Facilities for Nuclear Astrophysics Research

Alex Murphy

East Highland: latest pressure

Wednesday, 12 February 2014: dawn to dusk

Forecast issued: 0208 on Wednesday, 12 February 2014

Printable view

Overview for Wednesday

Mainly dry at first, but snow and blizzards spreading from south. Winds easing and turning showery this evening.

Hazards	Risk	Explanation
Blizzards	High	Through the afternoon above 300m
Heavy snow	High	Through the afternoon above 300m
Storm force winds	High	Gusts over 80mph late morning until late afternoon.
Gales	High	Until evening, and to low levels this afternoon.
Severe chill effect	High	Storm force winds and temperatures well below freezing. High frostbite risk.
Persistent and extensive hill fog	High	Becoming widespread above 600m, occasional to 300m

Outline

- Some astrophysics
- Some nuclear physics
- Some fairly new techniques
- Some very new techniques

What are we trying to do?

Provide experimental measurements and constraints on relevant nuclear properties*, at relevant energies

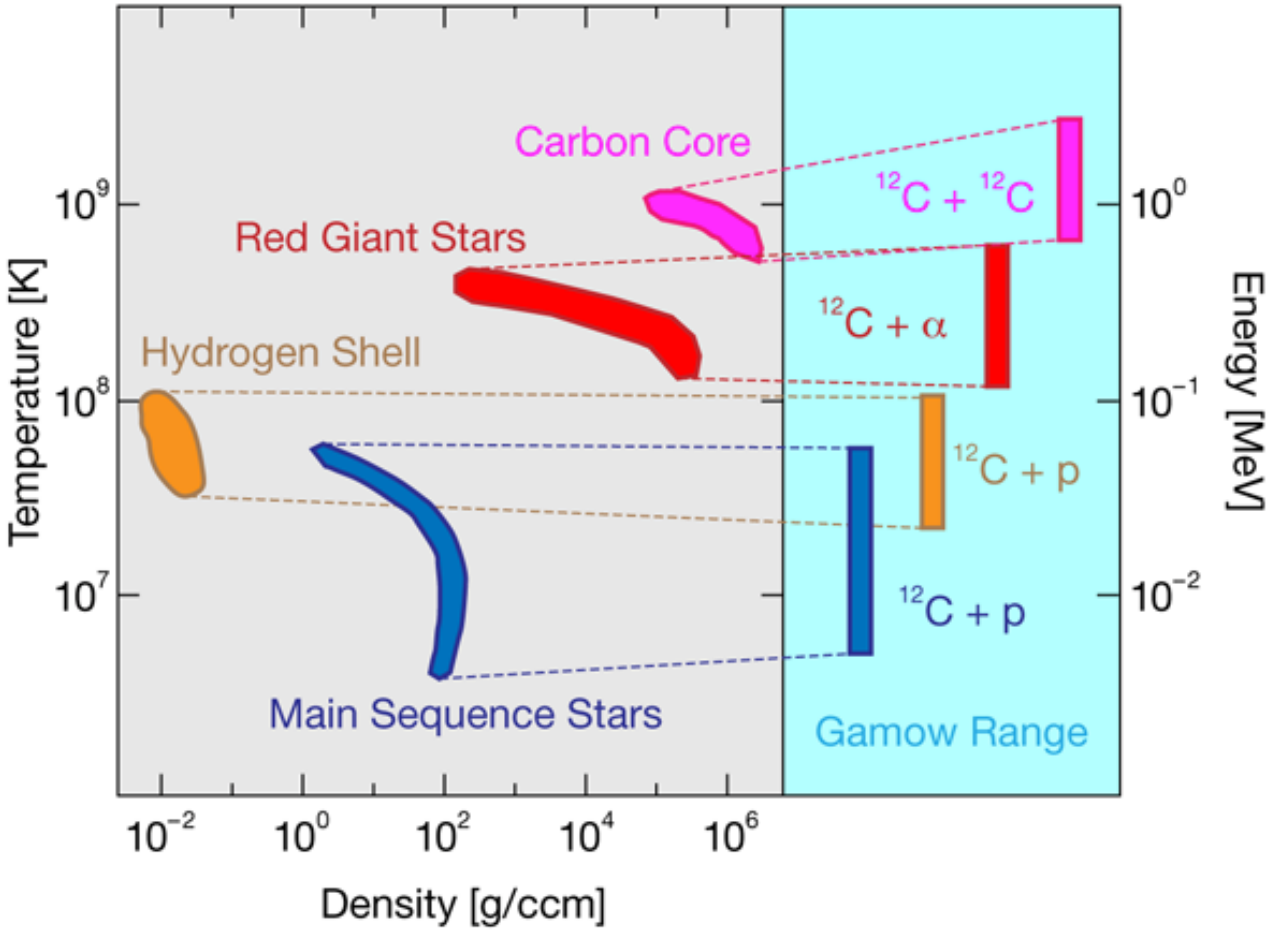
Understand the origin of the elements and sources of energy driving astrophysical blah blah blah…

* Reaction rates, masses, lifetimes, etc.

- What are the relevant reactions? ← That's a whole other talk…
- What are the relevant energies?
- What do we actually measure
- How do we perform these measurements?

The Basics

- The Gamow window
- The particle energies corresponding to the astrophysical burning regime

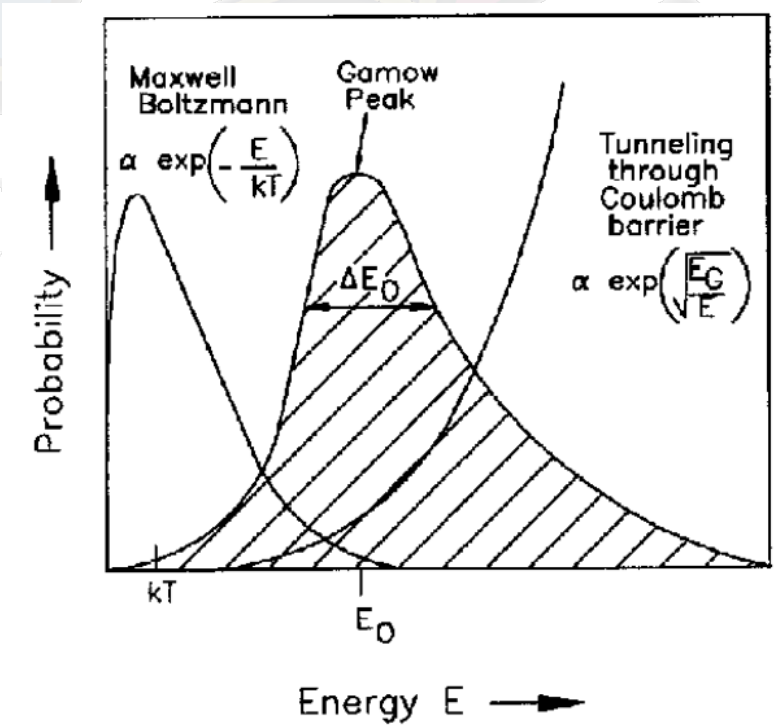


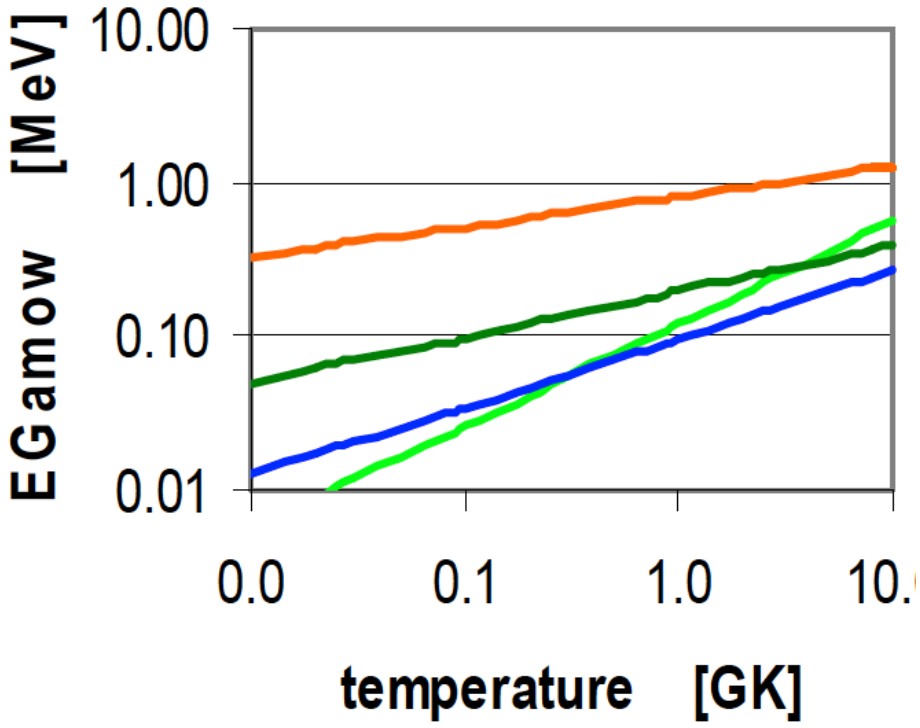
The Gamow window

- Convolution of temperature (M-B) with nuclear penetrability

$$E_0 = \left(\frac{bkT}{2}\right)^{3/2} = 0.122 \cdot \left(Z_1^2 Z_2^2 A\right)^{1/3} T_9^{2/3} \text{ MeV}$$

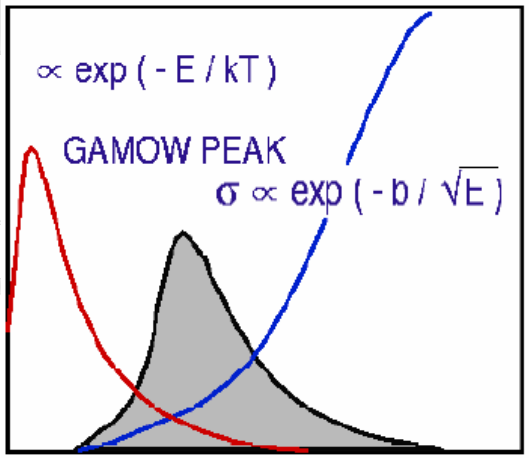
$$\Delta E = \frac{4}{\sqrt{3}} \sqrt{E_0 kT} = 0.2368 \cdot \left(Z_1^2 Z_2^2 A\right)^{1/6} T_9^{5/6} \text{ MeV}$$

