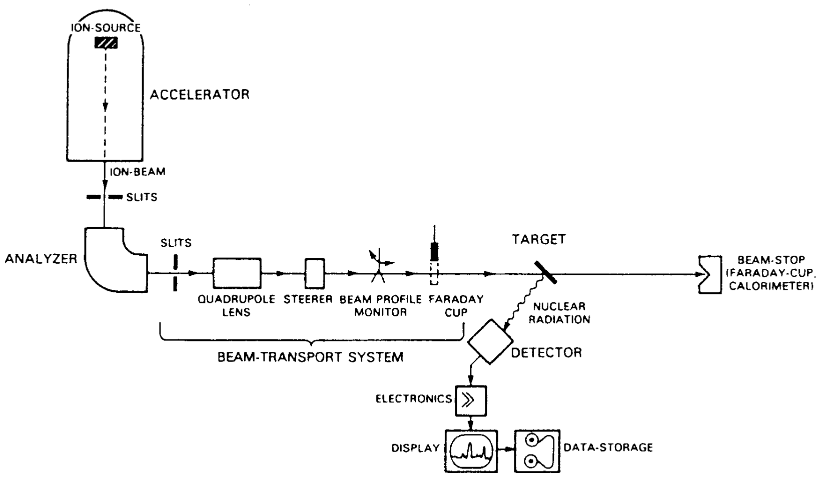
Experimental Approach

Laboratory requirements and techniques



Experimental Approach

Laboratory requirements and techniques

- yields and cross-section measurements
- reactions with stable beams
- reactions with RIBs
- reaction types
- direct and indirect approaches
- some selected examples

YIELD MEASUREMENTS AND CROSS SECTIONS

yield measurements and cross sections

$$\boxed{\text{Yield} = \frac{\text{total number of reactions}}{\text{total number of incident particles}} = \sigma N_t d}$$

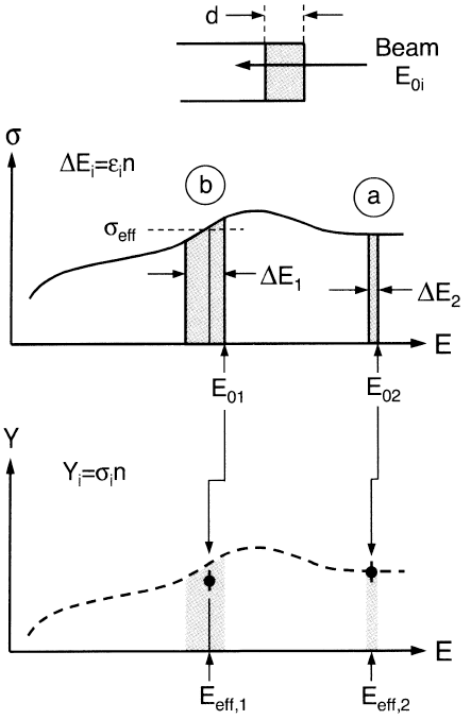
yield vs bombarding energy = *yield curve* or *excitation function*

for non-resonant reactions or for broad resonances

$$\boxed{Y(E_0) = \int_{E_0-\Delta E}^{E_0} \frac{\sigma(E)}{\varepsilon(E)} dE = \frac{\sigma(E_{eff})}{\varepsilon(E_0)} \Delta E(E_0)}$$

cross section and stopping power are almost constant within small energy region

E_{eff} = energy at which 50% of total yield is obtained



Iliadis, 2007

for resonant reactions: yield depends strongly on bombarding energy and target thickness

