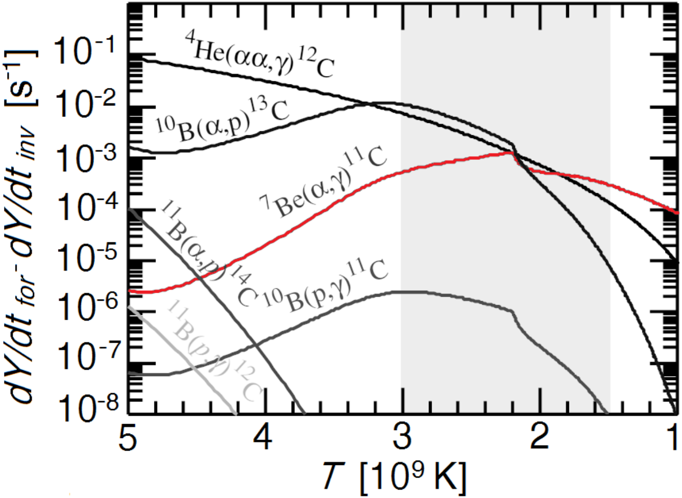
Bypasses the *rp*-process waiting-nuclei near A $\sim$ 60-70 and enables the reaction flow to heavier nuclei.

Can explain the abundances of ^{92,94}Mo & ^{96,98}Ru.

νp-process is very sensitive in both *supernova dynamics* & *nuclear physics*.

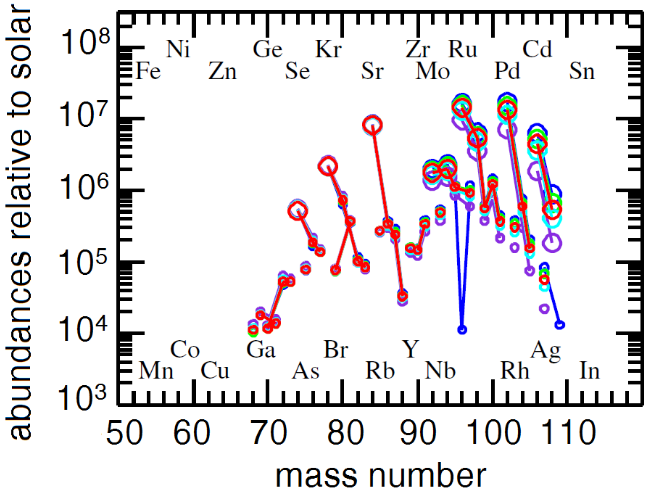
[S. Wanajo, Astrophys. J. **647**, 1323 (2006)]
[J. Pruet *et al.*, Astrophys. J. **644**, 1028 (2006)]
[C. Fröhlich *et al.*, Phys. Rev. Lett. **96**, 142502 (2006)]

^{7}Be$(\alpha,\gamma)^{11}$C reaction can compete with 3α process



[*Adapted from*: S. Wanajo, H.-T. Janka and S. Kubono, Astrophys. J. **729**, 46 (2011)]

$^7Be(\alpha,\gamma)^{11}C$ can alter νp-abundances A∼90-110



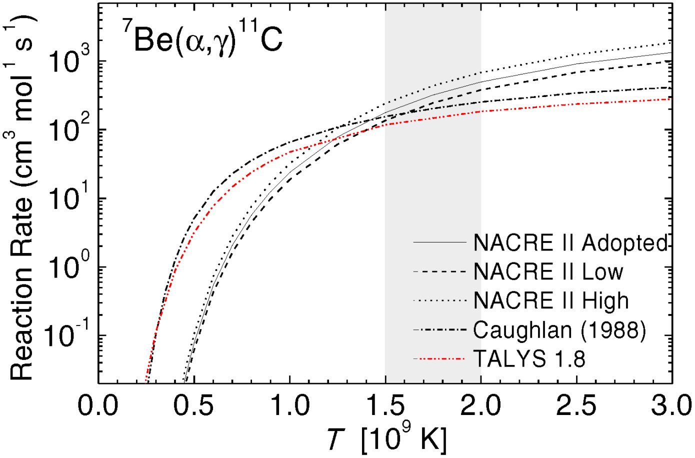
$^7Be(\alpha,\gamma)^{11}C$ reaction rate:

$\times$ 1 2 10

$\div$ 2 10

[*Adapted from*: S. Wanajo, H.-T. Janka and S. Kubono, Astrophys. J. **729**, 46 (2011)]

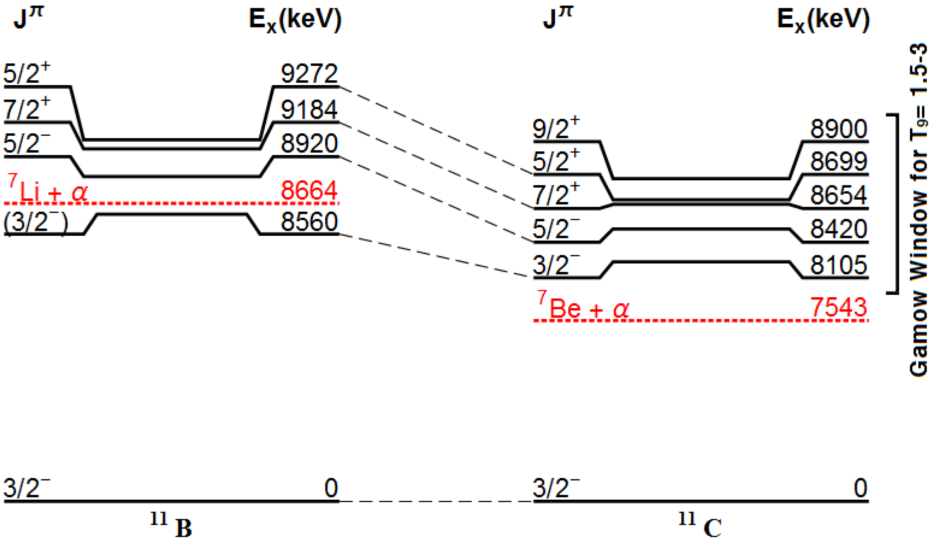
^{7}Be$(\alpha,\gamma)^{11}$C reaction rate is not well known



[G.R. Caughlan and W.A. Fowler: At. Data Nucl. Data Tables **40**, 283 (1988)]
[S. Goriely, S. Hilaire and A. J. Koning, A&A **487**, 767 (2008)]
[Y. Xu *et al.*, Nucl. Phys. A **918**, 61 (2013)]

What we know about $^{7}Be(\alpha,\gamma)^{11}C$

Joint Level Scheme ^{11}B & ^{11}C



Previous work related to the ^{7}Be$(\alpha,\gamma)^{11}$C reaction

PHYSICAL REVIEW C VOLUME 29, NUMBER 4 APRIL 1984

Resonant alpha capture by ^{7}Be and ^{7}Li

G. Hardie
Physics Department, Western Michigan University, Kalamazoo, Michigan 49008

B. W. Filippone* and A. J. Elwyn†
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

M. Wiescher
Physics Department, The Ohio State University, Columbus, Ohio 43210

R. E. Segel
Physics Department, Northwestern University, Evanston, Illinois 60201
(Received 2 December 1983)

Hardie *et al.* studied the first two resonances above the α-threshold ($\mathrm{E_x}$= 8105 keV and $\mathrm{E_x}$= 8421 keV) with a radioactive ^{7}Be target.

[G. Hardie *et al.*, Phys. Rev. C **29**, 1199 (1984)]

Previous work related to the $^{7}Be(\alpha,\gamma)^{11}C$ reaction

PHYSICAL REVIEW C

NUCLEAR PHYSICS

THIRD SERIES, VOLUME 28, NUMBER 4 OCTOBER 1983

^{11}C level structure via the $^{10}B(p,\gamma)$ reaction

M. Wiescher, R. N. Boyd, S. L. Blatt, L. J. Rybarcyk, and J. A. Spizuoco
Department of Physics, The Ohio State University, Columbus, Ohio 43210

R. E. Azuma, E. T. H. Clifford, and J. D. King
Department of Physics, University of Toronto, Toronto, Canada M5S 1A7

J. Görres, C. Rolfs, and A. Vlieks*
Institut für Kernphysik, Universitat Münster, Münster, Federal Republic of Germany
(Received 12 May 1983)

Wiescher *et al.* studied two resonances at E_x= 8654 keV and E_x= 8699 keV via the $^{10}B(p,\gamma)$ reaction but their (α,γ) resonance strengths remain still unknown.