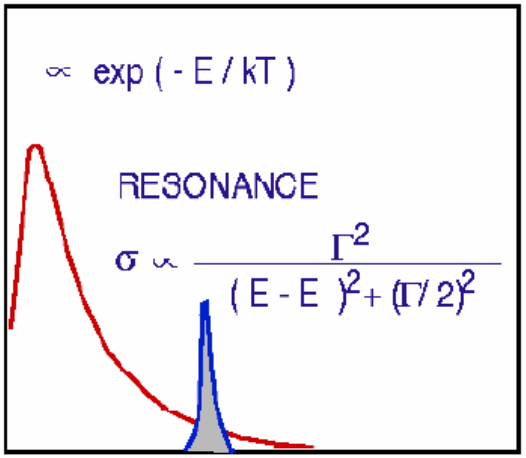




Reaction Rate

- Convolution of cross section with the thermal energy distribution





σ: cross section

ωγ: res. strength

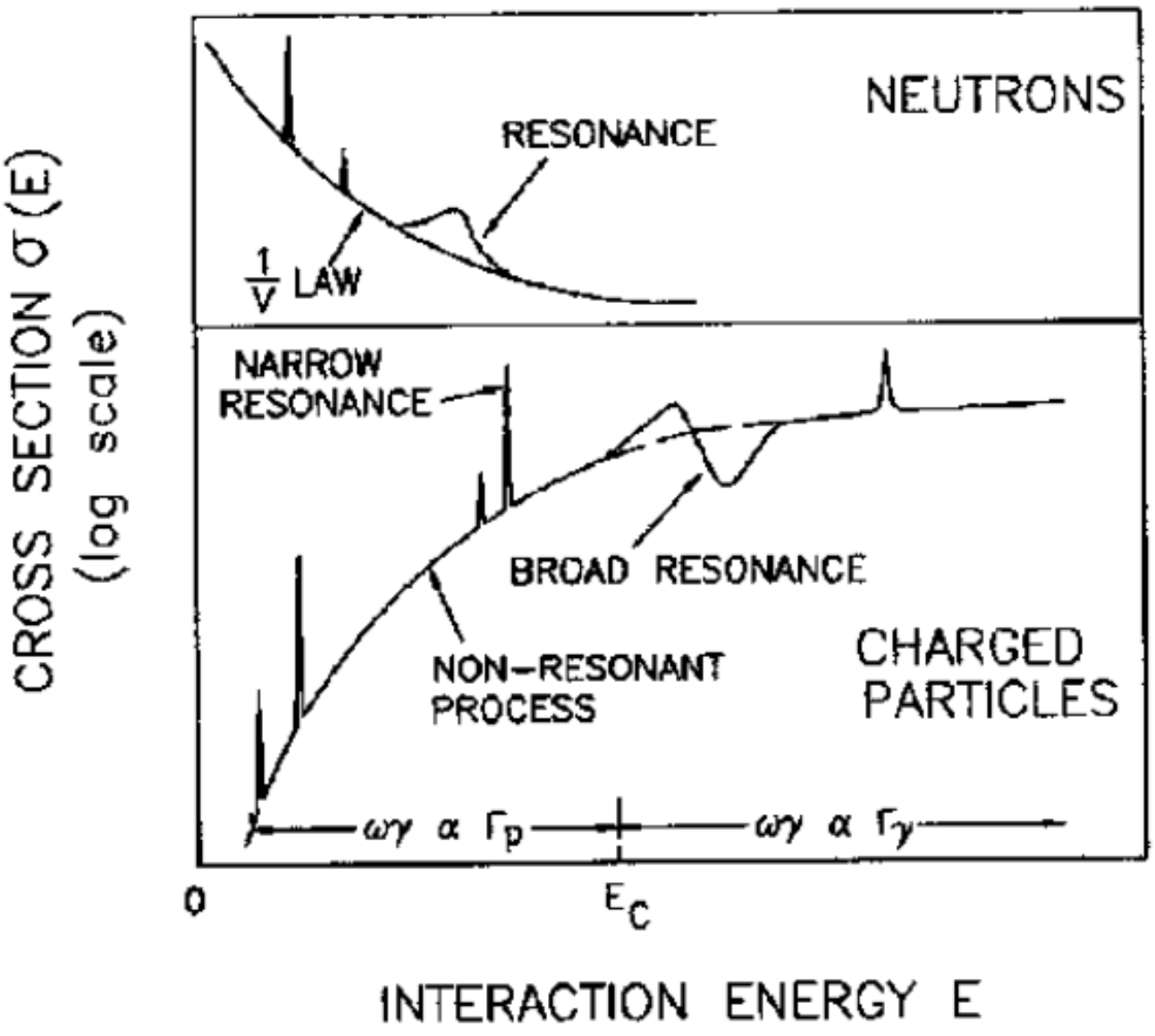
E_R: res. energy

Nonresonant Reaction Contributions

$$N_A \langle \sigma v \rangle \propto T^{-3/2} \int \sigma E \exp (- E / kT) \quad dE$$

Resonant Reaction Rate

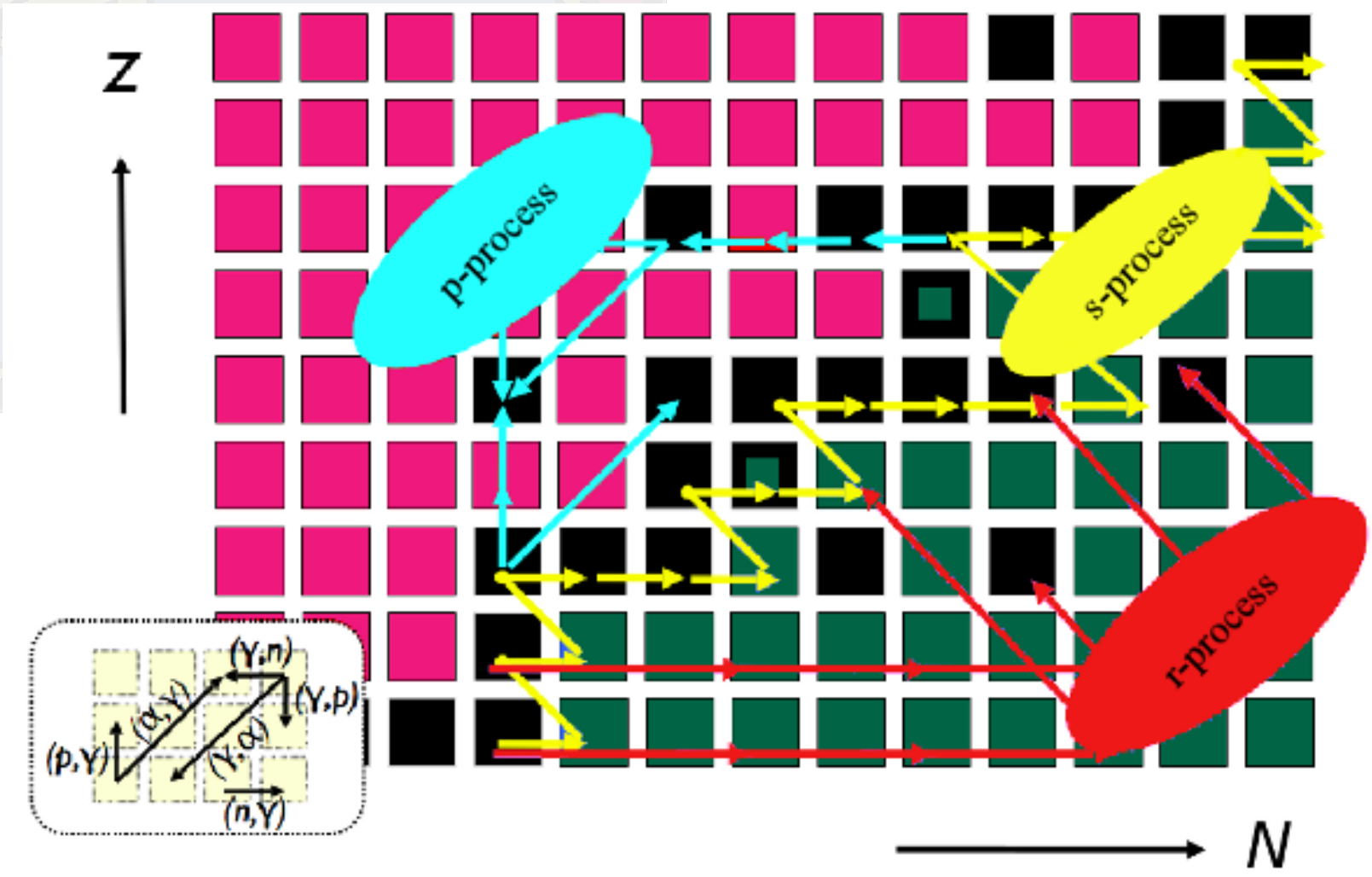
$$N_A \langle \sigma v \rangle \propto T^{-3/2} \omega\gamma \exp (- E_R / kT)$$


NEUTRONS
RESONANCE
1/v LAW
NARROW RESONANCE
BROAD RESONANCE
NON-RESONANT PROCESS
CHARGED PARTICLES
ωγ α Γp
ωγ α Γγ
0
EC
CROSS SECTION σ(E) (log scale)
INTERACTION ENERGY E

So what do we need…?

- Cross sections at c.m. energies <few MeV
- Typically reactions are between a nucleus and a…
  - proton, neutron, alpha, gamma
  - Occasionally heavier.
  - Neutrino reactions
- Reaction products are typically…
  - protons, neutrons, alphas, gammas

Reactions with unstable isotopes



By example…

‘Modern’

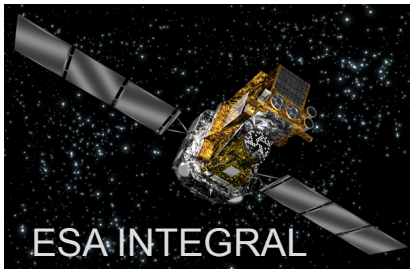
- $^{18}F(p,\alpha)^{15}O$
- $^{18}F(p,\gamma)^{19}Ne$

’Future’