thin target thickness $\Delta E \ll \Gamma$

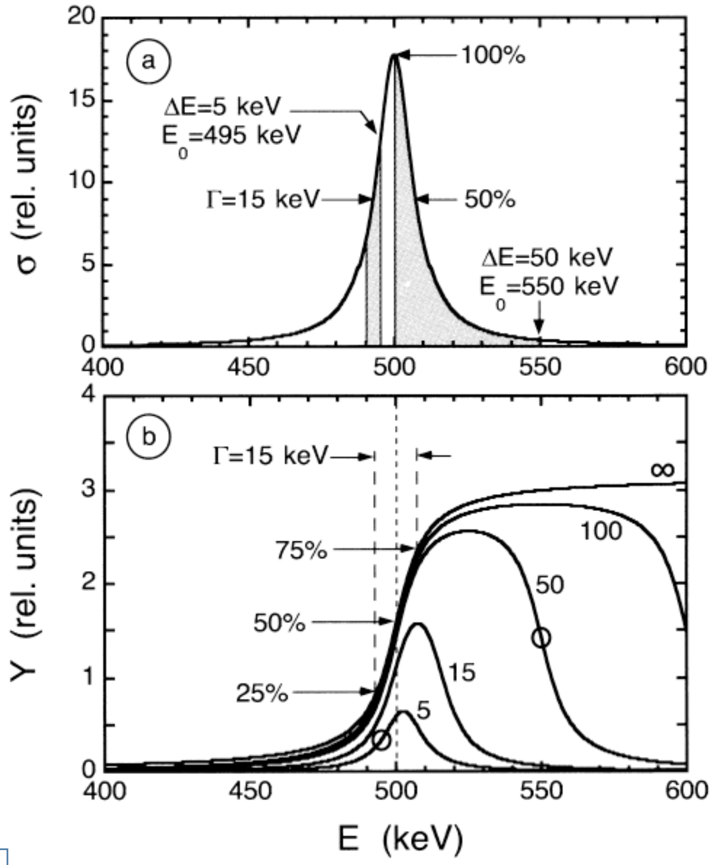
yield curve resembles cross section curve

- max yield at E_R
- FWHM ≈ Γ of resonant state

thick target thickness $\Delta E \gg \Gamma$

yield approaches flat plateau

- max yield at $E_R + \Delta E/2$
- FWHM ≈ ΔE
- Γ = energy difference for $Y_{75\%}$-$Y_{25\%}$



$\Delta E \rightarrow \infty$

$$\boxed{Y_{\max}(\infty) = \frac{\lambda^2}{2}\frac{m_p + m_T}{m_T}\frac{1}{\varepsilon}\omega\gamma}$$

yield measurement gives **directly** ωγ

Stellar evolution

Quiescent burning modes

- stable nuclei
- timescales ~ 10^9 y
- E_0 ~ few keV

Features

- 10^{-18} barn < σ < 10^{-9} barn
- extrapolations
- background

Problems

- long measurements
- pure targets
- high beam currents
- underground laboratories

Requirements

Explosive burning modes

- unstable nuclei
- timescales ~ $10^{-3} – 10^2$ s
- E_0 ~ MeV

Features

- unknown nuclear properties
- low beam intensities
- beam-induced background

Problems

- radioactive ion beams
- large area detectors
- high detection efficiency

Requirements

STABLE BEAM EXPERIMENTS

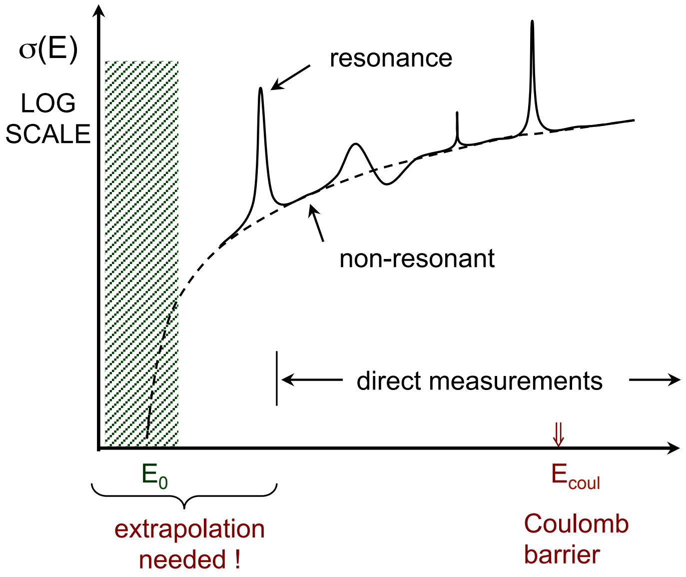
Gamow peak: energy window where information on nuclear processes must be obtained

BUT

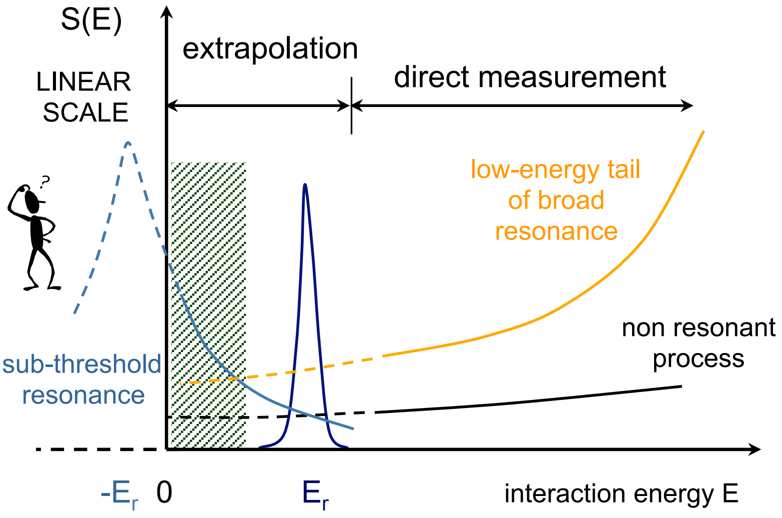
$kT << E_0 << E_{coul}$ ➡ 10^{-18} barn $< \sigma <$ 10^{-9} barn ➡ Major experimental difficulties

