Radioactive beam experiments relevant to gamma-ray emitters in novae and supernovae

Alex Murphy
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New estimates of the gamma-ray line emission of the Cygnus region from INTEGRAL/SPI observations

Pierrick Martin$^{1,2}$, Jürgen Knödlseder$^{1,2}$, Roland Diehl$^3$, and Georges Meynet$^4$

**Fig. 1.** Spectrum of the 1809 keV emission from the Cygnus region, from about 4 years of INTEGRAL/SPI observations. The red line represents the best Gaussian fit to the data points.
Constraints on the kinematics of the $^{44}$Ti ejecta of Cassiopeia A from INTEGRAL/SPI

Pierrick Martin$^{1,2}$, Jürgen Knödlseder$^{1,2}$, Jacco Vink$^{3}$, Anne Decourchelle$^{4}$, and Matthieu Renaud$^{5}$
## Gamma Ray Emitters

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>lifetime</th>
<th>Emission</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{13}$B</td>
<td>862 s</td>
<td>511 keV</td>
<td>CO Novae, ONe Novae</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>158 m</td>
<td>511 keV</td>
<td>CO Novae, ONe Novae</td>
</tr>
<tr>
<td>$^{7}$Be</td>
<td>77 d</td>
<td>478 keV</td>
<td>CO Novae</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>3.75 yr</td>
<td>1275 keV</td>
<td>ONe Novae</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>1.0 Myr</td>
<td>1809 keV</td>
<td>WR, CC SNe?</td>
</tr>
<tr>
<td>$^{44}$Ti</td>
<td>87 yr</td>
<td>1157 keV</td>
<td>CC SNe</td>
</tr>
<tr>
<td>$^{60}$Fe</td>
<td>2.2 Myr</td>
<td>1173,1333 keV</td>
<td>CC SNe</td>
</tr>
</tbody>
</table>
\[ ^{18}\text{F}(p,\alpha)^{15}\text{O} \text{ in novae} \]

- \(^{18}\text{F}\) is the leading candidate for satellite gamma-ray observation from Novae
- \(^{18}\text{F}(p,\alpha)^{15}\text{O}\) is the main nuclear physics uncertainty in \(^{18}\text{F}\) production
- Issues concerning \(\ell=0\) resonances, missing, broad and sub-threshold resonances

- Recent data from TRIUMF and GANIL
Nuclear Physics: Options

**Direct**
- Explicitly perform the reaction, 1 event at a time
- Event rate very low at relevant temperatures

**Indirect**
- ‘Use’ nuclear physics to access experimentally challenging region
- But... issues: extrapolation, interference, structure differences...

![Graph showing nuclear physics phenomena](image)
Indirect: TRIUMF
(Typical) TRIUMF set-up
(Typical) TRIUMF set-up
Thick Target Technique

Data cover wide range of energies

Yield is combination of Coulomb scattering and resonant contribution

Detailed shape of excitation function contains required nuclear information

$^{18}\text{F}(p,p)^{18}\text{F}$
Thick Target Technique

Data cover wide range of energies

Yield is from resonant contribution only

Shape is simpler

\[ ^{18}\text{F}(p,\alpha)^{15}\text{O} \]
Data

- R-matrix analysis
- Analysis based on (p,p) only would have been VERY different to that based on simultaneous (p,p) and (p,α)
- Deduce $E, \Gamma_p, \Gamma_\alpha, \ell$. interference

ASM et al. PRC 79 (2009)
Search for astrophysically important $^{19}\text{Ne}$ levels with a thick-target $^{18}\text{F} (p,p) ^{18}\text{F}$ measurement


![Graph with energy levels and counts per 10 channels vs. E_{cm} (MeV).]
...No state at 1009 keV!

PHYSICAL REVIEW C 79, 058801 (2009)

Simultaneous measurement of the $^{18}$F$(p, p)^{18}$F and $^{18}$F$(p, \alpha)^{15}$O reactions: Implications for the level structure of $^{19}$Ne, and for $^{18}$F production in novae

A. St. J. Murphy, A. M. Laird, C. Angulo, L. Buchmann, T. Davinson, P. Descouvemont, S. P. Fox, J. José, R. Lewis, C. Ruiz, K. Vaughan, and P. Walden

The IoP one day meeting on Radioactivity in Astrophysics: 10 December 2010
Broad $\ell = 0$ state at $\sim 1.5$ MeV?

The $^{18}\text{F}(p,\alpha)^{15}\text{O}$ low-energy S-factor: A microscopic approach

M. Dufour, P. Descouvemont

S-factor after addition of new states

Alternative S-factor
Broad $\ell = 0$ state at $\sim 1.5$ MeV?

Dalouzy et al. PRL 102 (2009) 162503

Use inelastic scattering

$^1H(^{19}Ne,p)^{19}Ne^*(p)^{18}F$

$E_x = 7863 \pm 39$ keV

$\Gamma_{\text{tot}} = 292 \pm 107$ keV

$E_x = 1573 \pm 641 = 7984$ keV

$\Gamma_p = 8^{+8}_{-4}$ keV

$\Gamma_\alpha = 34 \pm 13$ keV
Indirect: GANIL
GANIL: Preliminary results

\[ ^{18}\text{F}(p,p) \]

- More work needed
- Broadly consistent with TRIUMF data
- Confirms 1009 keV resonance result
- Unclear regards 1.49 MeV state
More work needed!

Backgrounds clearly need to be better understood

However... one might argue that there is ‘no room’ for the 1.49 MeV state...