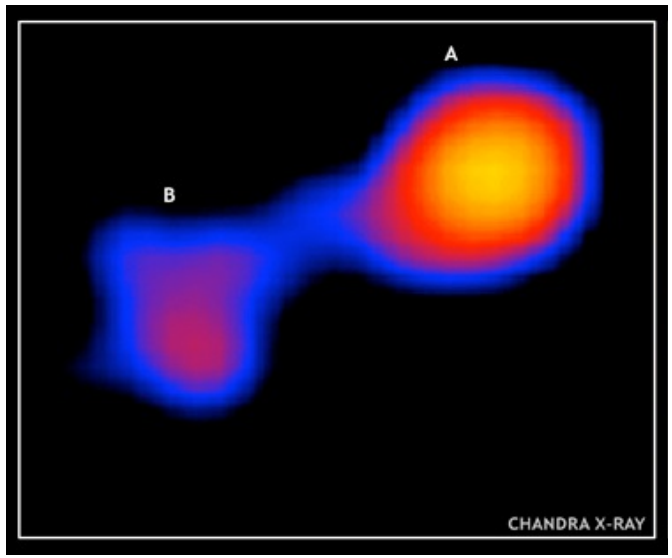
- Storage ring
- Laser plasma
- ERAWAST

Not even close to a full list…

$^{18}F(p,\alpha)^{15}O$

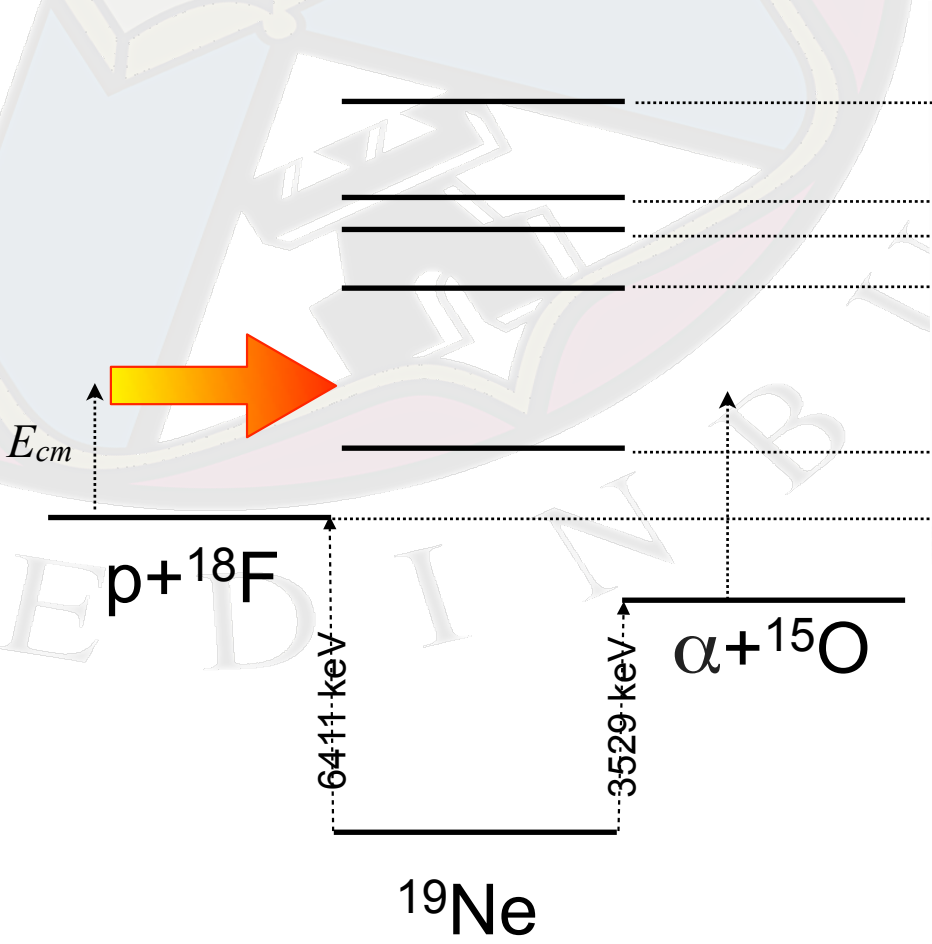


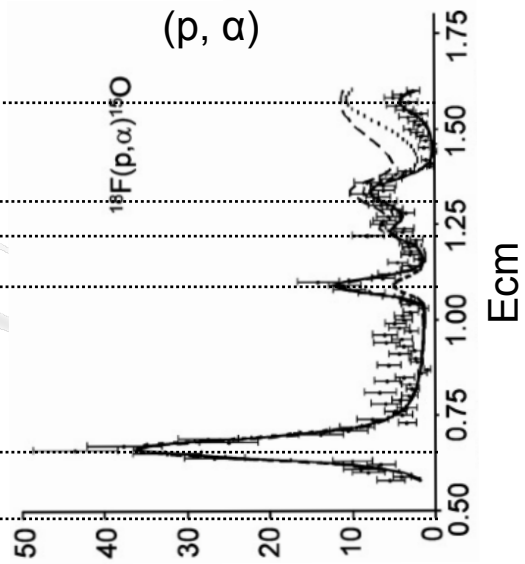
- ^{18}F is a gamma ray emitter expected to be seen in nova ejecta
- Reaction rate rate needs to be better known to estimate & interpret a signal
- Reaction proceeds through resonances in ^{19}Ne
- Measure resonance parameters and deduce reaction rate

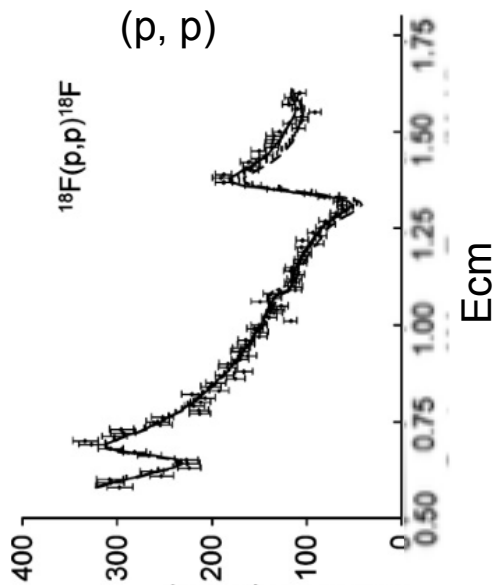


$^{18}F(p,\alpha)^{15}O$

Mountford *et al.* PRC (R) 2012 022801(R)





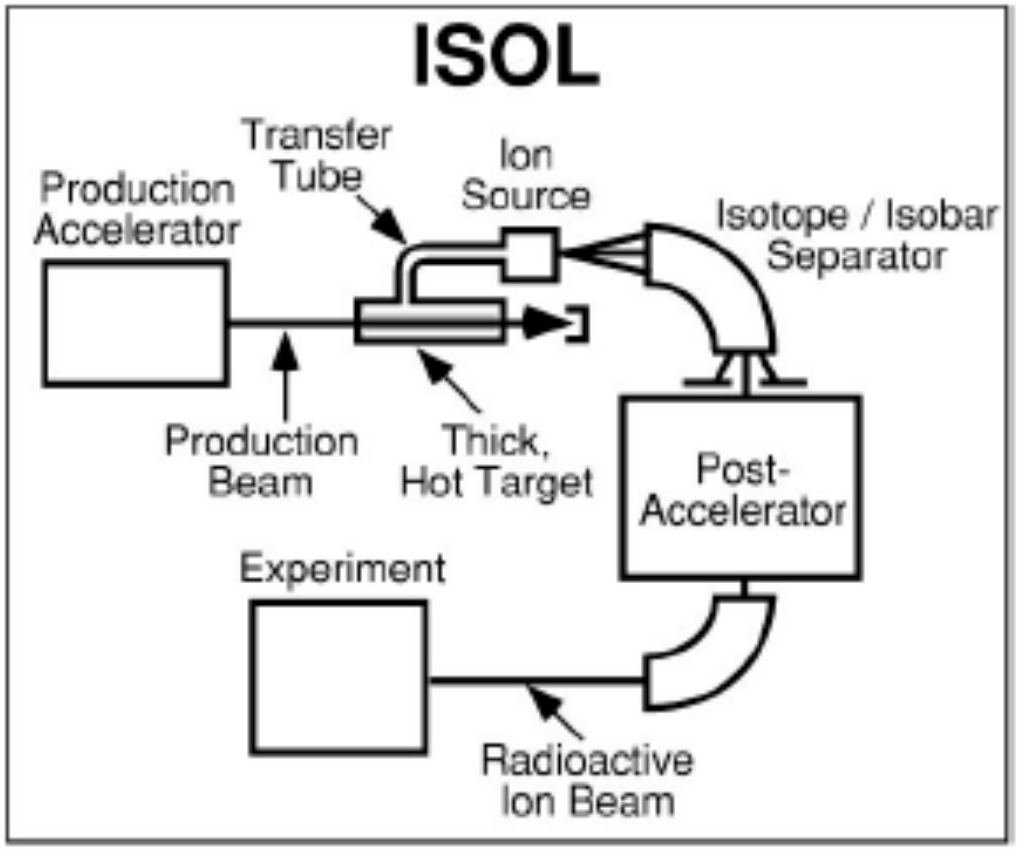


- Energies, widths, shapes all give nuclear structure information
- Build in to R-Matrix and estimate cross section at all energies.
- Calculate Reaction rate

So how do we do this?

ISOL

Isotop
Separator
On Line



Radioactive beam!

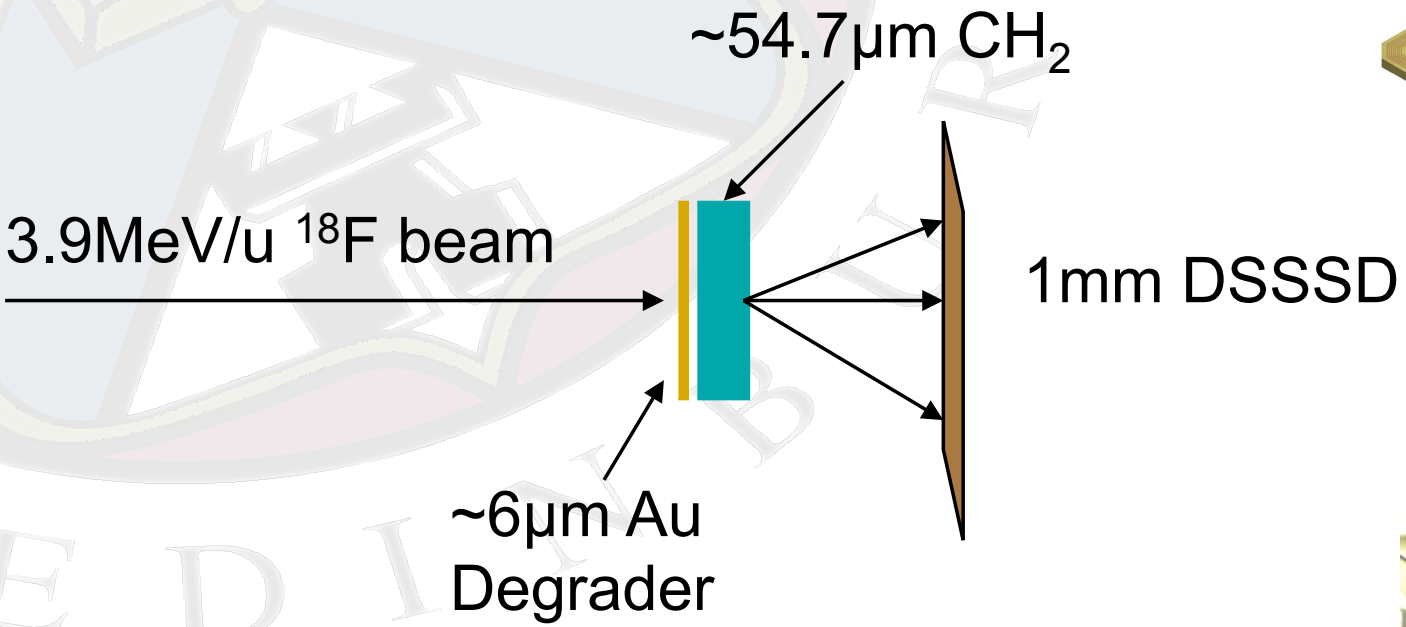
$t_{1/2}$ ^{18}F 110 m

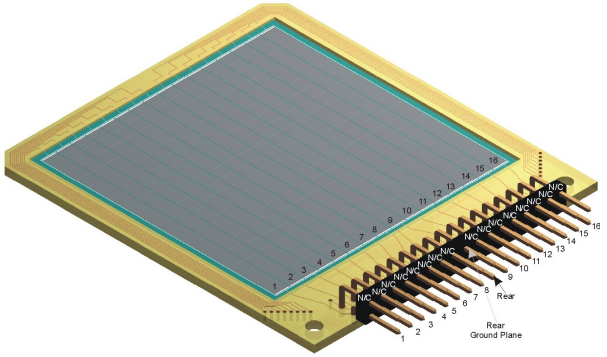
- Excellent beam quality
- High purity
- ‘High’ intensities
- Low energies
- Limited beam species (chemistry)
- Limited to > ~1s lifetimes