[M. Wiescher *et al.*, Phys. Rev. C **28**, 1431 (1983)]

Previous work related to the ^{7}Be$(\alpha,\gamma)^{11}$C reaction

PHYSICAL REVIEW C **87**, 034303 (2013)

α-resonance structure in ^{11}C studied via resonant scattering of ^{7}Be + α and with the ^{7}Be(α, p) reaction

H. Yamaguchi (山口英斉)* and D. Kahl
Center for Nuclear Study, the University of Tokyo, RIKEN Campus, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Y. Wakabayashi (若林 泰生) and S. Kubono (久保野 茂)
The Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

T. Hashimoto (橋本 尚志)
Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

S. Hayakawa (早川 勢也)
Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, Via S. Sofia 62, 95125 Catania, Italy

T. Kawabata (川畑 貴裕)
Department of Physics, Kyoto University, Kita-Shirakawa, Kyoto 606-8502, Japan

N. Iwasa (岩佐 直仁)
Department of Physics, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan

T. Teranishi (寺西 高)
Department of Physics, Kyushu University, 6-10-1 Hakozaki, Fukuoka 812-8581, Japan

Y. K. Kwon (권영관)
Institute for Basic Science, 70, Yuseong-daero 1689-gil, Yuseong-gu, Daejeon 305-811, Korea

D. N. Binh, L. H. Khiem, and N. N. Duy
Institute of Physics, Vietnam Academy of Science and Technology, 18 Hong Quoc Viet, Nghia do, Hanoi, Vietnam
(Received 21 December 2012; published 4 March 2013)

Yamaguchi *et al.* found a new reasonance at 8900 keV with inelastic scattering of ^{7}Be + α that is expected to enhance the total reaction rate of ^{7}Be$(\alpha,\gamma)^{11}$C by 10%.

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

Previous work related to the ^{7}Be$(\alpha, \gamma)^{11}$C reaction

E_x (keV)	E_r (keV)	J^{π}	Γ_{α} (eV)	Γ_{γ} (eV)	$\omega\gamma$ (eV)
8104.7(17)	560(17)	$3/2^-$	6^{+12}_{-2}	0.350 ± 0.056	0.331
8420(2)	877(2)	$5/2^-$	12.6 ± 3.8	3.1 ± 1.3	3.80

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8654(4)	1110(4)	$7/2^+$	$\leqslant 5$ keV	-	-
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8900	1356	$(9/2^+)$	8 keV	-	-