Thesis work of David Mountford (Edinburgh)
Direct: TRIUMF

Thesis work of Clare Beer (York)
$^{18}$F(p,α) in the Gamow Window

Key issue to be resolved: What is the cross section in the Gamow window?

Solution: Make a measurement at low energy 250 keV
Thin target

S2-2 (10 - 29 deg)
63 mm
S2-1 (3.8 - 9.9 deg)
165 mm

Target

LEDA 2
(120 - 146 deg)
75 mm

LEDA 1
(45 - 69 deg)
50 mm

Diagnostics
(~ 3 deg)
650 mm

Faraday Cup
Kinematics work!

Figure 4.10: Kinematic $\theta_{lab}$ vs. $E_{cm}$ and $\theta_{lab}$ vs. $E_{lab}$ plots, calculated using Kin2b for the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction at $E_{cm} = 2.50$ keV.

Figure 6.1: Raw data recorded for a single $^{18}\text{F} \ E_{beam} = 12.96$ MeV run.

Thesis work of Clare Beer (York)
Rare event searches!

Graph showing the relationship between alpha energy and heavy ion energy, with points indicating the reactions $^{18}\text{O}(p,\alpha)^{15}\text{N}$ and $^{18}\text{F}(p,\alpha)^{15}\text{O}$. The axes are labeled Alpha Energy (40 keV/Channel) and Heavy Ion Energy (40 keV/Channel).
Rare event searches!

Two $E_{cm}=250$ keV events! No background!!

Graph showing $^{18}$O$(p,\alpha)^{15}$N and $^{18}$F$(p,\alpha)^{15}$O reactions with $E_{cm}$ values at 12.960 MeV, 8.820 MeV, 6.660 MeV, and 4.752 MeV.
Direct measurement: Results

The higher cross section interference possibilities are favoured by the new data.
It could be we are seeing the contribution from a sub-threshold state...
\(^{44}\text{Ti}\) and Core Collapse Supernovae
The Disappearance of the Red Supergiant Progenitor of Supernova 2008bk

Seppo Mattila,¹,²* Stephen Smartt,³ Justyn Maund,⁴,⁵ Stefano Benetti,⁶ Mattias Ergon¹
Presolar grains

A grain from the Murchison Meteorite
The Neutrino Mechanism

Nonburning hydrogen
Hydrogen fusion
Helium fusion
Carbon fusion
Oxygen fusion
Neon fusion
Magnesium fusion
Silicon fusion
Iron ash

Neutrino Heating

Wilson. (1985)
44Ti production as a diagnostic

- Amount ejected sensitively depends on location of the ‘mass cut’
  - Material that ‘falls back’ is not available for detection
- 44Ti yield a sensitive diagnostic of the explosion mechanism
- Thus, very useful for models to make comparisons against

Timmes et al. (1996)
Key Reactions

- $^{40}\text{Ca}(\alpha,\gamma)$
  - Recent from Nassar et al. \textit{(PRL 96 (2006) 041102)}
  - Results from Vockenhuber et al. \textit{(PRC 76 (2007) 035801)}
- Triple–$\alpha$
  - Ubiquitous; not the focus here
- $^{44}\text{Ti}(\alpha,p)$
  - Sonzogni et al. \textit{PRL 84 (2000) 1651}: Measured above Gamow window
- $^{44}\text{Ti}(\alpha,\gamma)$
  - No relevant data
- $^{45}\text{V}(p,\gamma)^{46}\text{Cr}$
  - Interesting, no relevant data, hard...
$^44\text{Ti}(\alpha,p)$: Sonzogni data

Note: Astrophysical region is $\sim 1$-4 MeV
Need to be able to access cross sections to $< 1$ mb
Accuracy of HFSM reduces at lower energies
The ERAWAST Project

- “Exotic Radionuclei from Accelerator Waste”
- Nuclear Astrophysics, geophysics, medicine, industry, etc etc...
- 3.5 MBq presently available (~2x10^{17} ions); 20 ml 1M HNO₃

- Hot Ti within SUPERNANOGAN?
- Impinge accelerated beam on to ^4\text{He} gas cell / windowless gas target
- Could consider making ^{44}\text{Ti} target
Reclaiming of $^{44}$Ti
Proposals

October 6, 2010

Dr. A.J. Murphy
University of Edinburgh
amurphy@ph.ed.ac.uk

Dear Dr. Murphy:

I am pleased to inform you that, at its meeting held July 29 & 30, 2010, the Subatomic Physics Experiments Evaluation Committee recommended that your experiment S1289 be given stage 1 approval at medium-high priority. Please see the committee recommendation on the next page.

As you are aware, your experiment will have to undergo a formal safety review by the TRIUMF Science Division Safety Committee before being allocated beam time. In addition, a Technical Review will be required outlining technical demands the experiment will place on TRIUMF (space, cryogenics and electrical support, machine shop, electronics shop, drawing office, detector facility, electronics pool, and wire chamber support). According to our policy, no experiments will be scheduled for beam without the relevant safety approvals and technical reviews.

At year-end, the TRIUMF Publications Office may request a report on your experiment for the TRIUMF Annual Report. We would also like to request that you give appropriate acknowledgement to TRIUMF in any of your talks or publications.

Let me congratulate you and your colleagues, and wish you every success with your experiment. Please do not hesitate to contact me if I can be of help in any way.

Yours sincerely,

Richard Widelshyn
for Gordon C. Ball
Science Division Head

S1289

The IoP one day meeting on Radioactivity in Astrophysics: 10 December 2010
Rocket Science!

30x better narrow line sensitivity
Thank you