Direct and resonant reaction studies for nuclear astrophysics at HIE-ISOLDE

Alex Murphy
University of Edinburgh
IPPP Durham Senior Experimental Fellow

ISOLDE:
A Facility for Nuclear Astrophysics

- The capabilities of REX-ISOLDE are well matched to the needs of nuclear astrophysics
- Stars generally have long lifetimes

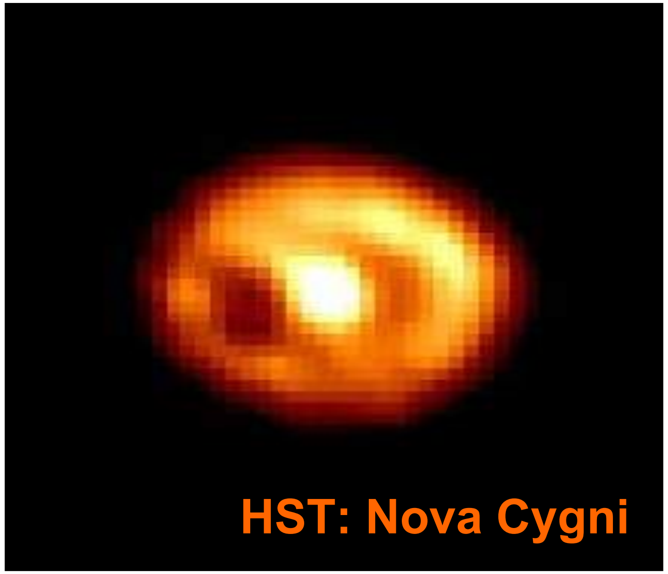
  → Nuclear reactions are slow, energies are below the Coulomb barrier, cross sections are very small, the nuclei involved are stable
- Occasionally, stars undergo rapid transitions

  → Nuclear reactions are faster, energies approach the Coulomb barrier, cross sections are not quite so small, radioactive nuclei are involved

Nuclear Astrophysics experiments often require intense stable and radioactive ~MeV/u beams

Novae & X-Ray bursters

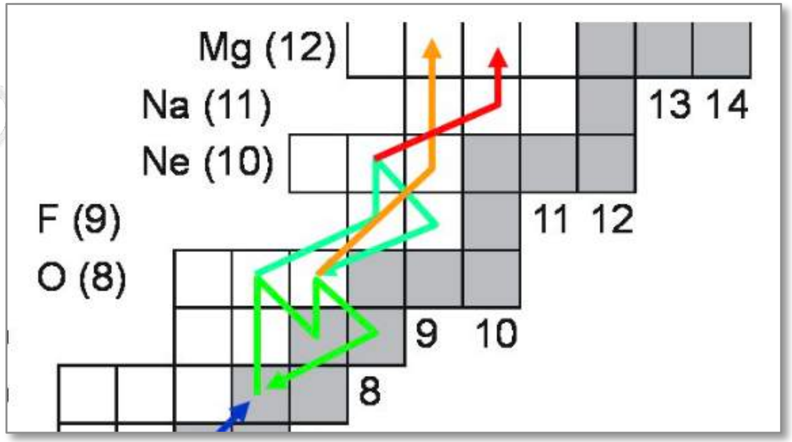
- About ½ of all stars are in binary systems
- For certain separations and mass ranges, this configuration leads to (inevitable) thermonuclear nuclear runaway scenarios
  - Novae: Accretion on to CO or ONe WD
  - X-Ray burster: Accretion on to a neutron star
- Novae produce significant contributions of some isotopes to the ISM
- Possibilities for gamma ray observations.
- Specific nuclear reactions can affect explosion onset, ejecta abundances, etc

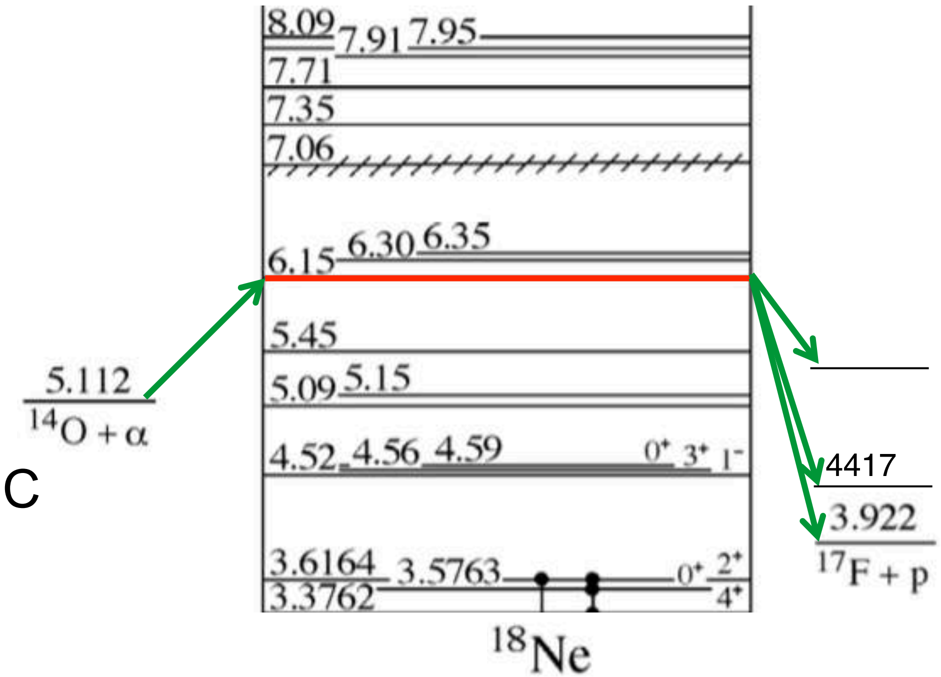


$^{14}O(\alpha,p)^{17}F$

- May trigger break out from the hot CNO cycles
- Direct measurement difficult
- Expected to be dominated by a single 1^- resonance
- Γ_{tot}= 50 keV via $^{17}F(p,p)$
- Γ_{α}=3.2 eV via $^{17}F(p,\alpha)$
  - But this only give the ^{17}Fgs production contribution
- Hence a study of

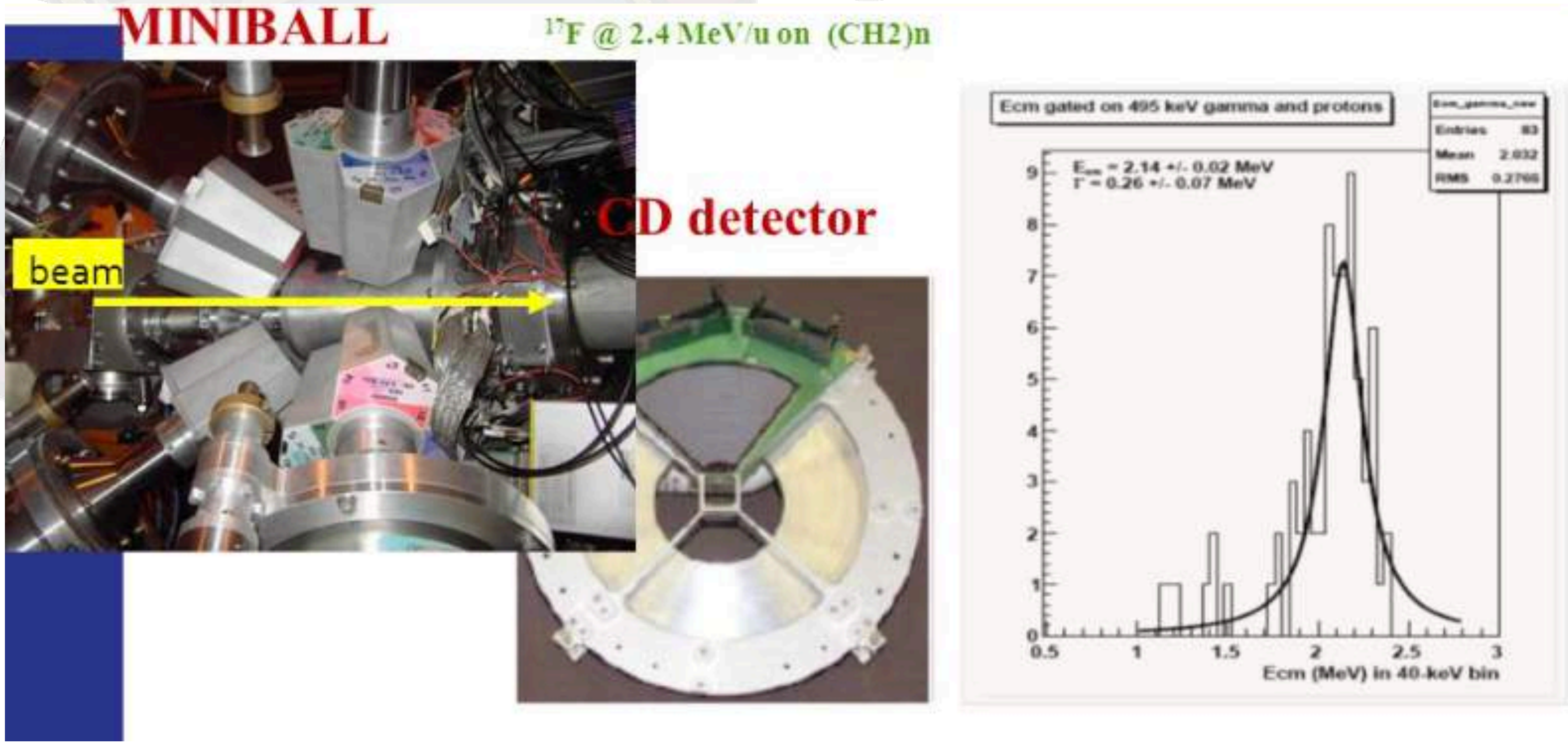
  $^{17}F(p,p')^{17}F$: He *et al.* Phys. Rev. C 80 042801R (2009)