Procedure: measure $\sigma(E)$ over as wide a range as possible, then extrapolate down to E_0!

CROSS SECTION



S-FACTOR



DANGER OF EXTRAPOLATION !

the underground solution

Thermonuclear Reactions in Stars

low cross sections → low yields → poor signal-to-noise ratio

Yield = $N_{projectiles}$ x N_{target} x cross section x detection efficiency

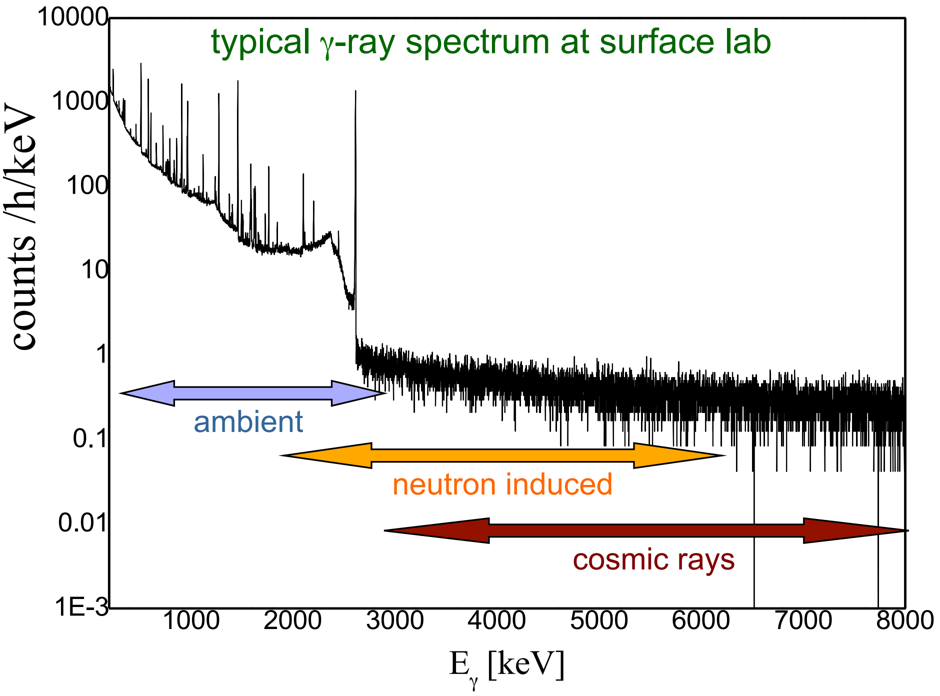
maximising the yield requires:

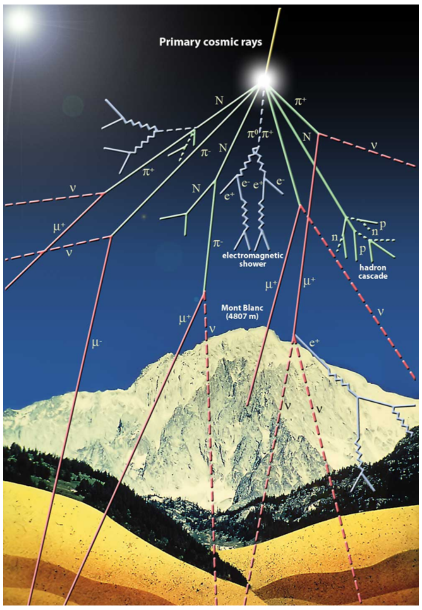
- improving "signal" (e.g. high beam currents, high target density, high efficiency)
- reducing "noise" (i.e. background)
- combination of both

the underground solution

Main Sources of Background:

- natural radioactivity (mainly from U and Th chains and from Rn)
- cosmic rays (muons, ^{1,3}H, ^{7}Be, ^{14}C, …)
- neutrons from (α,n) reactions and fission