Description of the Experiment

Objectives of the Experiment

1. First direct measurement of the 1110-keV & 1155-keV resonances. Measure their unknown strengths.

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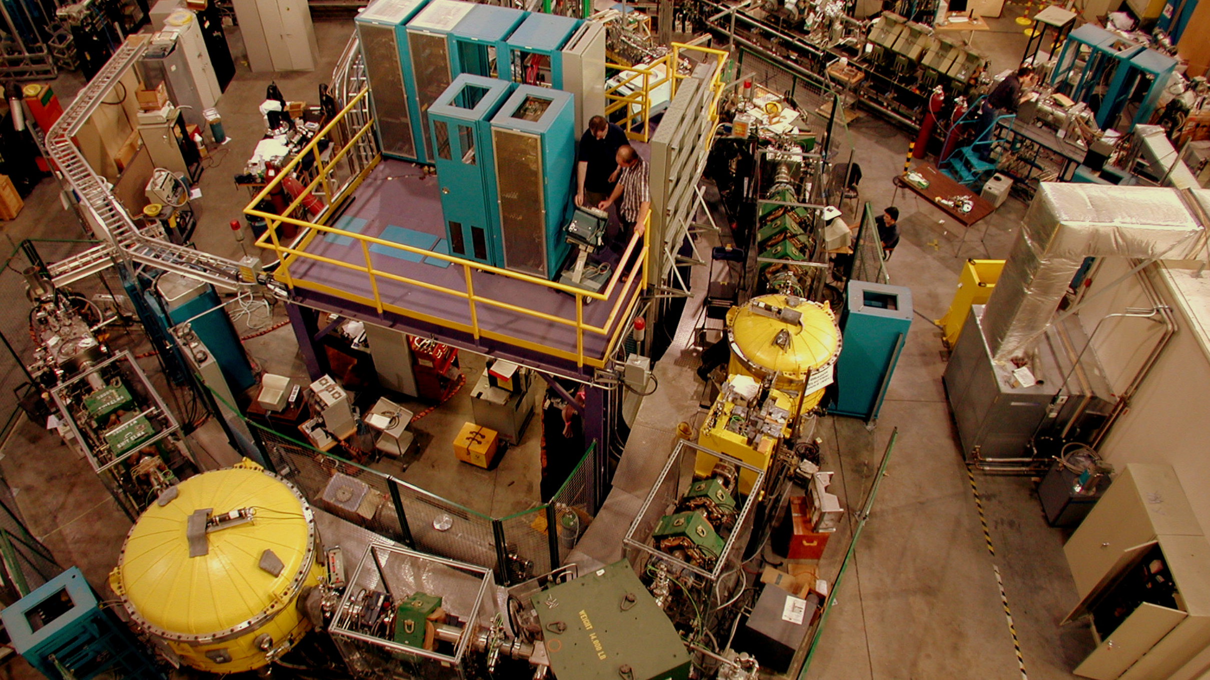
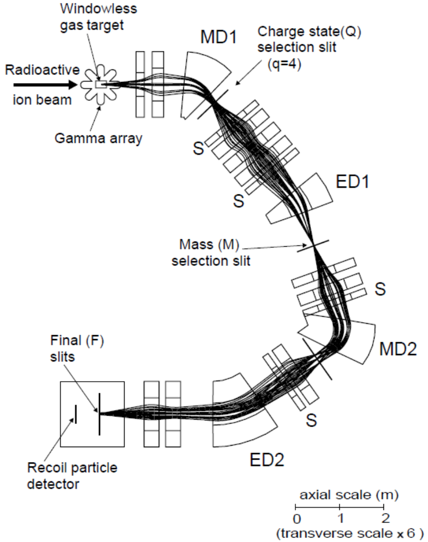
2. Exploratory measurement of the 1356-keV resonance.

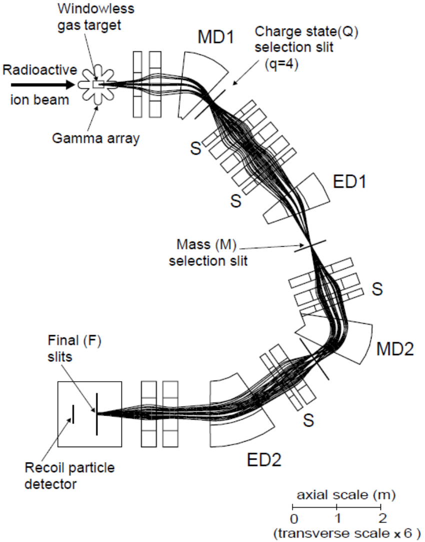

WEIGHT 14,000 LB

DRAGON recoil separator at TRIUMF



Main components of DRAGON are:

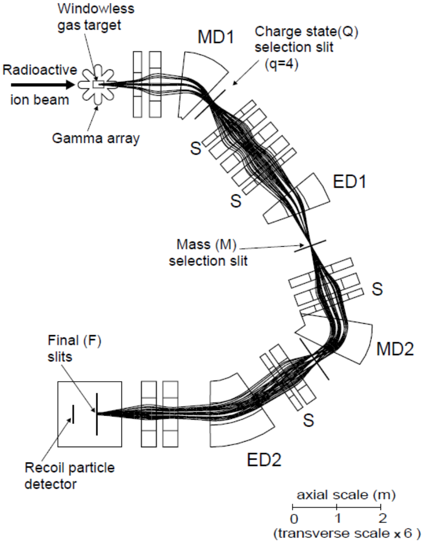
DRAGON recoil separator at TRIUMF



Main components of DRAGON are:

- Windowless gas target

DRAGON recoil separator at TRIUMF



Main components of DRAGON are:

- Windowless gas target
- BGO γ-ray detector array

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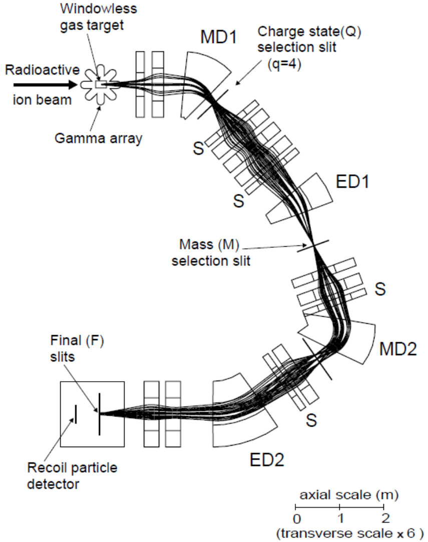

Main components of DRAGON are:

- Windowless gas target
- BGO γ-ray detector array
- Electromagnetic Separators (EMS)

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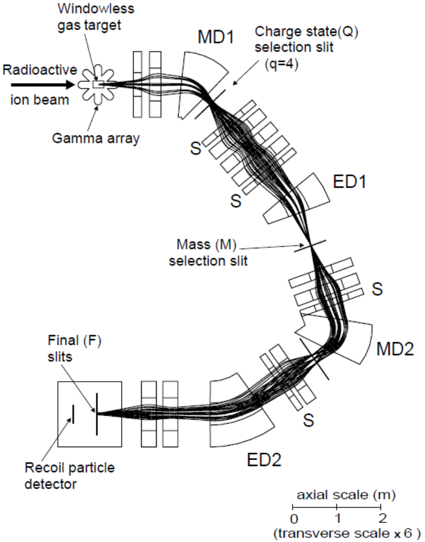

Main components of DRAGON are:

- Windowless gas target
- BGO γ-ray detector array
- Electromagnetic Separators (EMS)
- Recoil Detection system

[D.A. Hutcheon *et al.*, Nucl. Instr. Meth. Phys. Res. A **498**, 190 (2003)]

Momentum cone exceeds DRAGON’s acceptance

DRAGON’s acceptance:
22 mrad

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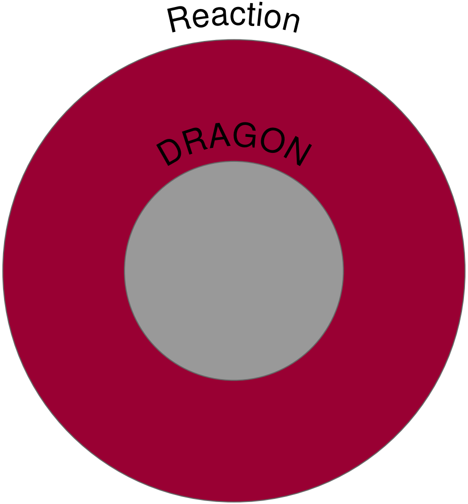

DRAGON's acceptance:
22 mrad

^{7}Be$(\alpha, \gamma)^{11}$C reaction:
43.3 mrad
$\mathrm{E_x}$= 8654 keV ($\mathrm{E_r}$= 1110 keV)

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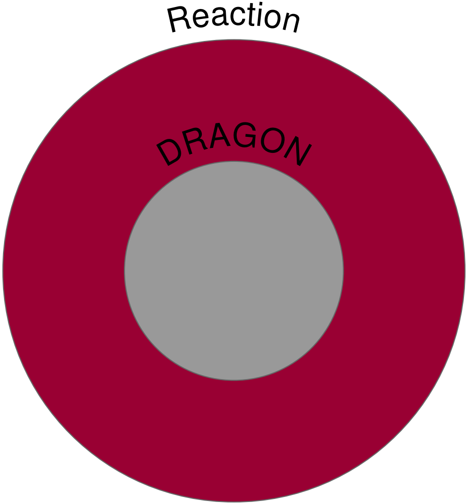

DRAGON's acceptance:
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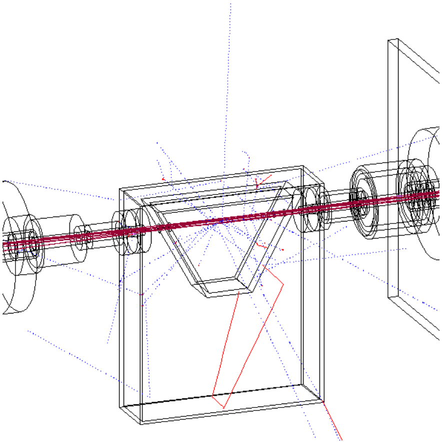
^{7}Be$(\alpha,\gamma)^{11}$C reaction:
43.3 mrad
$\mathrm{E_x}$= 8654 keV ($\mathrm{E_r}$= 1110 keV)
42.7 mrad
$\mathrm{E_x}$= 8699 keV ($\mathrm{E_r}$= 1155 keV)

Testing the DRAGON: GEANT simulations



An acceptance test in the low mass regime.