$^{14}O(\alpha,p)^{17}F$

- CD system + MINIBALL array



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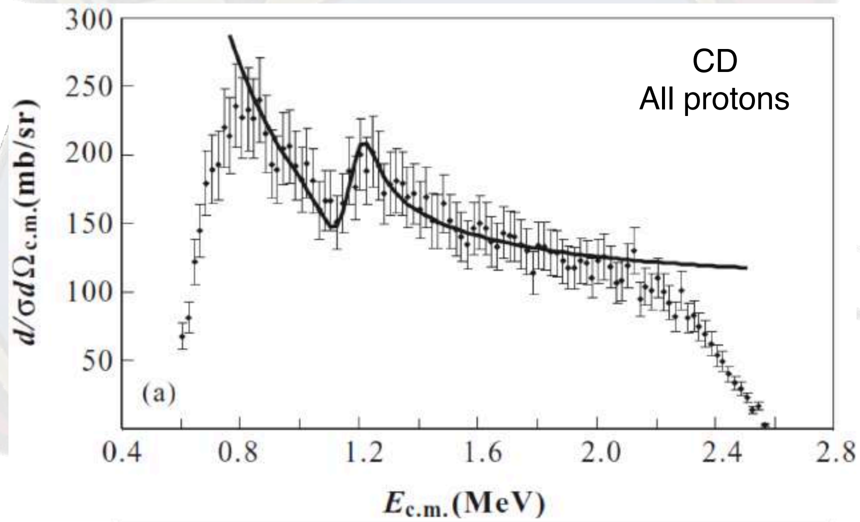

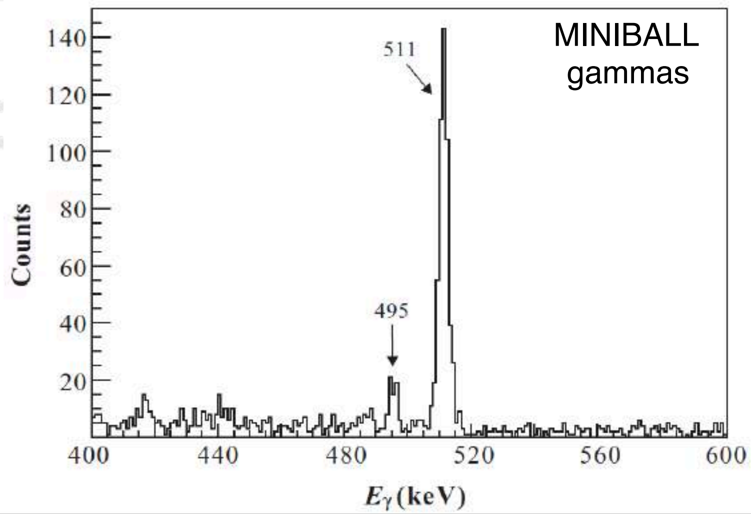

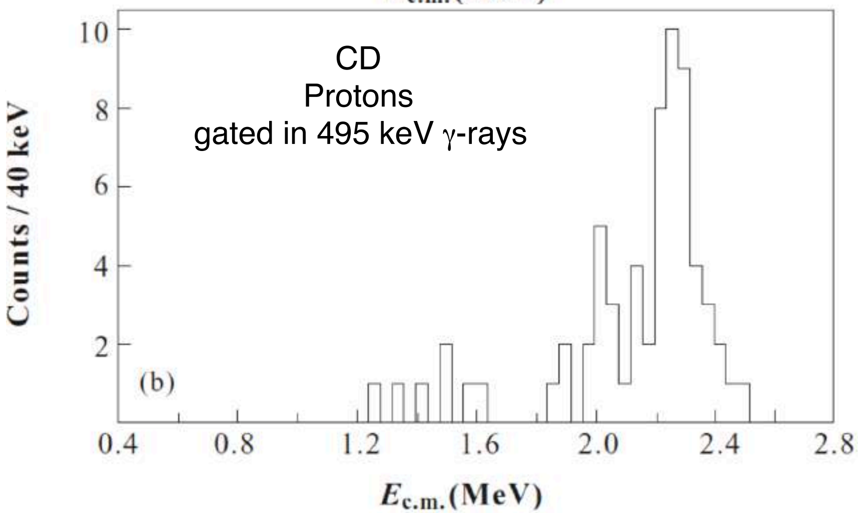

Analysis found $\Gamma_{p0} \sim \Gamma_{p'}$

→ 1^- resonance enhances
the reaction rate, contributing approximately as much as the ground-state component.

However, still unlikely the $^{14}O(\alpha, p)^{17}F$ reaction bypasses the $\beta+$ decay of ^{14}O in the hCNO cycles at novae temperatures and densities

$^{14}O(\alpha,p)^{17}F$

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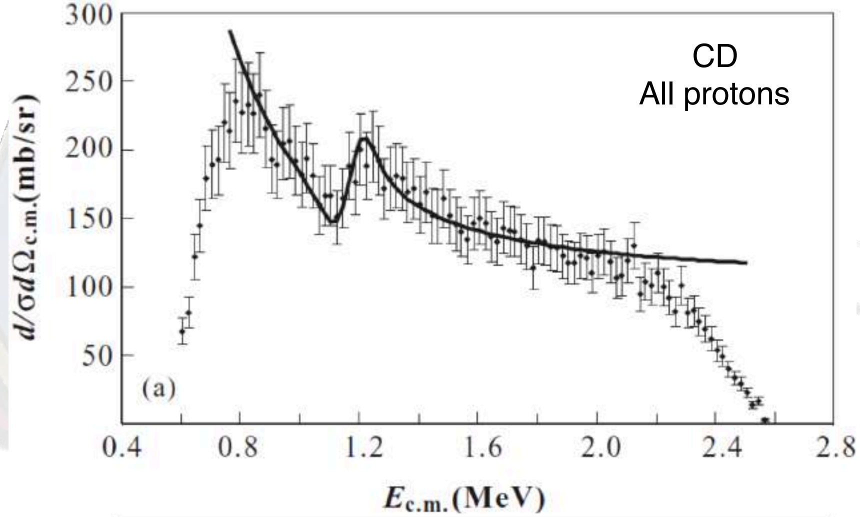