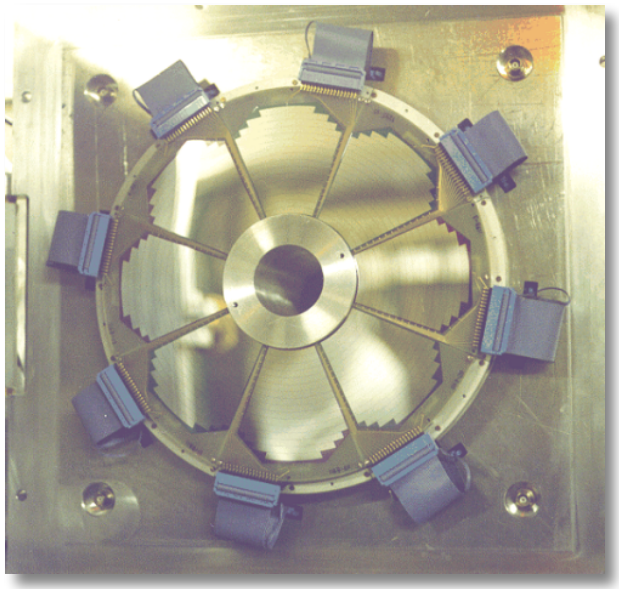
Facilities for this expt.

- ISOL method, GANIL, France
- Cycloton: 95 MeV/A ^{20}Ne on C
- ECR ion source
- Cyclotron re-acceleration
- 3.9 MeV/A ^{18}F
- High energy stripping to generate 9^{+} beam
- $2x10^{4}$ pps delivered on target
- Foil to degrade beam energy to requirements

Set up - really simple





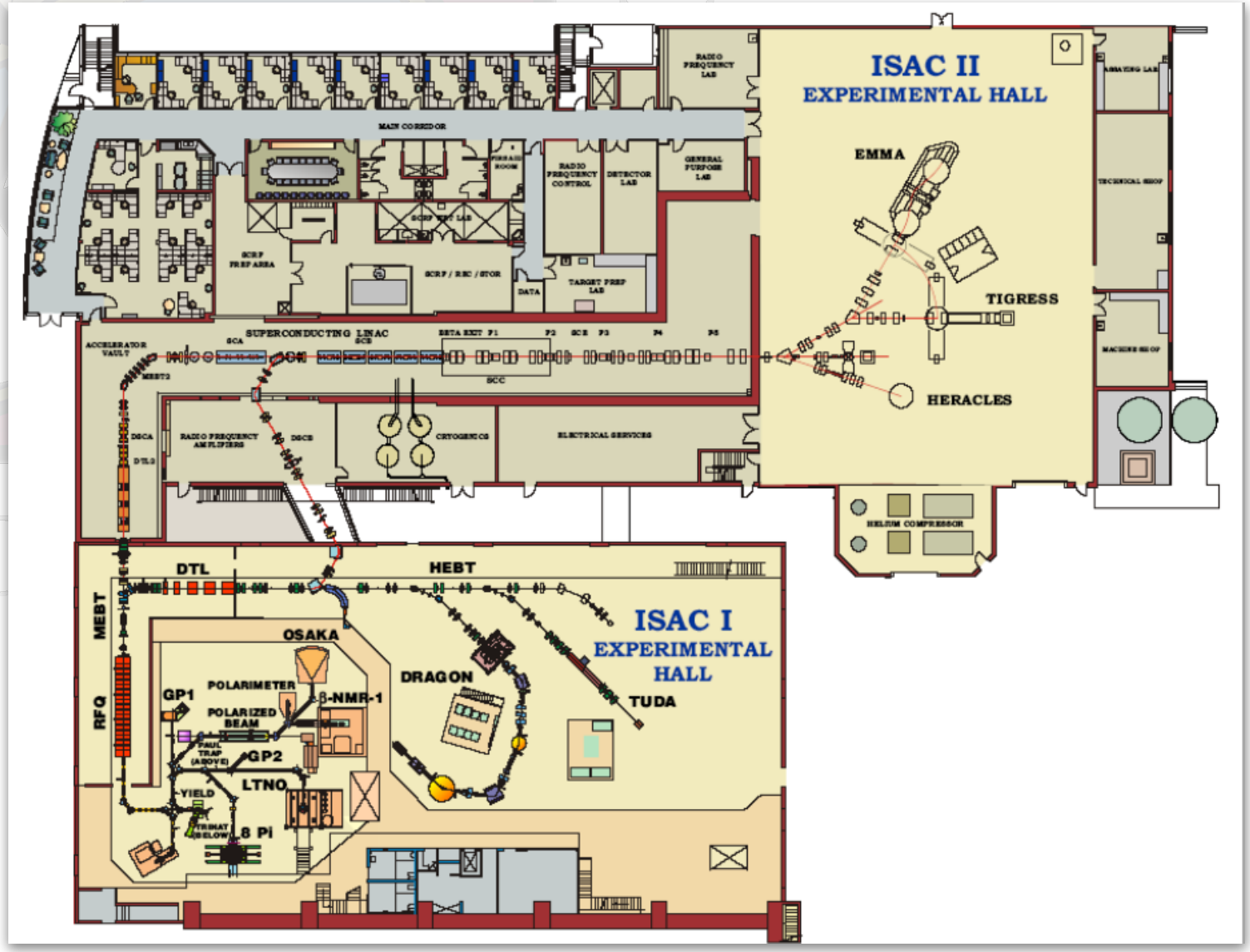


Beam energy degraded to ~2 MeV/A
Beam stops in target
Protons and alphas detected in DSSD

$^{18}F(p,\gamma)^{19}Ne$

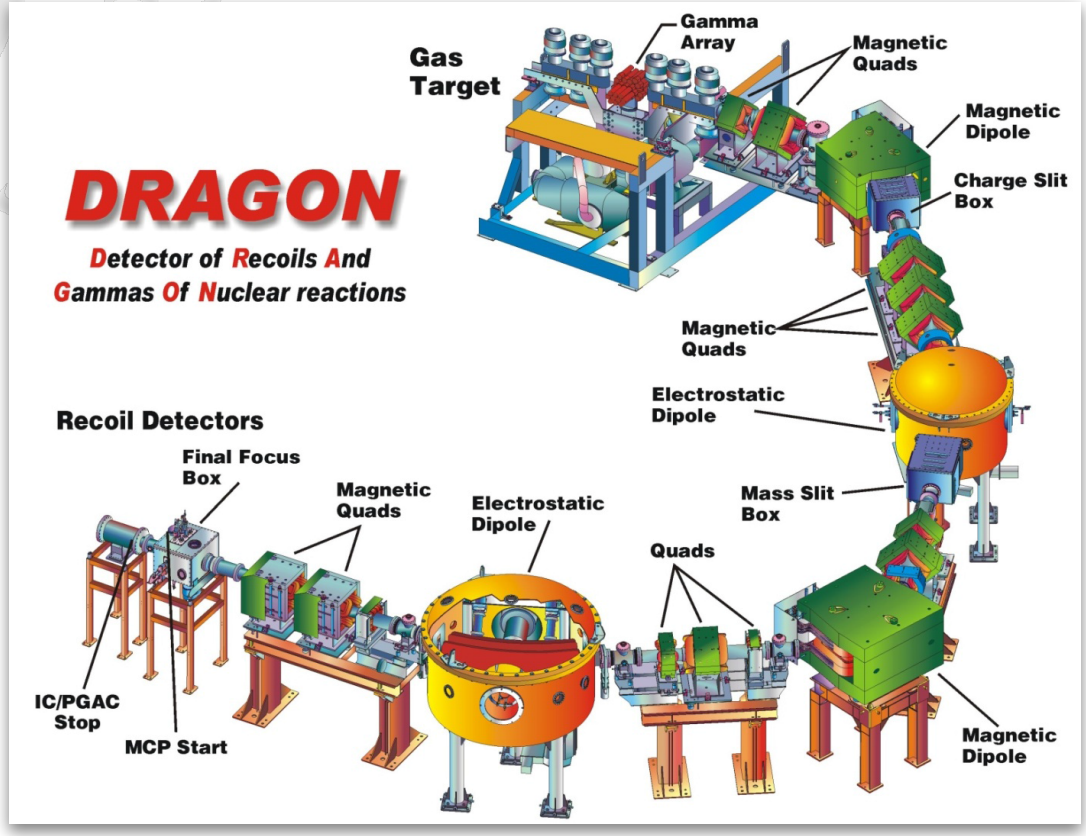
- At TRIUMF, Canada
- World's largest cyclotron…

ISAC Isotope Separator and Accelerator



DRAGON Detector of Recoils And Gammas Of Nuclear reactions

- Inverse kinematics: ^{18}F beam on windowless hydrogen gas target
- Detection of prompt gammas in BGO array
- Selection of ^{19}Ne recoils through separator
- Detection of recoils in end detector



Results…

PRL 110, 262502 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Measurement of Radiative Proton Capture on ^{18}F and Implications for Oxygen-Neon Novae

C. Akers,[1,2] A. M. Laird,[2] B. R. Fulton,[2] C. Ruiz,[1] D. W. Bardayan,[3] L. Buchmann,[1] G. Christian,[1] B. Davids,[1] L. Erikson,[4] J. Fallis,[1] U. Hager,[5] D. Hutcheon,[1] L. Martin,[1] A. St. J. Murphy,[6] K. Nelson,[7] A. Spyrou,[8,9] C. Stanford,[10] D. Ottewell,[1] and A. Rojas[1]