[D. Gigliotti, Ph.D. Thesis, Univ. of Northern British Columbia, (2004)]

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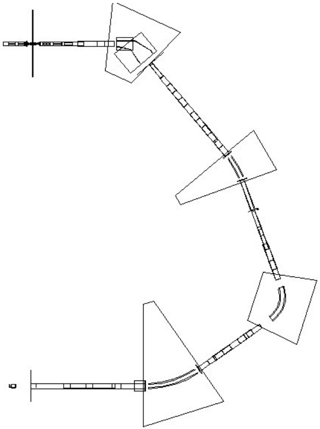

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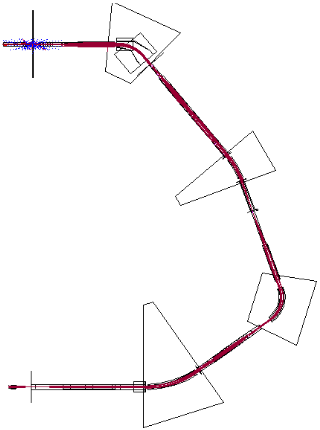
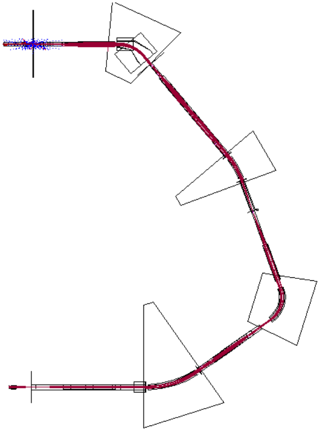


An acceptance test in the low mass regime.

$\mathrm{E_x}$ = 8105 & 8420 keV
unfavourable kinematics
$\sim$ 5% transmission

[D. Gigliotti, Ph.D. Thesis, Univ. of Northern British Columbia, (2004)]

Testing the DRAGON: GEANT simulations

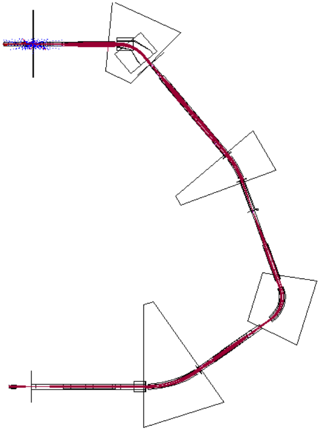


An acceptance test in the low mass regime.

^{6}Li(α, γ) reaction
$\mathrm{E_x}$= 5164 keV ($\mathrm{E_r}$= 703 keV)
as benchmark
60% transmission

[D. Gigliotti, Ph.D. Thesis, Univ. of Northern British Columbia, (2004)]

GEANT simulations: Results



E_x= 8654 keV
27 % transmission

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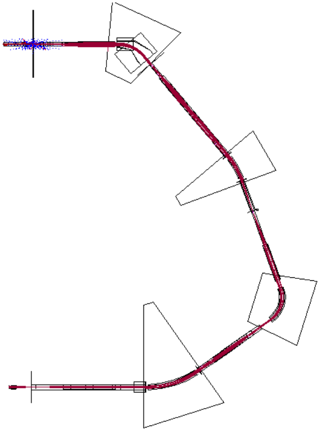

E_x= 8654 keV
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E_x= 8699 keV
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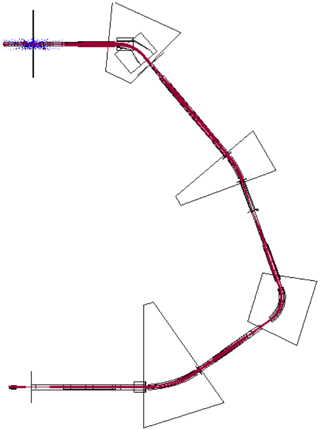
GEANT simulations: Results