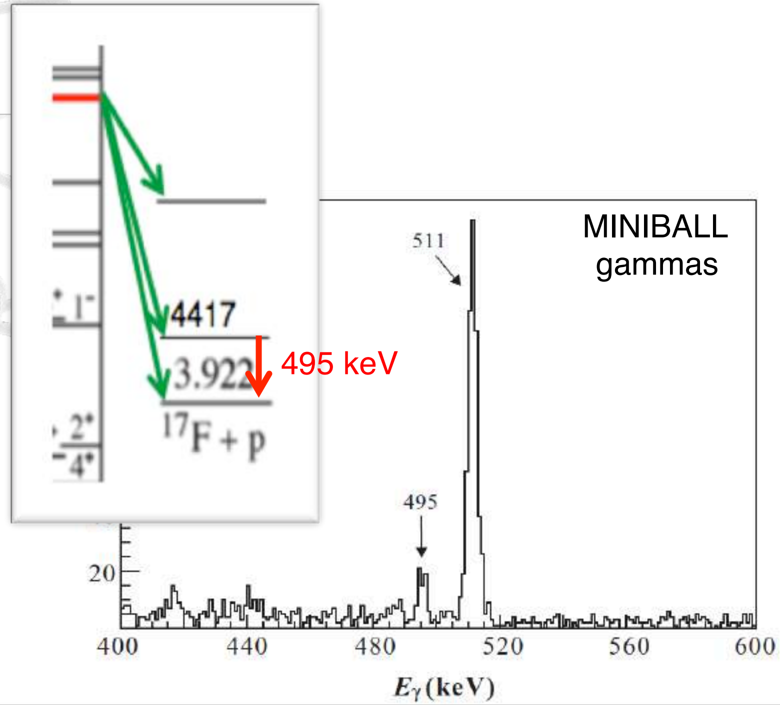

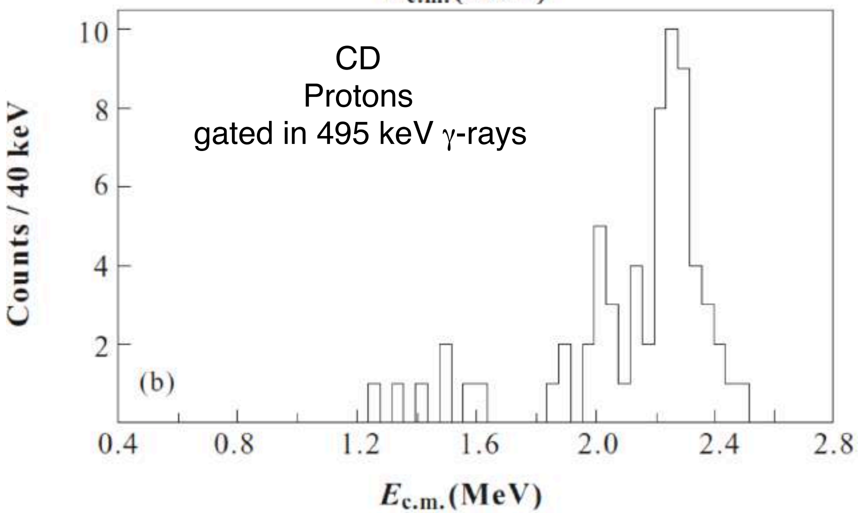

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However, it's unlikely the $^{14}O(\alpha, p)^{17}F$ reaction bypasses the β+ decay of ^{14}O in the hCNO cycles an novae temperatures and densities

Further ongoing discussions, see e.g. D. W. Bardayan, et al. PRC 85 065805 (2012)

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **80**, 042801(R) (2009)

Measurement of the inelastic branch of the $^{14}O(\alpha, p)^{17}F$ reaction: Implications for explosive burning in novae and x-ray bursters

J. J. He,[1,2] P. J. Woods,[1] T. Davinson,[1] M. Aliotta,[1] J. Büscher,[3] E. Clement,[4] P. Delahaye,[4] M. Hass,[5] D. G. Jenkins,[6] V. Kumar,[5] A. St. J. Murphy,[1] P. Neyskens,[3] R. Raabe,[3] A. P. Robinson,[6] D. Voulot,[4] J. van der Walle,[4] N. Warr,[7] and F. Wenander[4]

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[4]*CERN, CH-1211 Geneva 23, Switzerland*
[5]*Weizmann Institute of Science, Rehovot, Il-76100, Israel*
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(Received 3 August 2009; published 27 October 2009)

A measurement of the inelastic component of the key astrophysical resonance in the $^{14}O(\alpha, p)^{17}F$ reaction for burning and breakout from hot carbon-nitrogen-oxygen (CNO) cycles is reported. The inelastic component is found to be comparable to the ground-state branch and will enhance the $^{14}O(\alpha, p)^{17}F$ reaction rate. The current results for the reaction rate confirm that the $^{14}O(\alpha, p)^{17}F$ reaction is unlikely to contribute substantially to burning and breakout from the CNO cycles under novae conditions. The reaction can, however, contribute strongly to the breakout from the hot CNO cycles under the more extreme conditions found in x-ray bursters.

DOI: 10.1103/PhysRevC.80.042801 PACS number(s): 23.20.Lv, 21.10.Dr, 26.50.+x, 27.30.+t

Astrophysical x-ray bursts have been interpreted as being generated by thermonuclear explosions in the atmosphere of an accreting neutron star in a close binary system [1]. These bursts are characterized by sudden enormous spikes in x-ray emission, lasting a few seconds, with repeating cycles on a time scale of hours to days. These spectacular astrophysical phenomena are now being studied in detail in a number of x-ray satellite observatory missions, including Chandra, XMM-Newton, and Integral. The extreme temperatures and densities open up new pathways for increased energy generation and nucleosynthesis. Thermal runaway reactions can be ignited through both the triple-α reaction and breakout from the hot carbon-nitrogen-oxygen (CNO) cycles into the rapid proton capture process (rp process). The rp process may thence proceed as far along the proton drip line as the Sb and Te isotopes, and may possibly be the origin of p nuclei, such as ^{92}Mo and ^{96}Ru [2,3]. In both the triple-α and CNO breakout mechanisms, energy generation increases rapidly as a function of temperature, and hence the rate of energy release can increase faster than the rate of cooling, ultimately leading to x-ray bursts [4]. In the period between bursts, energy is generated at a constant rate by the β-limited hot CNO cycles, the half-lives of the waiting point nuclei ^{14}O and ^{15}O being 71 and 122 s, respectively. As a consequence, novae ejecta are rich in the daughter products ^{14}N and ^{15}N. However, in x-ray burst scenarios, temperatures are such that these waiting points can be bypassed. In particular, the $^{14}O(\alpha, p)^{17}F$ reaction can trigger the breakout from the hot CNO cycles via the $^{17}F(p,\gamma)^{18}Ne(\alpha, p)^{21}Na$ sequence [5].

The $^{14}O(\alpha, p)^{17}F$ reaction rate is thought to be dominated by capture onto a single 1^- resonance $E_r = 1.04$ MeV, corresponding to an excited state in ^{18}Ne at 6.15 MeV [6]. The total width of the state is dominated by proton emission and has already been studied using the elastic scattering of ^{17}F ions on protons in inverse kinematics [7]. The time reverse reaction $^{17}F(p,\alpha)^{14}O$ was later studied in inverse kinematics to obtain the first measurement of the much weaker partial α-decay width of the resonance [8]. A limitation of this latter approach is that it cannot take into account the inelastic reaction channel corresponding to the production of the $\frac{1}{2}^+$ first excited state at 0.495 MeV in ^{17}F in the astrophysical reaction. This reaction branch can be measured by studying the proton inelastic scattering reaction $^{17}F(p,p')^{17}F$, which is the method adopted in the present study. It is also the method reported in Ref. [9]. In that study, a thin $(CH_2)_n$ target was bombarded with ^{17}F ions in the region of the resonance energy ($E_{c.m.} = 2.22$ MeV for the $^{17}F + p$ entrance reaction channel), and inelastic and elastically scattered protons were detected and separated in energy in an annular silicon detector array [9]. A value of the ratio of inelastic scattering to elastic scattering of 2.4 was reported, indicating the inelastic contribution is dominant, although at the time of writing the present report no full value with error had been published.