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(Received 21 January 2013; published 28 June 2013)

Results…

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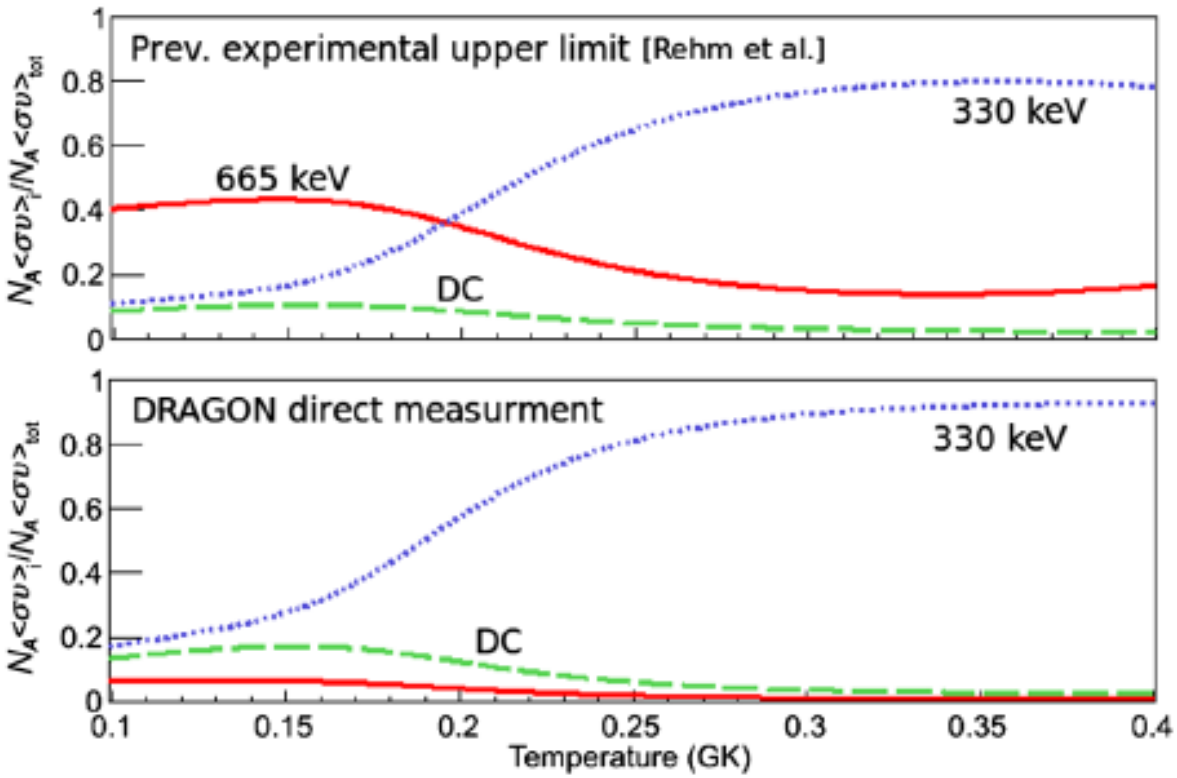
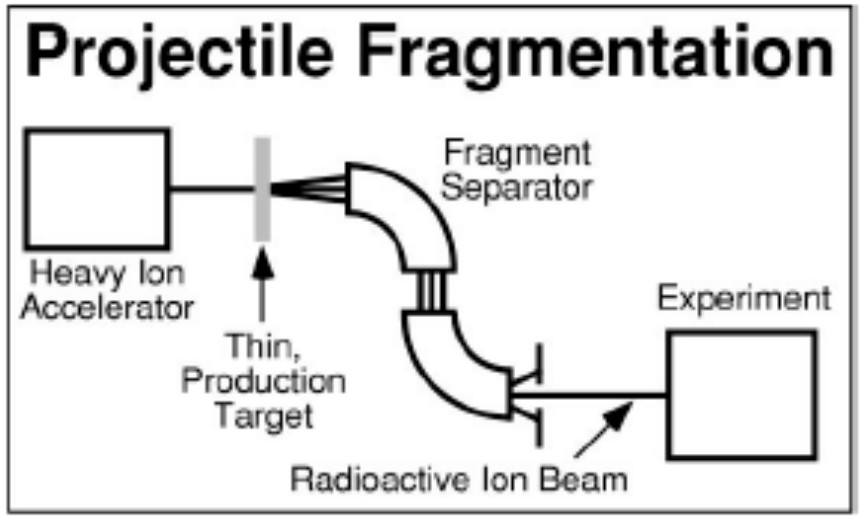
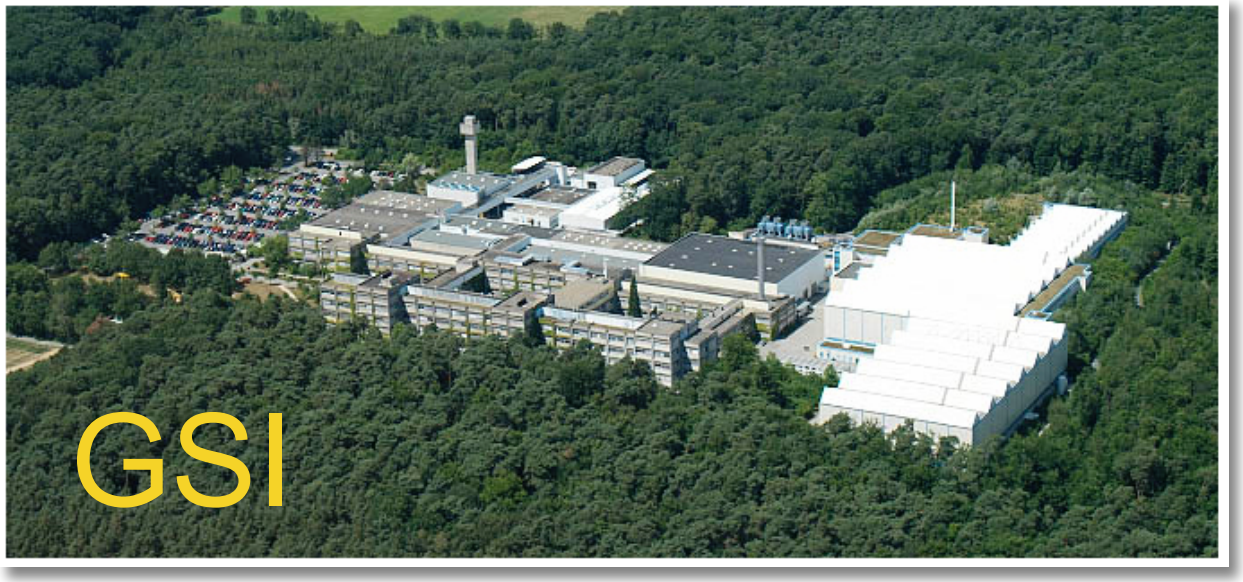
[9]*Department of Physics and Astronon*
[10]*University of*
(Received 2



- Long held assumption overturned…

Projectile Fragmentation

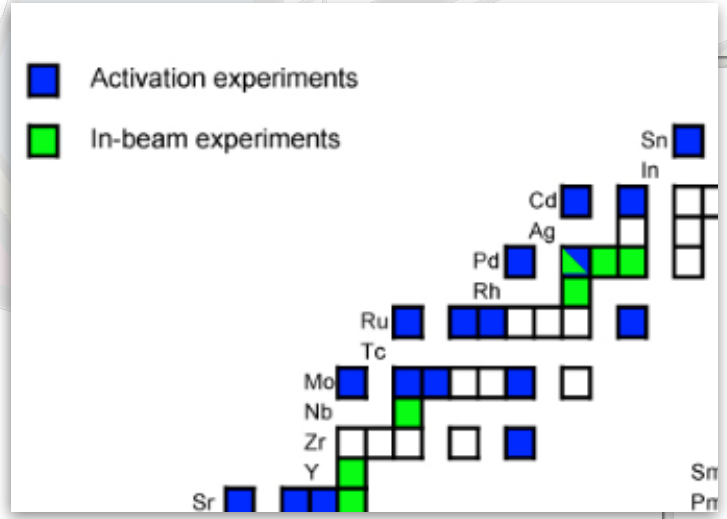


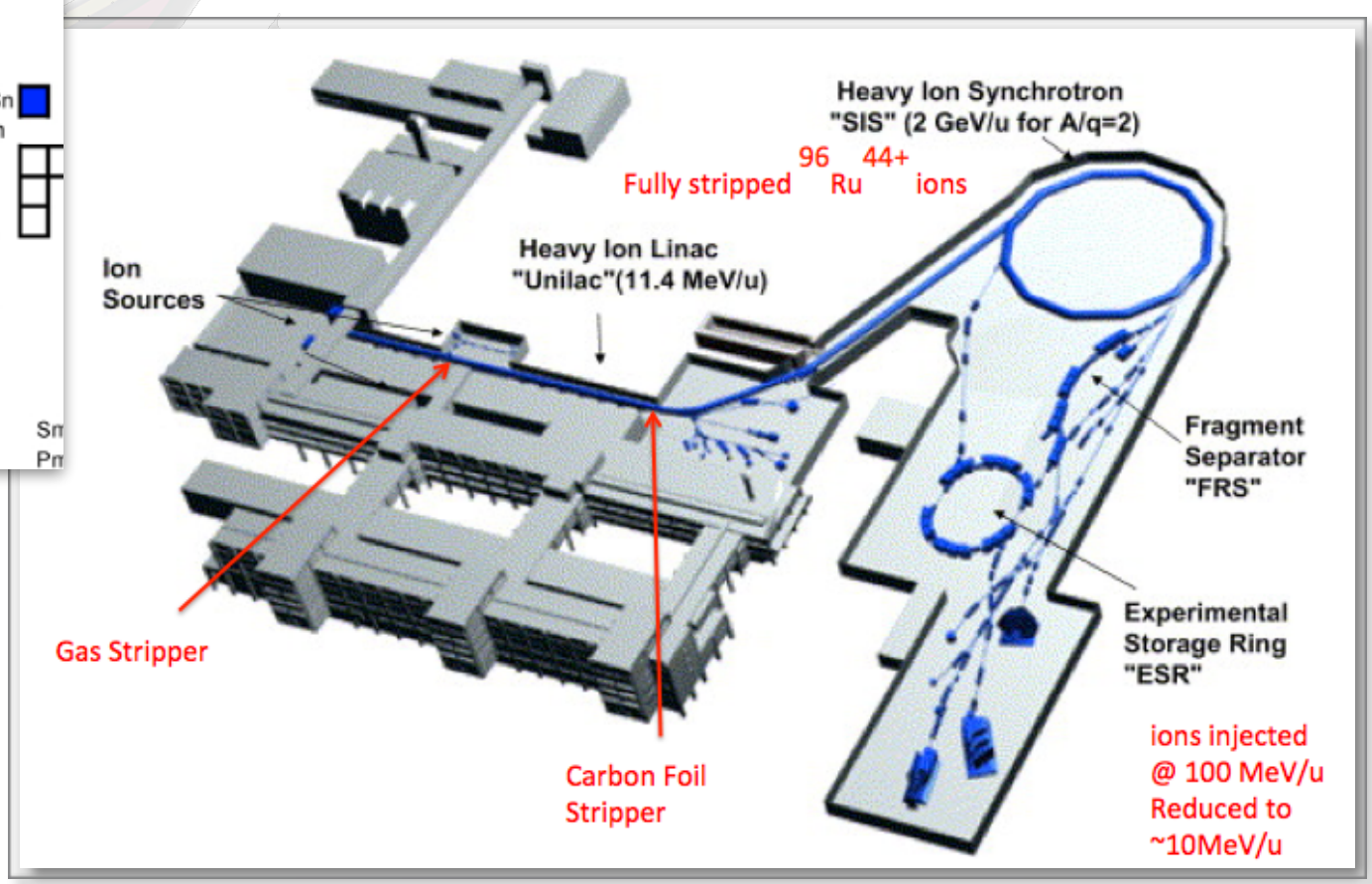


- Beam independent from chemical properties
- typical beam energies far too high for NA
- poorer beam quality (energy, size)
- possible beam contaminations