E_x= 8654 keV
27 % transmission

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18 % transmission

E_x= 8900 keV
branching ratios unknown

Experiment: Yield Estimate

Resonance strengths in the range of **1-5 eV**

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^{7}Be beam ($T_{1/2}$= 53.22 days) intensity of **10^7 particles per second**

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$\sim$ 3-13 counts per shift for E_x= 8654 keV

$\sim$ 2-9 counts per shift for E_x= 8699 keV

Experiment: Ion Beams

Radioactive Ion Beam - ISAC

4×10^7 particles per second ^7Be

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Stable Ion Beams - OLIS

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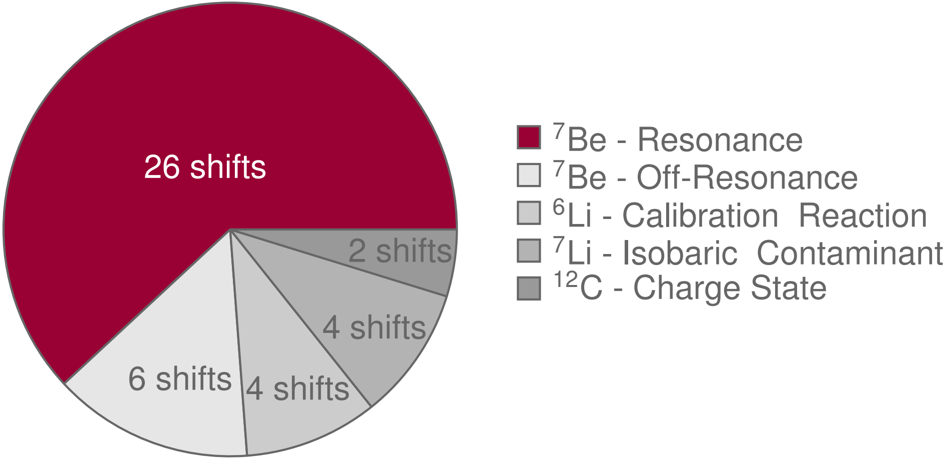
10^{11} particles per second ^6Li

10^{12} particles per second ^7Li

10^{12} particles per second ^{12}C

Beam Time Request

Shifts Requested are 42 : 32 RIB and 10 stable



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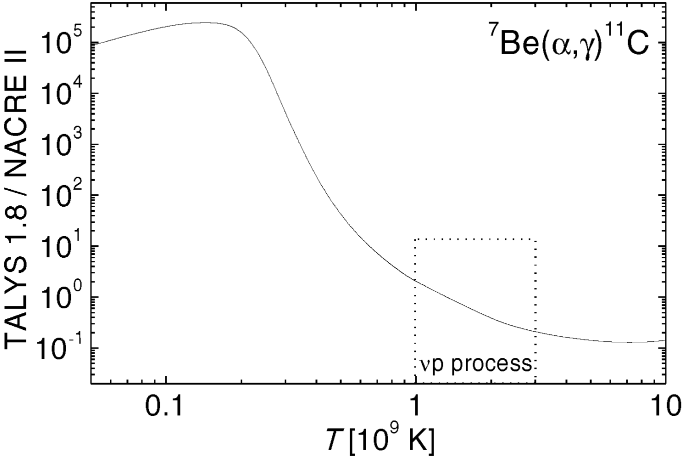
- The breakout reaction ^{7}Be$(\alpha, \gamma)^{11}$C can alter some nuclear inputs.
- DRAGON facility is ready to successfully perform this experiment.

Extra Slides

$^7Be(\alpha,\gamma)^{11}C$ reaction rate is not well known



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

GEANT simulations: Additional modifications

1. Mistuning an energy setting $\pm$ 3% can change the transmission by $<$**3%**. Already used successfully in DRAGON.

   [C. Matei *et al.*, Phys. Rev. Lett. **97**, 242503 (2006)]

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$$\pm \mathbf{2.8\%} \text{ for the } \mathrm{E_x} = 8654 \text{ keV}$$

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2. Angular distributions of γ-rays can alter the transmission by

   $\pm$ **2.8%** for the $\mathrm{E_x}$= 8654 keV
   $\pm$ **1.5%** for the $\mathrm{E_x}$= 8699 keV