The present experiment was performed at the CERN Radioactive Beam Experiment On-Line Isotope Mass Separator (REX-ISOLDE) facility [10]. A fully stripped $^{17}F^{9+}$ ion beam was selected to avoid intense isobaric contamination from ^{17}O ions. The beam energy 44.2 MeV ($E_{c.m.} =$ 2.46 MeV) was chosen, so ions entered just above the resonance energy and stopped inside a ~40 μm thick $(CH_2)_n$ target. Elastic and inelastically scattered protons were detected in the laboratory angular range 15°–50° using the double-sided silicon strip detector (CD) system, consisting of four Micron Semiconductor Ltd. (MSL) type QQQ/2, ~35 μm thick, ΔE detectors backed by four MSL type QQQ/1, ~0.5 mm thick, E detectors [11].

Core Collapse Supernovae

- Core Collapse Supernovae… are just exciting!
- There remains fundamental uncertainty in the explosion mechanism
- Gamma-rays from ^{44}Ti decay are one of the few ways in which data could improve models
- Major recent investment in gamma-ray observing satellites is producing new high-quality observational data
- The main nuclear uncertainty is the $^{44}Ti(\alpha,p)^{47}V$ reaction
- ^{44}Ti reclaimed from irradiated parts at PSI is now available
- So… perform a direct measurement of $^{44}Ti(\alpha,p)^{47}V$

Motivation - stronger than ever!

- First NuSTAR observation of Cas-A 1.5±0.3 x10^{-4} $M_\odot$ of ^{44}Ti
- Detailed mapping of turbulence.
- Unexpected separation of ^{44}Ti and Fe (in models, they are produced in the same zones)


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NATURE | LETTER

日本語要約

Asymmetries in core-collapse supernovae from maps of radioactive ^{44}Ti in Cassiopeia A

B. W. Grefenstette, F. A. Harrison, S. E. Boggs, S. P. Reynolds, C. L. Fryer, K. K. Madsen, D. R. Wik, A. Zoglauer, C. I. Ellinger, D. M. Alexander, H. An, D. Barret, F. E. Christensen, W. W. Craig, K. Forster, P. Giommi, C. J. Hailey, A. Hornstrup, V. M. Kaspi, T. Kitaguchi, J. E. Koglin, P. H. Mao, H. Miyasaka, K. Mori, M. Perri + et al.

Affiliations | Contributions | Corresponding authors

342 (20 February 2014) | doi:10.1038/nature12997

ist 2013 | Accepted 13 December 2013 | Published online 19 February 2014

Editor's summary العربية

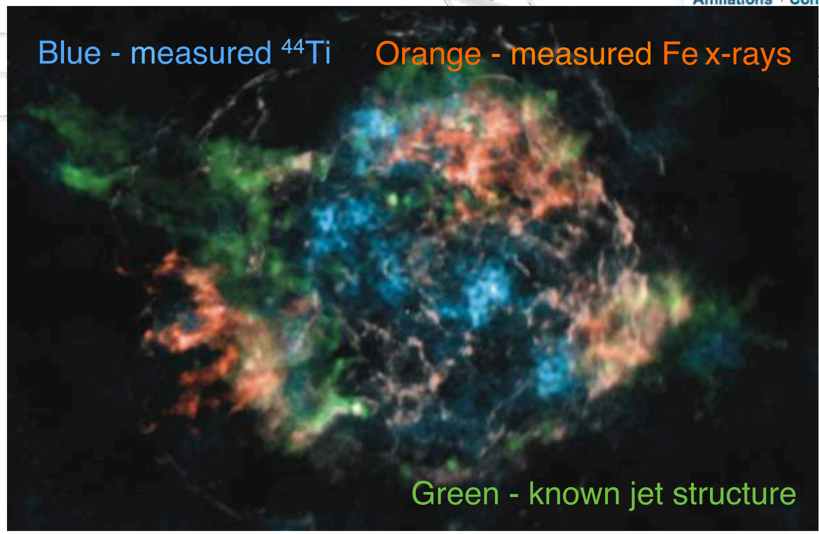
Most simulations of stellar core collapse events indicate that the explosions are asymmetric, but the resulting shapes differ in the various models. Brian Grefenstette *et al.* analysed the distribution…

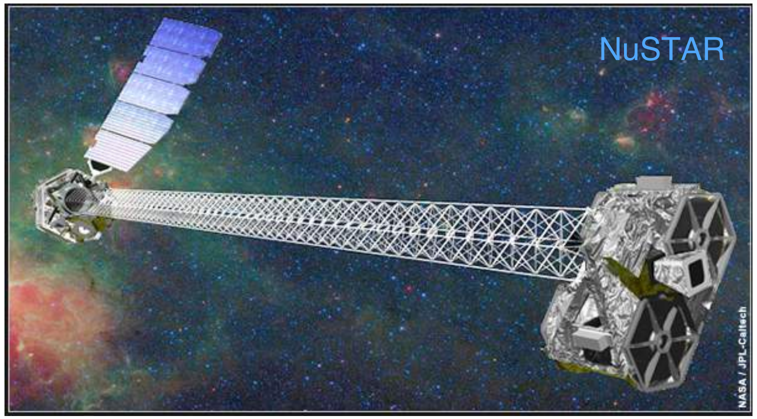
Associated links

News & Views

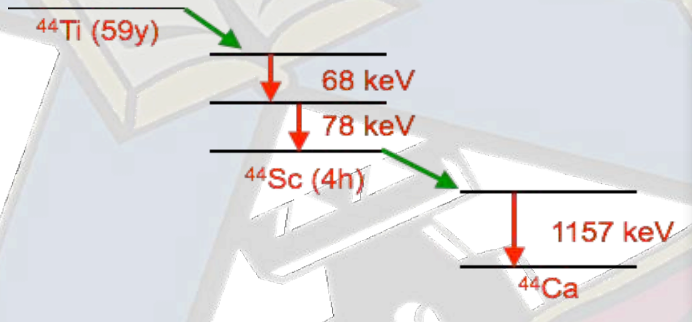
Astrophysics: Lopsided stellar death

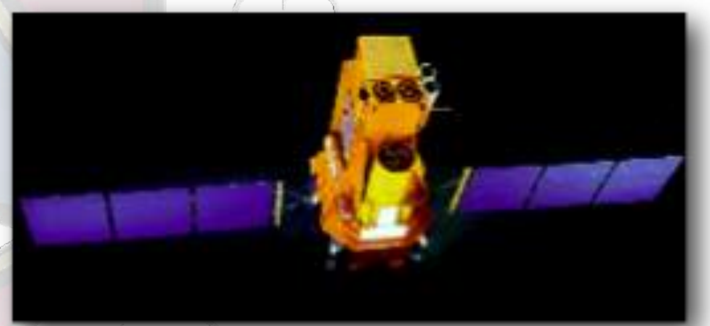
by Laming

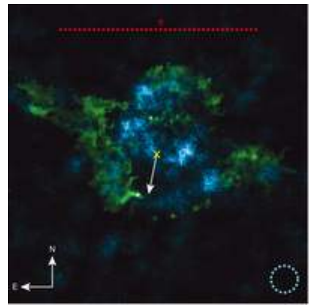




Yields of ^{44}Ti in CCSN







Observations			x10^{-4} M$_\odot$
	Cas-A	NuSTAR Nature 506 (2014) 339-342	1.25(0.3)
	SN1987A	NuSTAR Science 348 (2015) 670-671	1.5(0.3)
	Cas-A	COMPTEL, *BeppoSAX* PDS and ISGRI ApJ 647 (2006) L41-L44	1.6($^{+0.6}_{-0.3}$)
Models			
	Maximum	e.g. Tur et al. ApJ 718 (2010) 357-367	1.0
	Typical	e.g. Tur et al. ApJ 718 (2010) 357-367	0.2-0.4