Storage rings

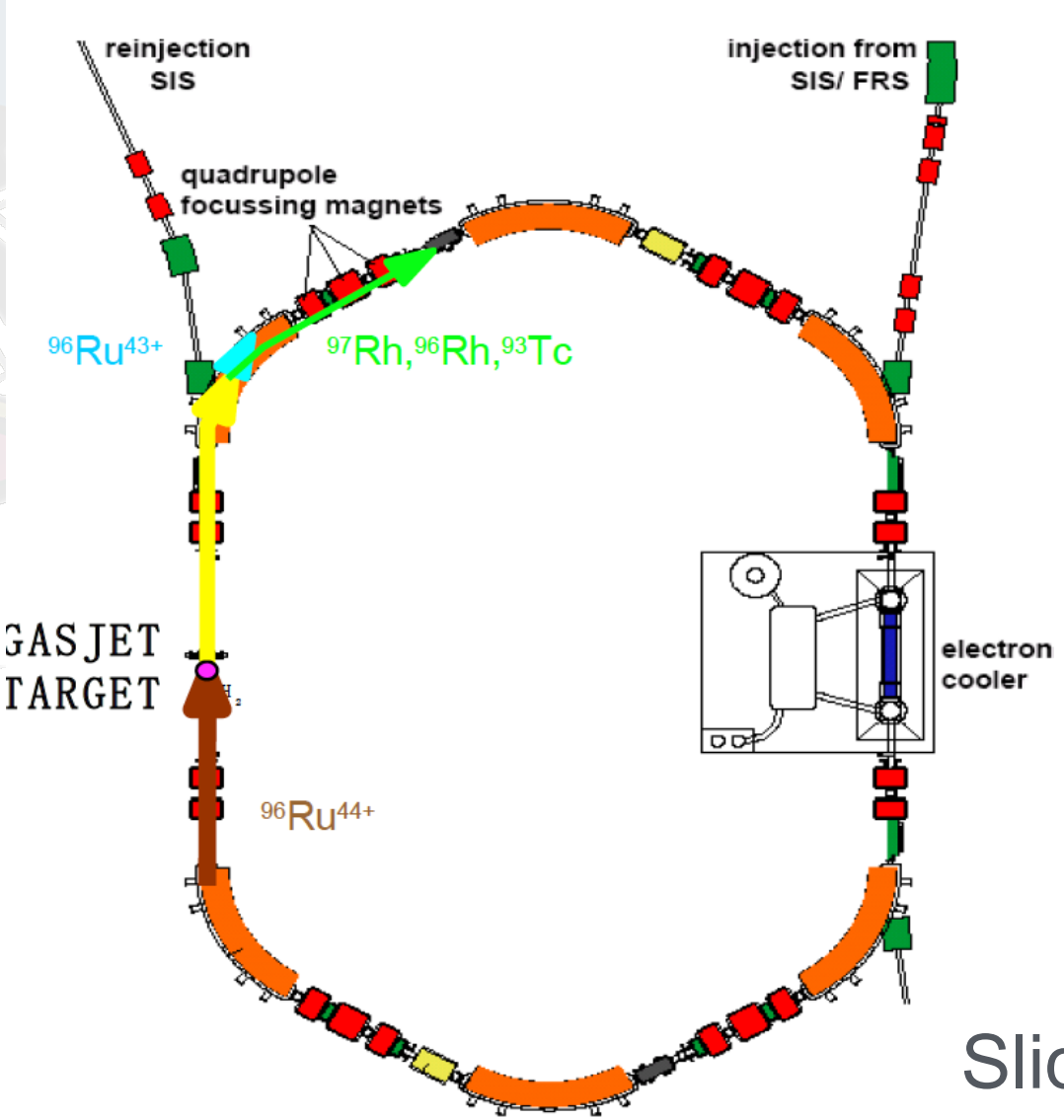
Study of $^{96}Ru(p,\gamma)^{97}Rh$ reaction with decelerated beams using the ESR storage ring at GSI





ESR for NA

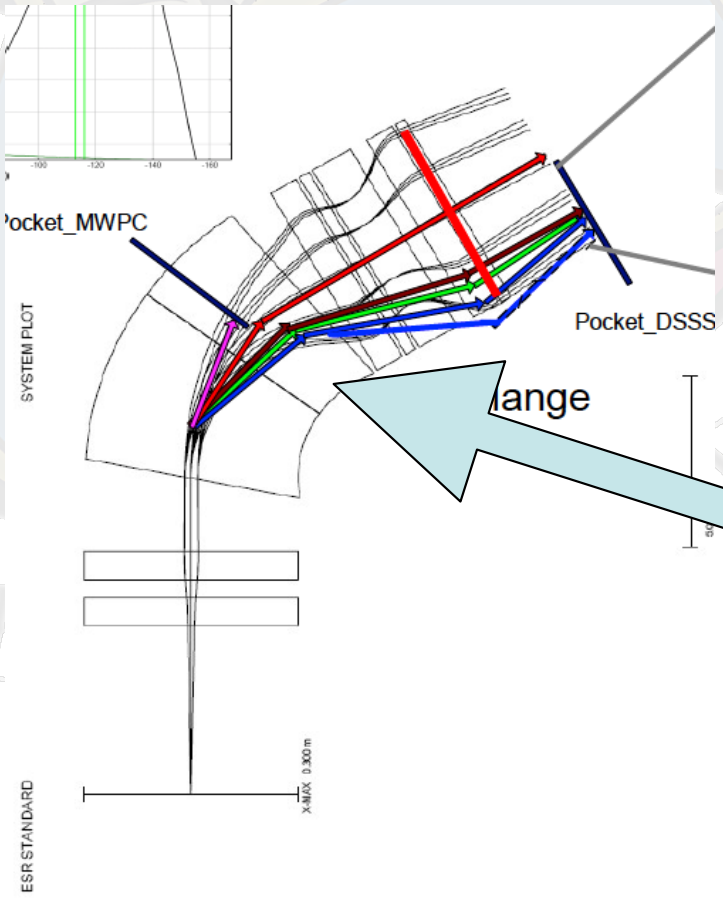
New Technique!