Observed ^{44}Ti yield consistently greater than predicted by model

^{44}Ti production at PSI

IOPscience Journals Login

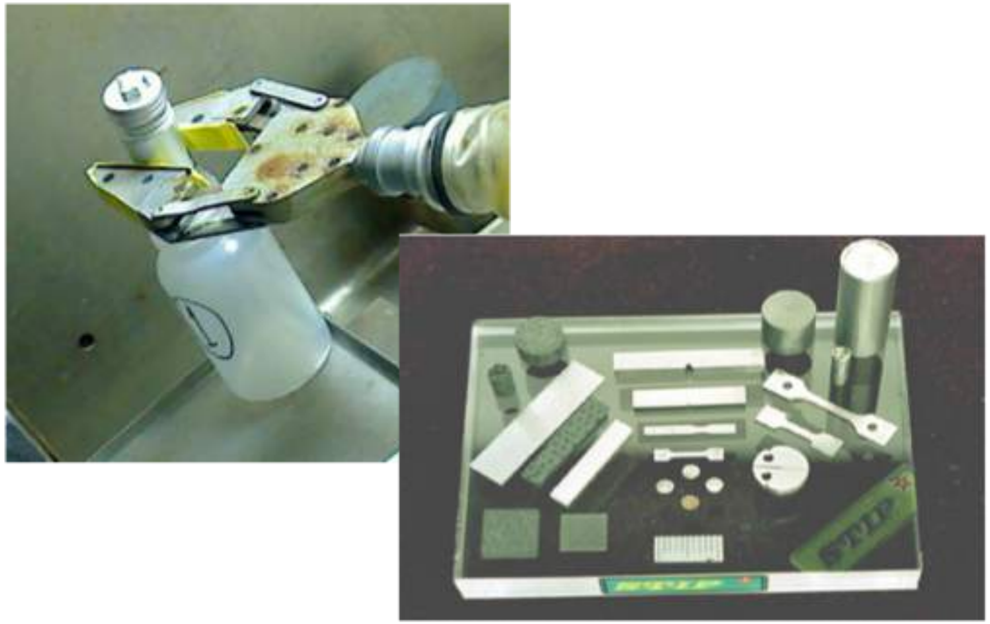
Journal of Physics G: Nuclear and Particle Physics

Journal of Physics G: Nuclear and Particle Physics > Volume 39 > Number 10
R Dressler *et al* 2012 *J. Phys. G: Nucl. Part. Phys.* **39** 105201 doi:10.1088/0954-3899/39/10/105201

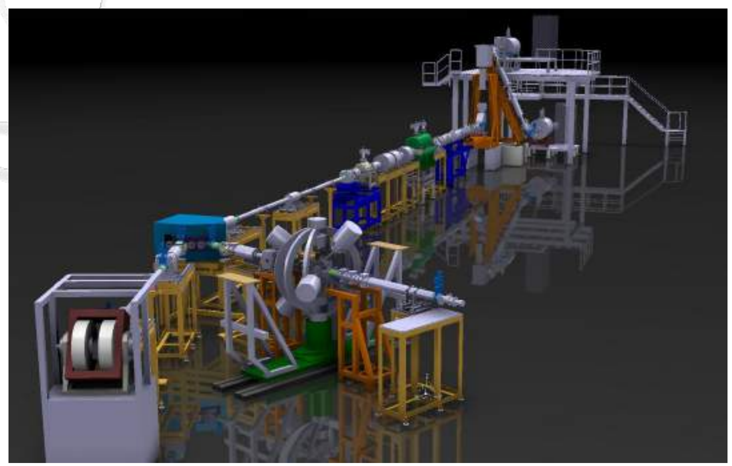
^{44}Ti, ^{26}Al and ^{53}Mn samples for nuclear astrophysics: the needs, the possibilities and the sources

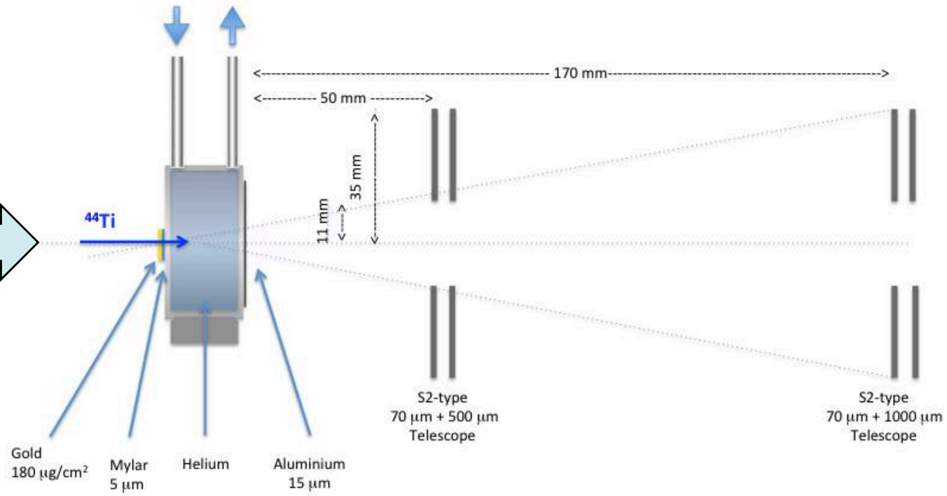
FREE ARTICLE

R Dressler[1], M Ayranov[1], D Bemmerer[2], M Bunka[1], Y Dai[1], C Lederer[3], J Fallis[4], A StJ Murphy[5], M Pignatari[6], D Schumann[1], T Stora[7], T Stowasser[1], F-K Thielemann[6] and P J Woods[5]
Show affiliations