Slides: Q Zhong

Slides: Q Zhong

Reaction by position



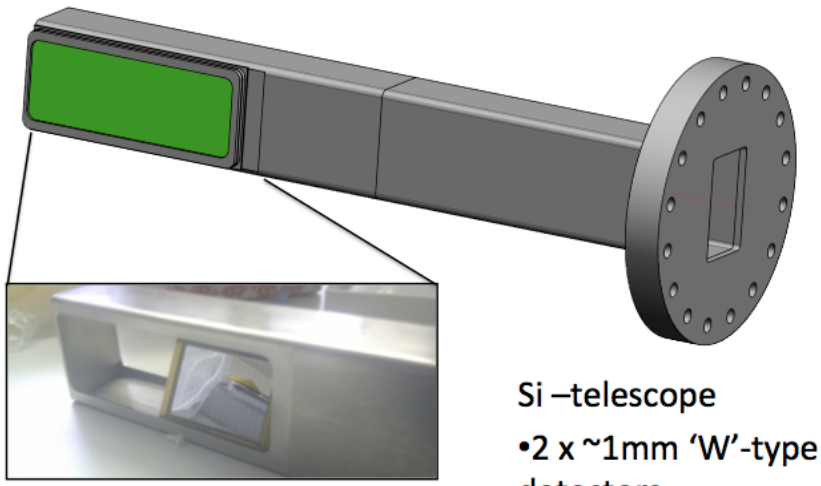
$^{96}Ru(p,\gamma)^{97}Rh$

$^{96}Ru(p,n)^{96}Rh$

$^{96}Ru(p,\alpha)^{93}Tc$

$^{96}Ru^{44+} \rightarrow {}^{96}Ru^{43+}$

Detector Pocket

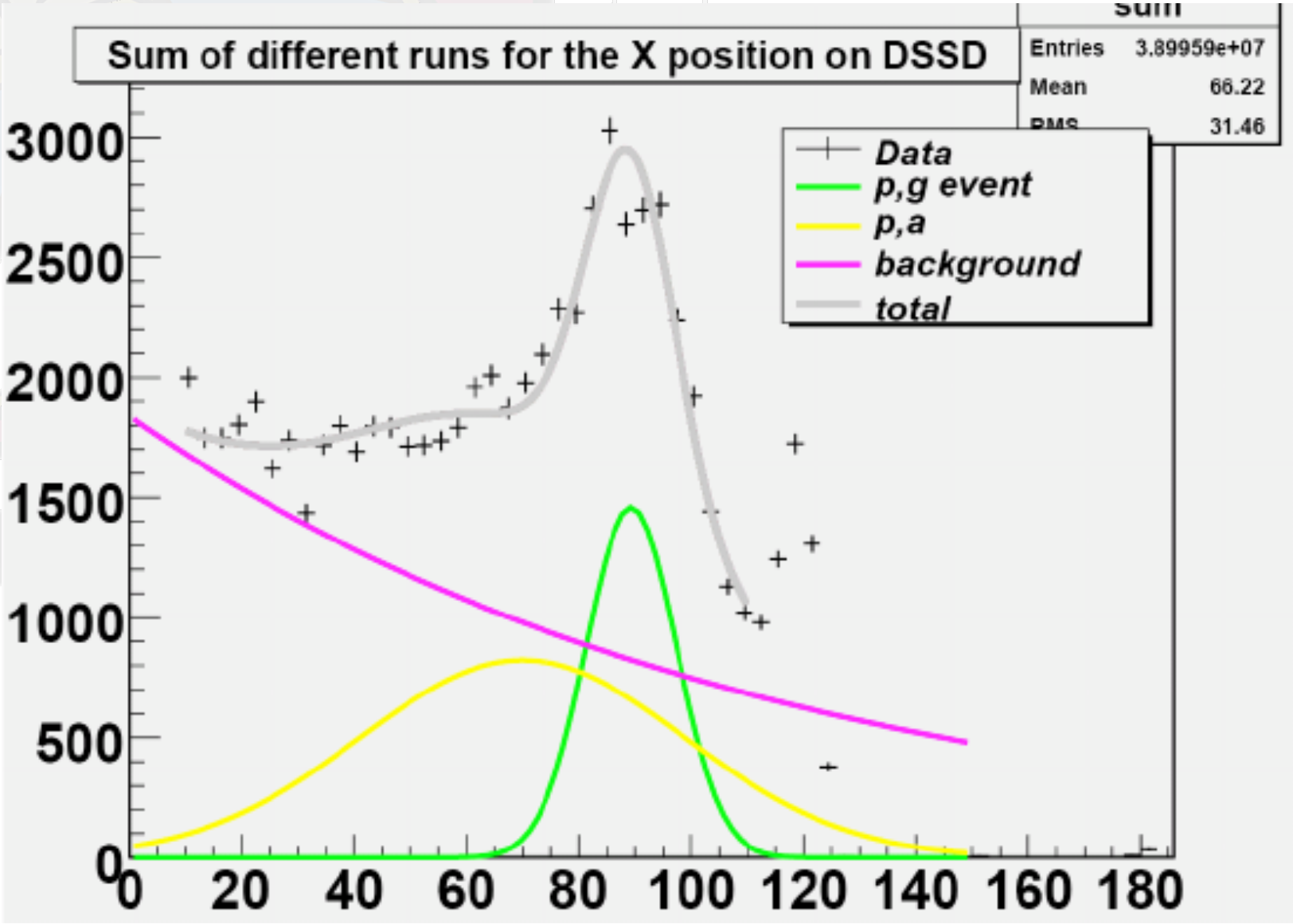


Si –telescope

- 2 x ~1mm 'W'-type detectors
- 16x16 strips

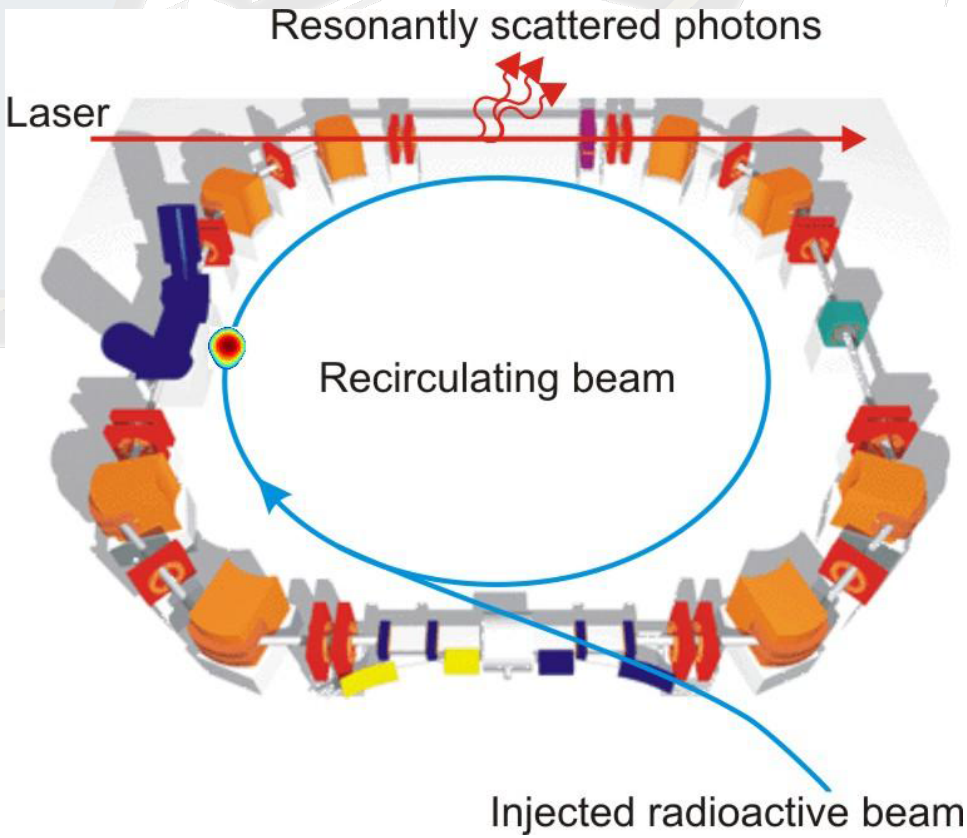
Result

Slides: Q Zhong
Analysis ongoing



One ring to rule them all

- Move of the TSR at MPI Heidelberg to CERN HIE-ISOLDE



- Major future UK NP Project
- Full proposal now being submitted.

See the proposal

ERAWAST

Exotic Radionuclides from Accelerator WAste for Science and Technology

PAUL SCHERRER INSTITUT

PSI

SINQ neutron spallation facility:

- ~2mA protons on Copper (and other) targets for >20 years

- A lot of highly activated material…

… could this be usefully used?

Long lived radionuclides for beams

- Chemically separate ^{44}Ti from highly irradiated accelerator components of PSI
- SINQ neutron spallation facility:
  - >10 yrs of irradiation
  - >10 yrs of cooling

IOPscience Journals Login

Journal of Physics G: Nuclear and Particle Physics

Journal of Physics G: Nuclear and Particle Physics > Volume 39 > Number 10

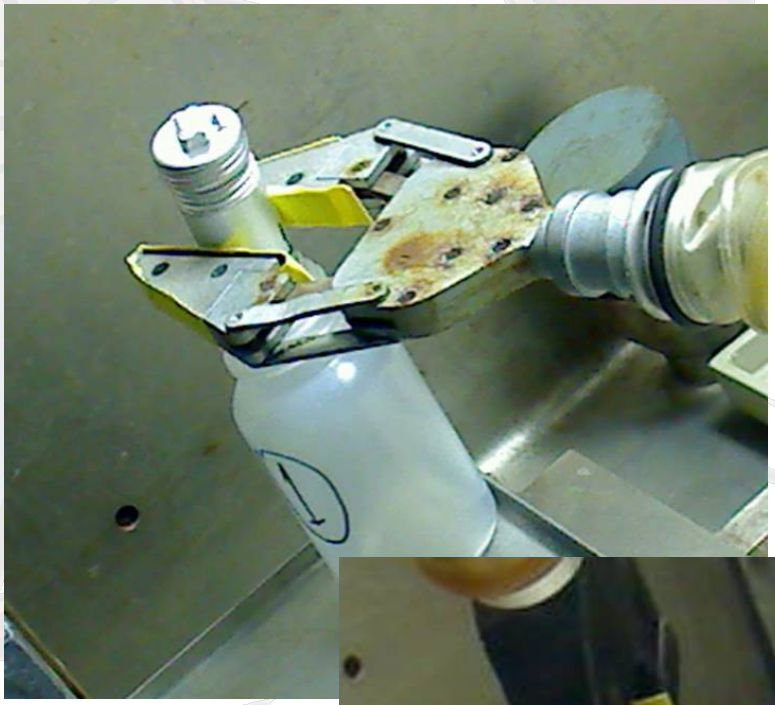
R Dressler *et al* 2012 *J. Phys. G: Nucl. Part. Phys.* **39** 105201 doi:10.1088/0954-3899/39/10/105201

^{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



courtesy Dorothea Schumann, PSI

Separation scheme of STIP samples

STIP sample

dissolution in 8 M HCl + conc. HNO_3

Fe, Cr, Ni, Mo, Mn, Co, Al, Ti

extraction into di-ethyl-ether

organic phase
$FeCl_4$ MoO_2Cl_3

aqueous phase
Cr Ni Mn Co Al Ti traces of Fe and Mo

precipitation with NH_3

filtrate
CrO_4^{2-} $[Ni(NH_3)_6]^{2+}$
MoO_4^{2+} $[Co(NH_3)_6]^{2+}$

precipitate
$Al(OH)_3$ $Fe(OH)_3$ $Ti(OH)_4$ $Cr(OH)_3$ $Mn(OH)_2$

dissolution in 1 M HCl
precipitation with H_2O_2 + NaOH

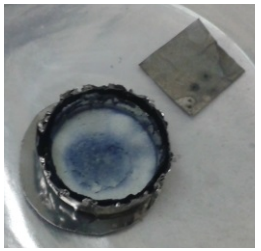
filtrate
$[Al(OH)_4]^-$ CrO_4^{2-}

precipitate
$Fe(OH)_3$ $Ti(OH)_4$ MnO_2

dissolution in 7 M HCl
extraction with di-ethyl-ether

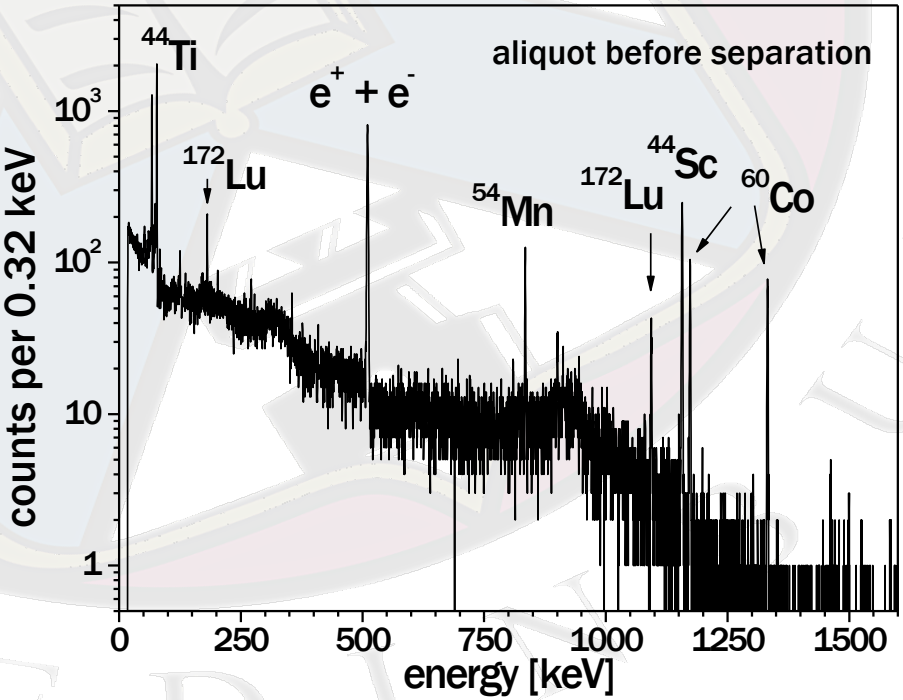
final organic phase
Fe

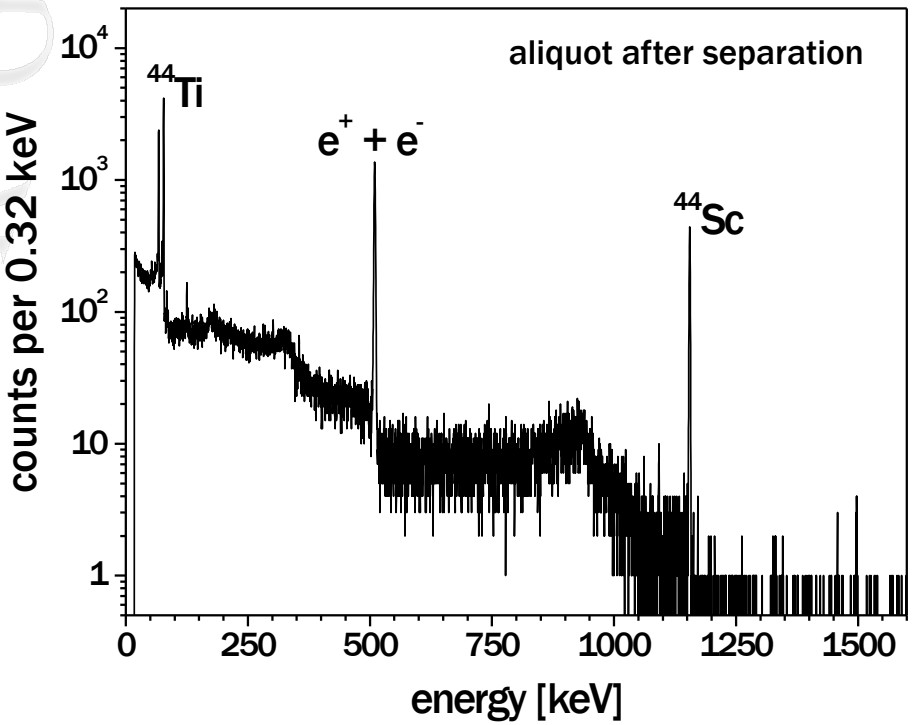
final aqueous phase
Ti, Mn



courtesy Dorothea Schumann, PSI

Quality of chemical separation





- ^{44}Ti: Available: few x 100 MBq; separated 135 MBq; **used 50 MBq**
- ^{26}Al: 300 Bq ≈ 9.8 x 10^{15} atoms
- ^{54}Mn:70 MBq
- ^{53}Mn: ~ 3 x 10^{19} atoms

courtesy Dorothea Schumann, PSI


DANGER
DANGER
RADIOACTIVE II
Radioactive material, Type A Package, UN 2915 DOT 7A TYPE A


Süd
Kingersheim
Müllheim
Mulhouse
Rixheim
Lure
Belfort
Isteiner Klotz
Lörrach
Saint-Louis
Basel
Tiengen
Schaffhausen
Montbéliard
Audincourt
Baden
District 11
Aarau
Altstetten
Zurich
Olten
Delemont
Besançon
Solothurn
Menziken
Horgen
Zug
Grenchen
Ornans
La Chaux-de-Fonds
Biel/Bienne
Burgdorf
Lucerne
Schwyz
Morteau
Neuchatel
Pontarlier
Bümpliz-Oberbottigen
Berne
Stans
Brunnen
Sarnen
Fribourg
Thun
Engelberg
Yverdon-les-Bains
Interlaken
Spiez
Bulle
Lausanne
Saanen
Vevey
Morges
Nyon
Montreux
Thonon-les-Bains
Crans-Montana
Brig
Monthey
Sion
Sierre
Visp
Geneva
Haute-Nendaz
Cluses
Martigny
Verbier
Zermatt


RADIOACTIVE II

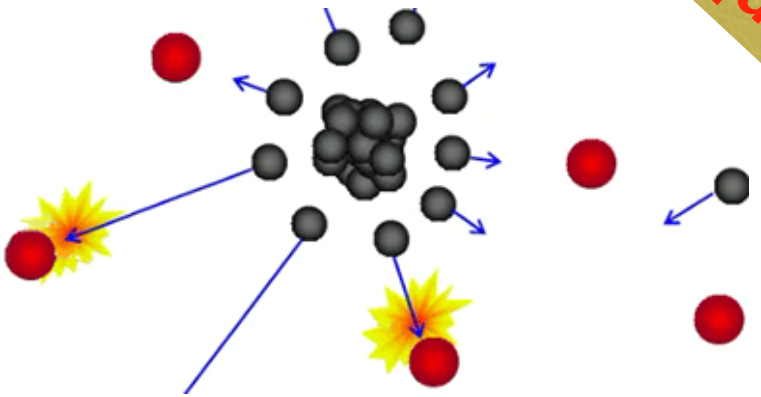
Producing a ^{44}Ti beam

- ^{44}Ti sample in diluted HF acid
- Evaporated on ion source foil
- Foil inserted in a standard target container in the ISOLDE Class A target laboratory,
- Connected to VADIS FEBIAD ion source (VD5 config')
- A large CF_4 gas leak ➔ TiFx molecular ions.
- Installed on GPS Front End
- TiF^{3+} molecular beam extracted.
- Dissociation during charge breeding in REX-ISOLDE
- Accelerated
- ~$5x10^6$ decreasing to ~$5x10^5$ pps over ~100 hours.
- No significant apparent isobaric contamination
- Science… See Vincent's talk later today

Laser Plasma

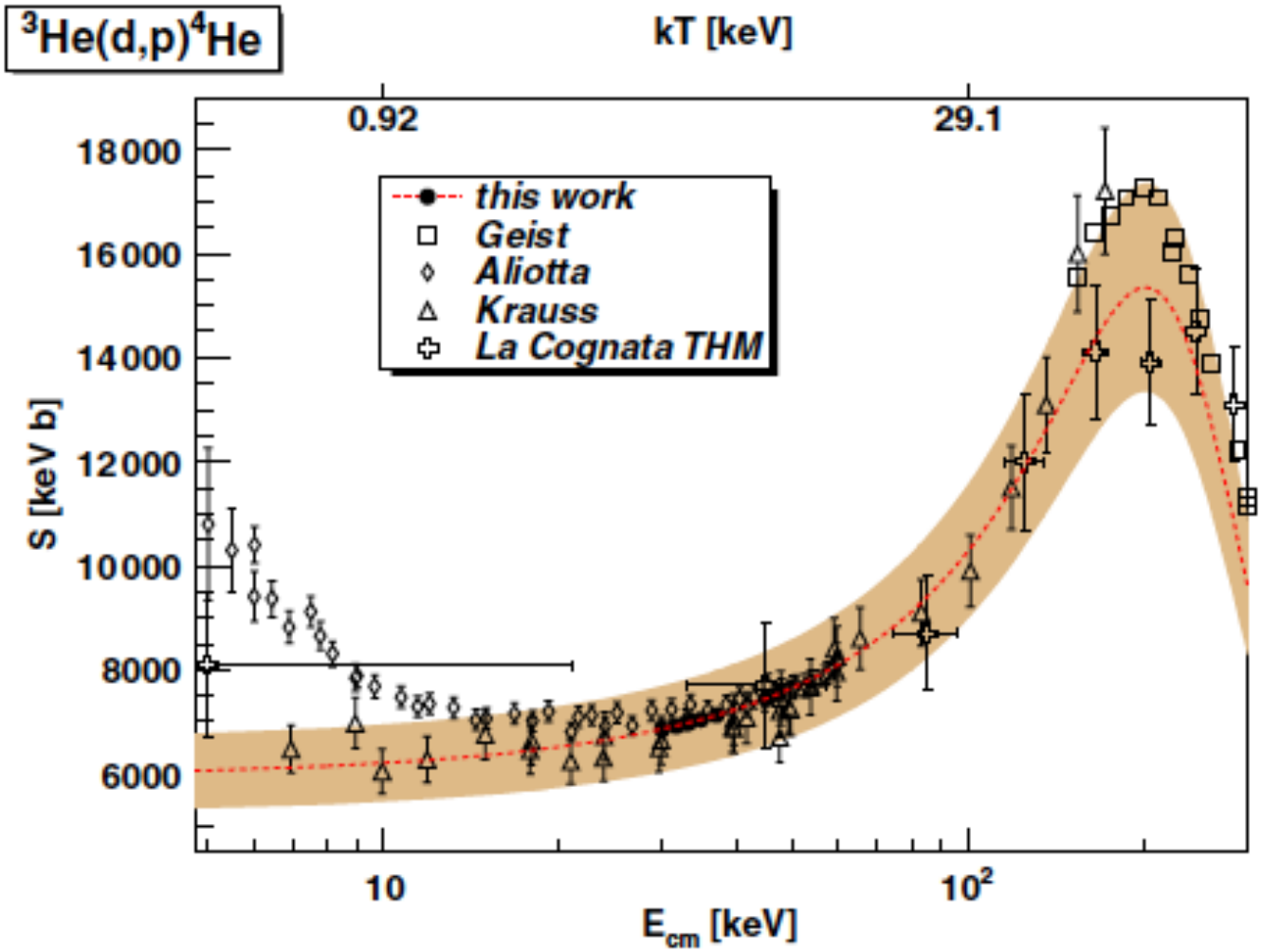
New Technique!

Measurement of the Plasma Astrophysical *S* Factor for the $^3He(d,p)^4He$ Reaction in Exploding Molecular Clusters
M. Barbui, W. Bang, A. Bonasera, K. Hagel, K. Schmidt, J. B. Natowitz, R. Burch, G. Giuliani, M. Barbarino, H. Zheng, G. Dyer, H. J. Quevedo, E. Gaul, A. C. Bernstein, M. Donovan, S. Kimura, M. Mazzocco, F. Consoli, R. De Angelis, P. Andreoli, and T. Ditmire
Phys. Rev. Lett. **111**, 082502 (2013)



- Laser pulses of energy ranging from 90 to 180 J and 150–270 fs
- D_2 and CD_4 clusters in ^3He gas
- 3He does not cluster… no efficient absorption of laser energy; no acceleration.
- Energy distribution of d fast nuclei is Maxwellian
- 14.7 MeV p from (d,p) reactions measured in plastic scintillator

Laser Plasma



Summary

Diverse, expanding & exciting opportunities for nuclear astrophysics

Thank you all for listening!