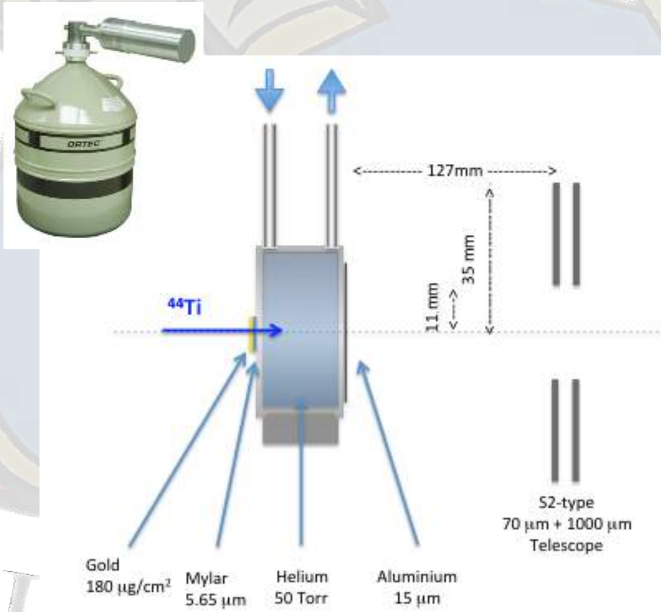


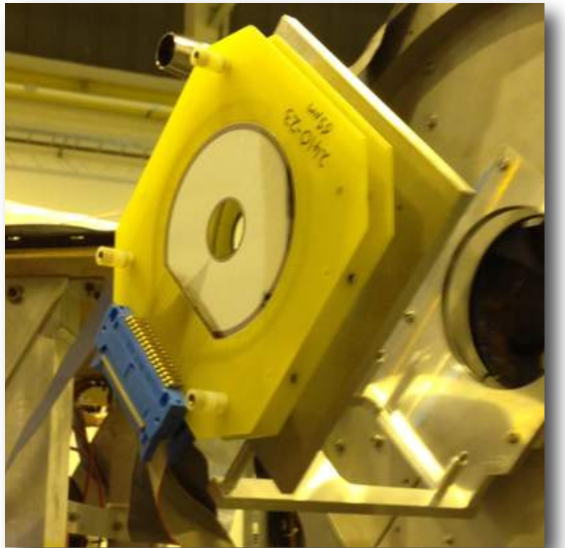
Delivering the beam





Experiment design





2cm 60 Torr ^{4}He gas cell

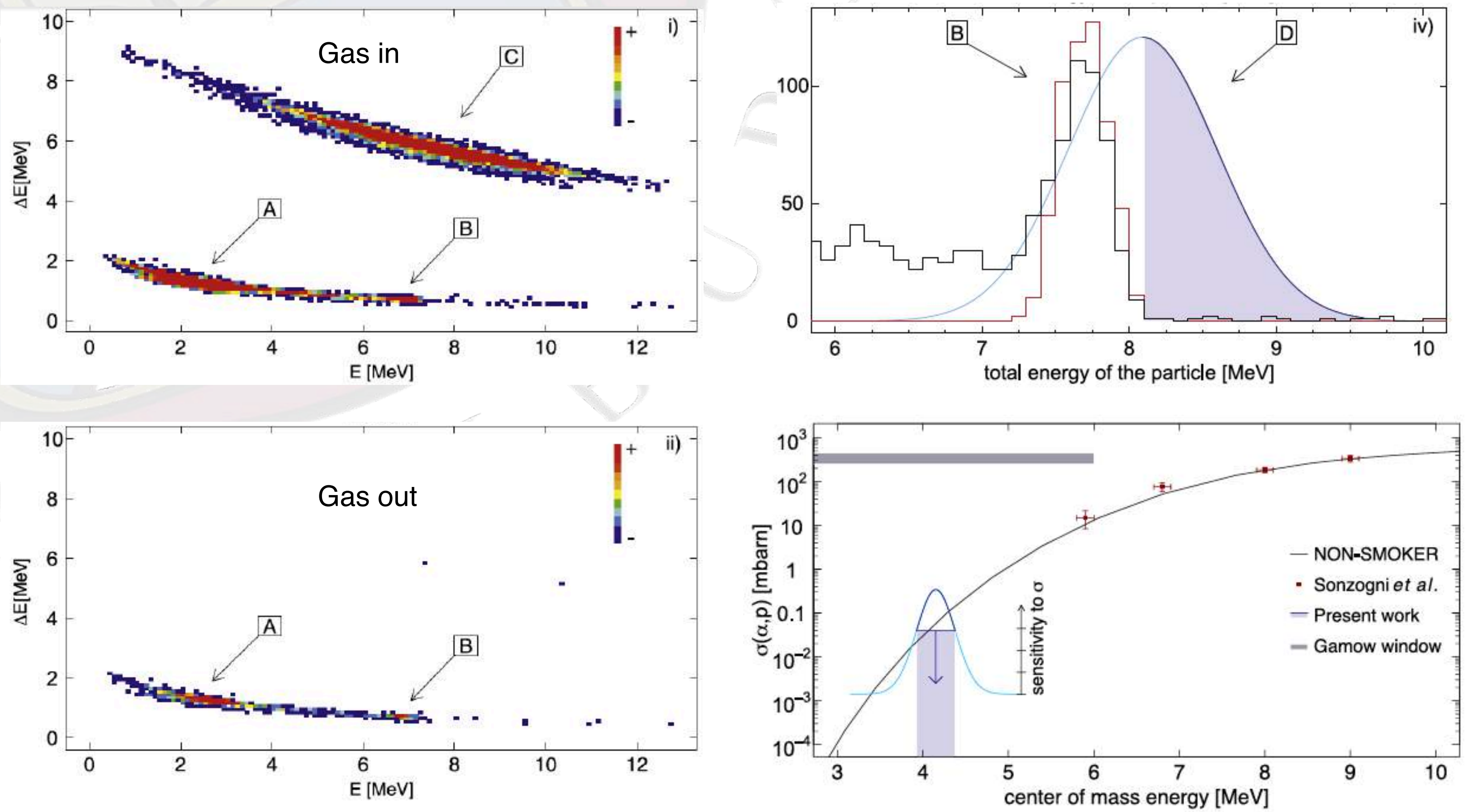
~6µm Al entrance window; 15 µm exit window

MSL S2-type DSSD, inner diameter 18 mm, outer diameter 100 mm

48 circular strips, 16 azimuthal sectors

127 & 137 mm downstream: ΔE 65 µm; E 10000 µm

Results



If typical, rate reduced by ~ factor of 2

Publications

Physics Letters B

Study of the $^{44}Ti(\alpha, p)^{47}V$ reaction and implications for core collapse supernovae

V. Margerin, A.St.J. Murphy, T. Davinson, R. Dressler, J. Fallis, A. Kankainen, A.M. Laird, G. Lotay, D.J. Mountford, C.D. Murphy, C. Seiffert, D. Schumann, T. Stowasser, T. Stora, C.H.-T. Wang, P.J. Woods

New Scientist

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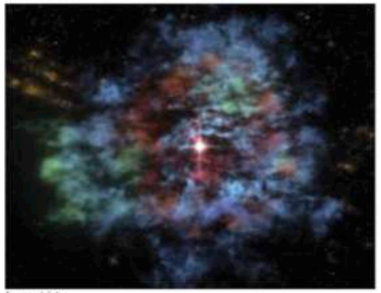
THIS WEEK 2 April 2014

Radioactive waste used to peek inside a star explosion

By Katia Moskvitch



Heavy metal star
Image: NASA/CXC/JPL-Caltech/MIT

RADIOACTIVE waste has helped us peer inside a star explosion and solve a long-standing

THE ASTROPHYSICAL JOURNAL

PUSHING CORE-COLLAPSE SUPERNOVAE TO EXPLOSIONS IN SPHERICAL SYMMETRY. I. THE MODEL AND THE CASE OF SN 1987A

A. Perego[1], M. Hempel[2], C. Fröhlich[3], K. Ebinger[2], M. Eichler[2], J. Casanova[3], M. Liebendörfer[2], and F.-K. Thielemann[2]

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Assuming reduced cross section is typical…

The model is now very close to the observation!

FEBRUARY 11-15 AAAS 2016 ANNUAL MEETING GLOBAL SCIENCE ENGAGEMENT WASHINGTON, DC

Planned future nuclear astrophysics studies at HIE-ISOLDE

A Direct study of $^{44}Ti(\alpha,p)^{47}V$

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Repeat

IS543: Spokesperson A. Murphy

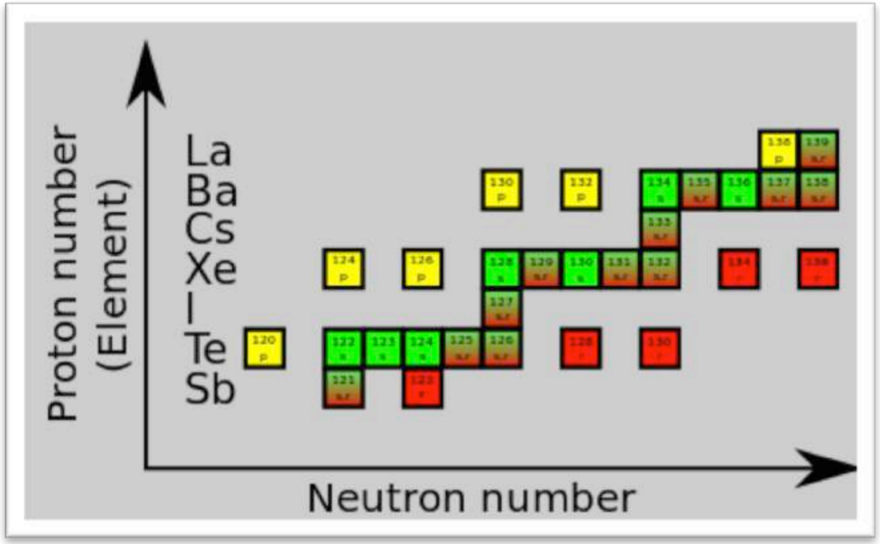
Plan for a run 2

Essentially identical to run 1

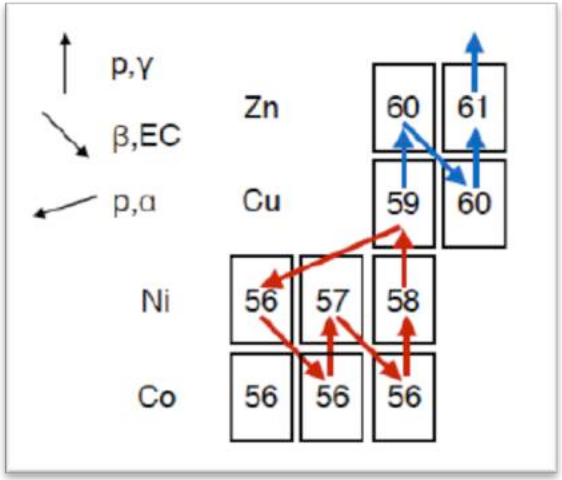
- 100 MBq of ^{44}Ti is available & reserved at PSI
- Good reason to expect significantly more beam
- Aim for 3 – 4 measurements (not upper limits)
- An option for thinner cell windows, resulting in better resolution, is still being explored.

The νp process and ^{59}Cu(p,α)

- How are the 'p-nuclei' made?
- Photo-dissociation of heavy seeds fails to reproduce some nuclei (e.g. ^{92,94}Mo and ^{96,98}Ru)
- A νp-process: antineutrino absorptions in proton-rich environment → neutrons to be captured by neutron-deficient nuclei.
- Speeds up the reaction flow, permitting element formation up to A~100.



- Arcones *et al.* have identified an end point nuclear cycle that could limit processing A>64.
- At high temperatures ^{59}Cu(p,α)^{56}Ni dominates over ^{59}Cu(p,γ), ending the process
- However, ^{59}Cu(p,α) is presently unmeasured…



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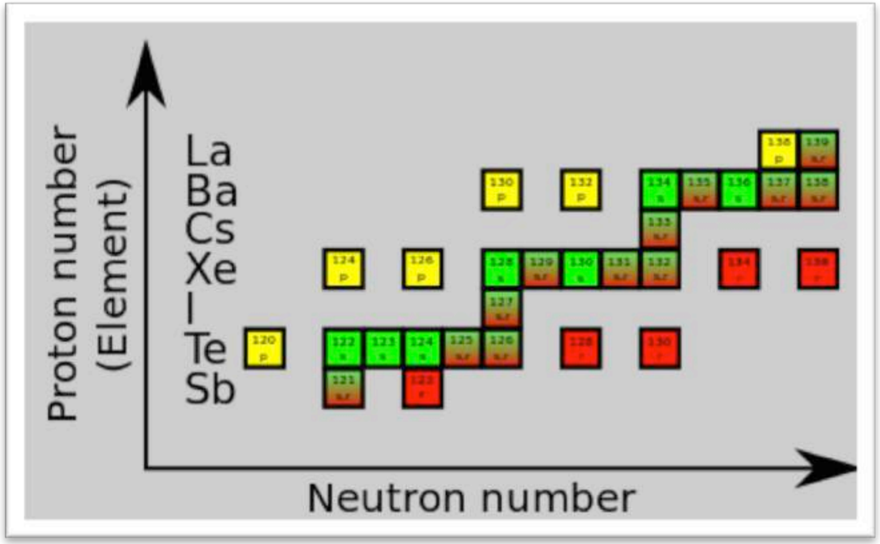

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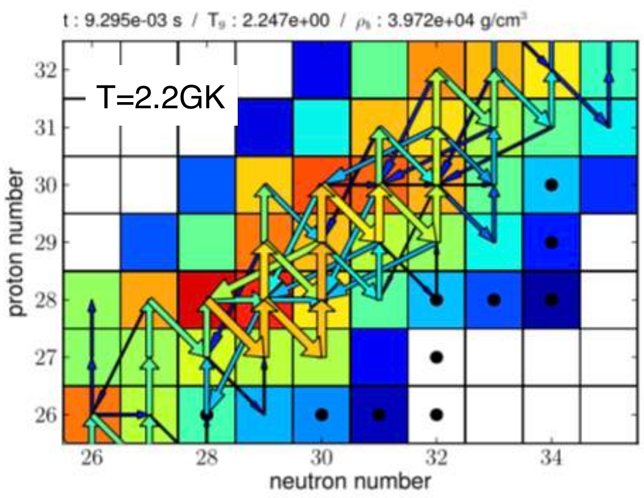

THE ASTROPHYSICAL JOURNAL, 750:18 (9pp), 2012

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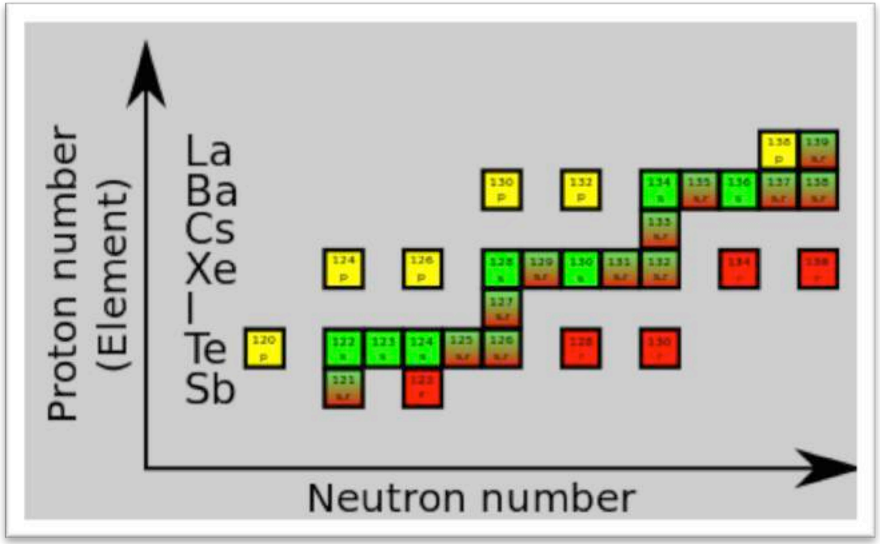

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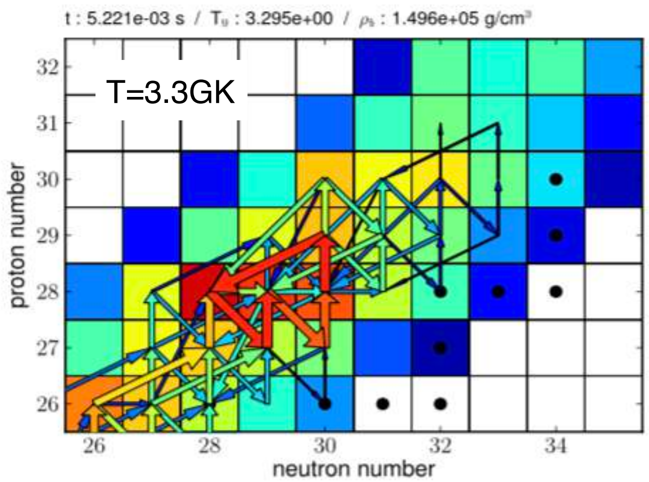
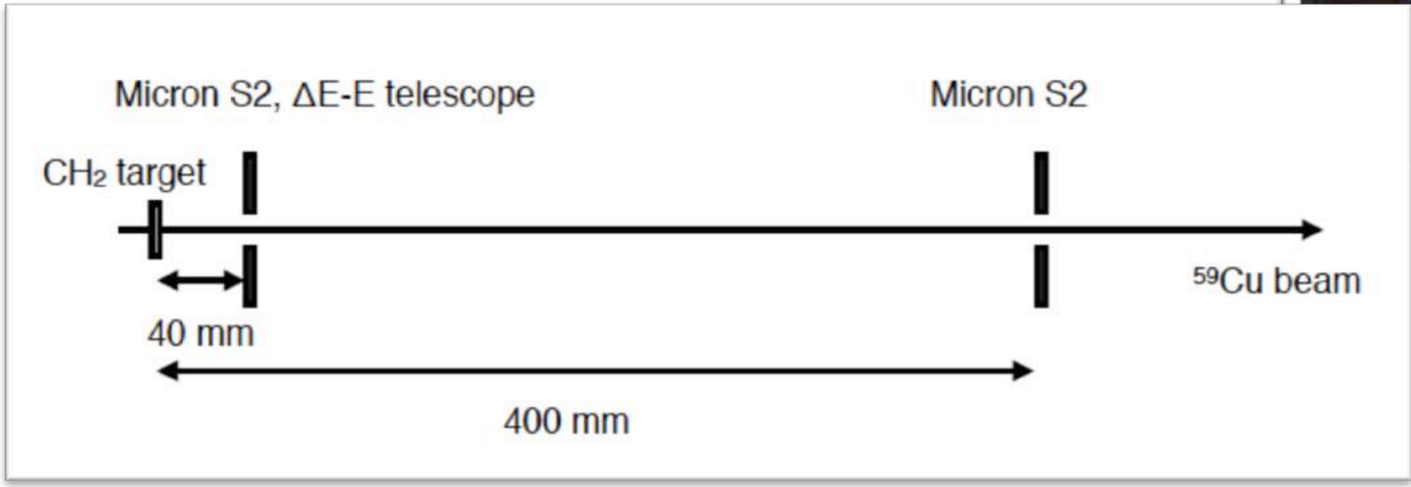


THE ASTROPHYSICAL JOURNAL, 750:18 (9pp), 2012

The νp process and ^{59}Cu(p,α): IS607

- ^{59}Cu beam impinging CH_2 target
- Highly segmented silicon strip detectors, covering lab angles of 2.8 – 40 degrees
- Coincident detection of both ejectile and recoil
- 5 energy steps, E_{beam}: 3.8 – 5 MeV/u
- Anticipating high level density



Spokesperson: C. Lederer

A possible solution to the cosmological lithium problem: IS-554

- Big Bang Nucleosynthesis is well established
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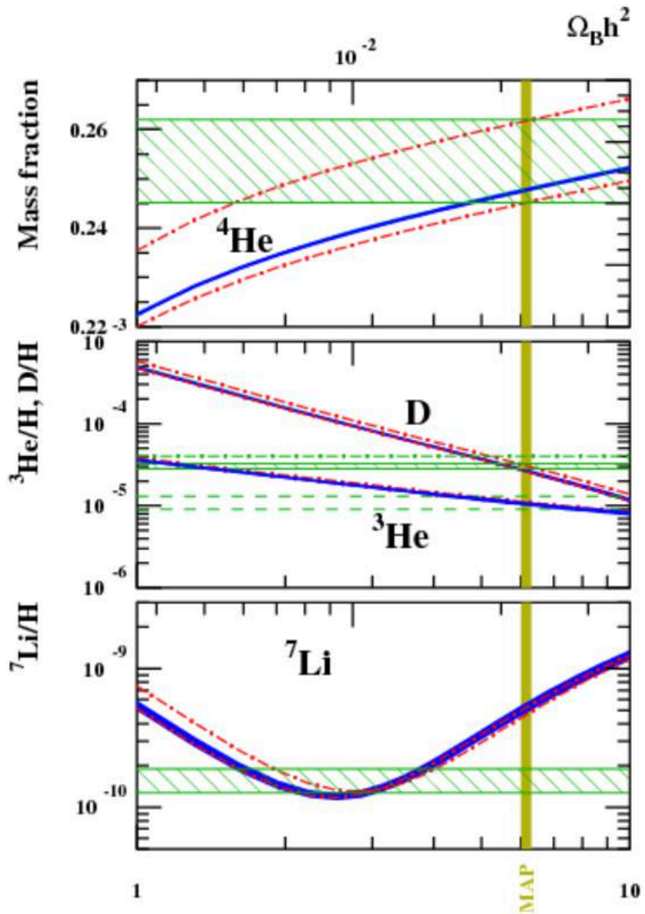

Coc, Alain et al. Phys.Rev. D87 (2013) no.12, 123530

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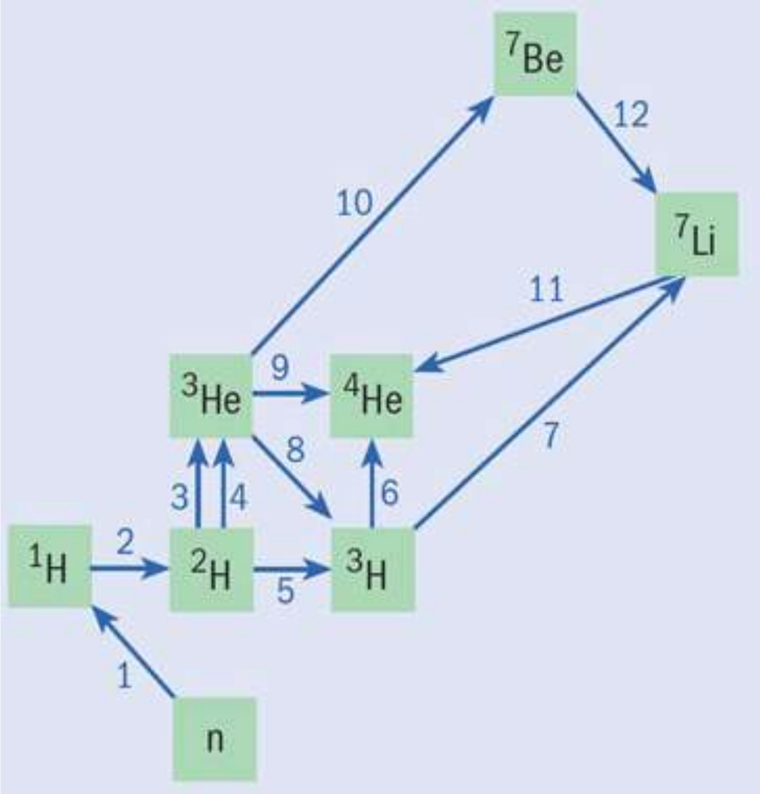

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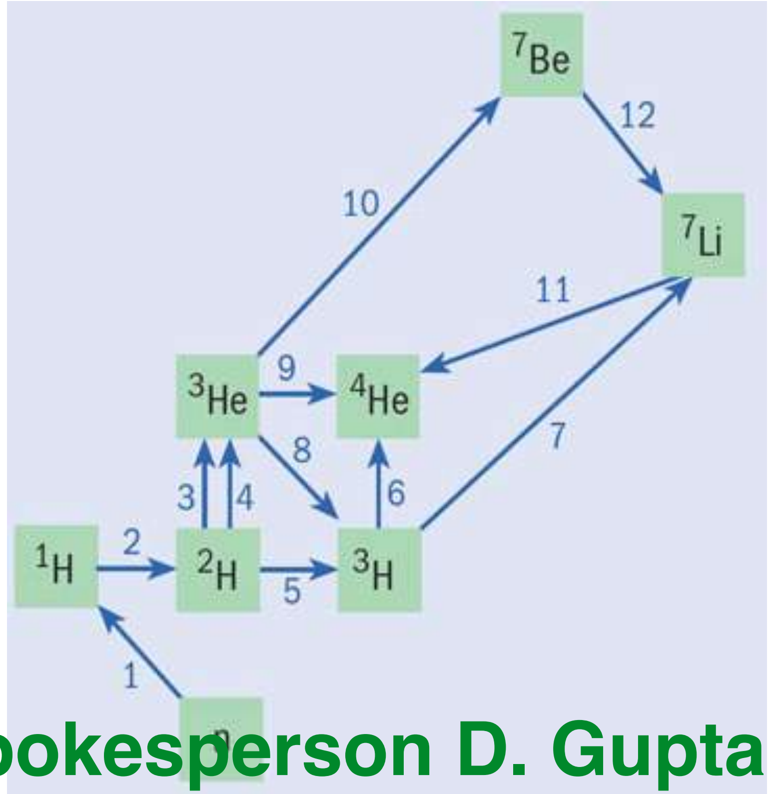

IS-554: Spokesperson D. Gupta

Summary

- The capabilities of REX-ISOLDE are well matched to the needs of nuclear astrophysics
  - Note the (disproportionate) number of talks here on nuclear astrophysics!
- The work is quite diverse
  - Experimental and theoretical nuclear physics, several different techniques,
  - Astrophysics & astronomy
  - Modeling & computational physics
  - Nuclear chemistry
  - …

REX-ISOLDE work fits well within the wider ENSAR2 activities.