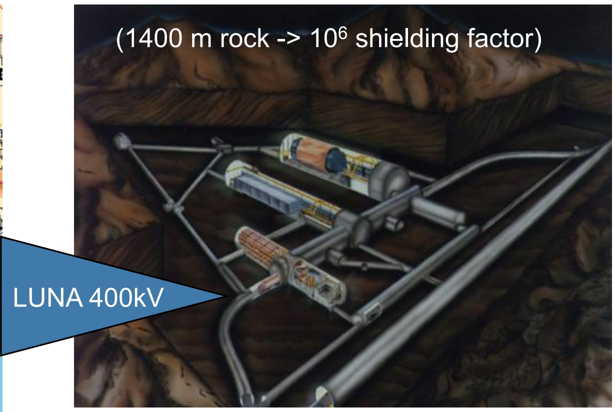
ideal location: underground + low concentration of U and Th

The LUNA facility

LUNA (Laboratory for Underground Nuclear Astrophysics)

Gran Sasso - Italy

Laboratori Nazionali del Gran Sasso



(1400 m rock -> 10^6 shielding factor)

Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}
photons	10^{-1}

The LUNA Collaboration

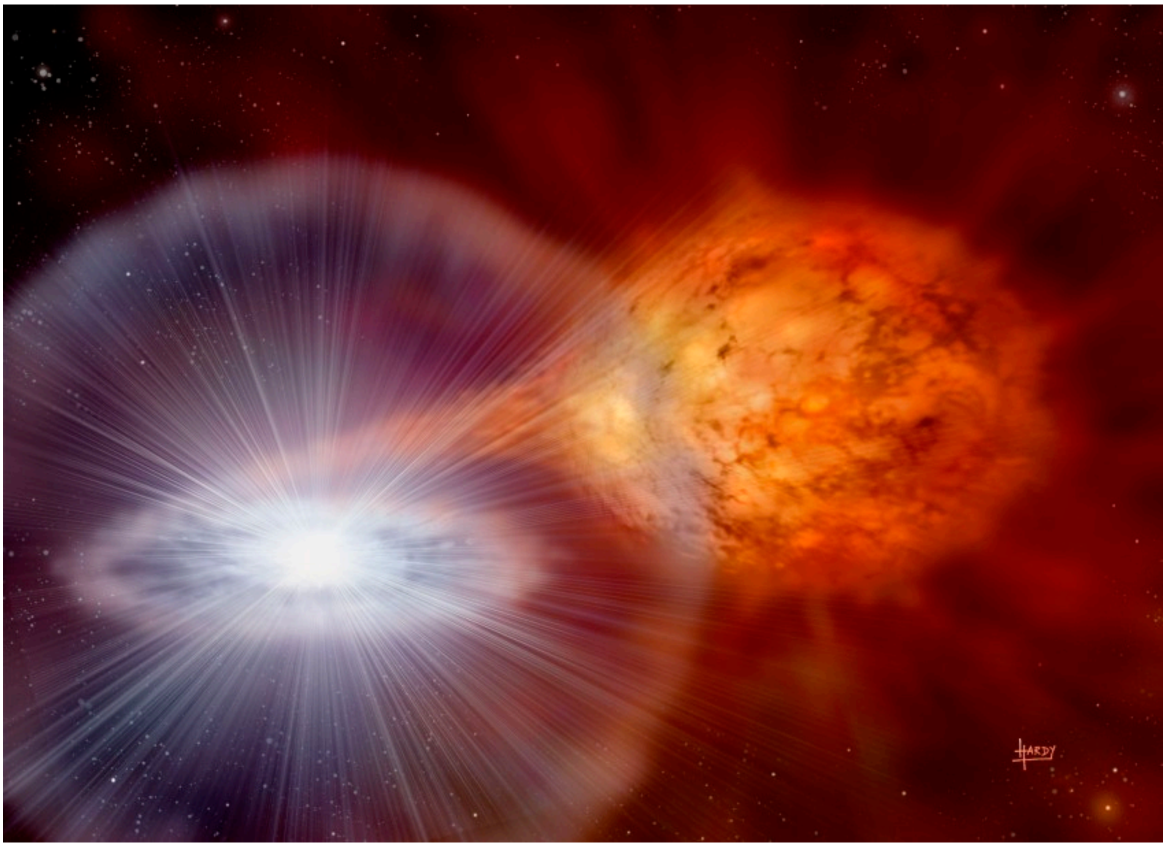
Italy (INFN Gran Sasso, Napoli, Genova, Padova, Milano, Torino, Legnaro)

Germany (Ruhr-Universität Bochum)

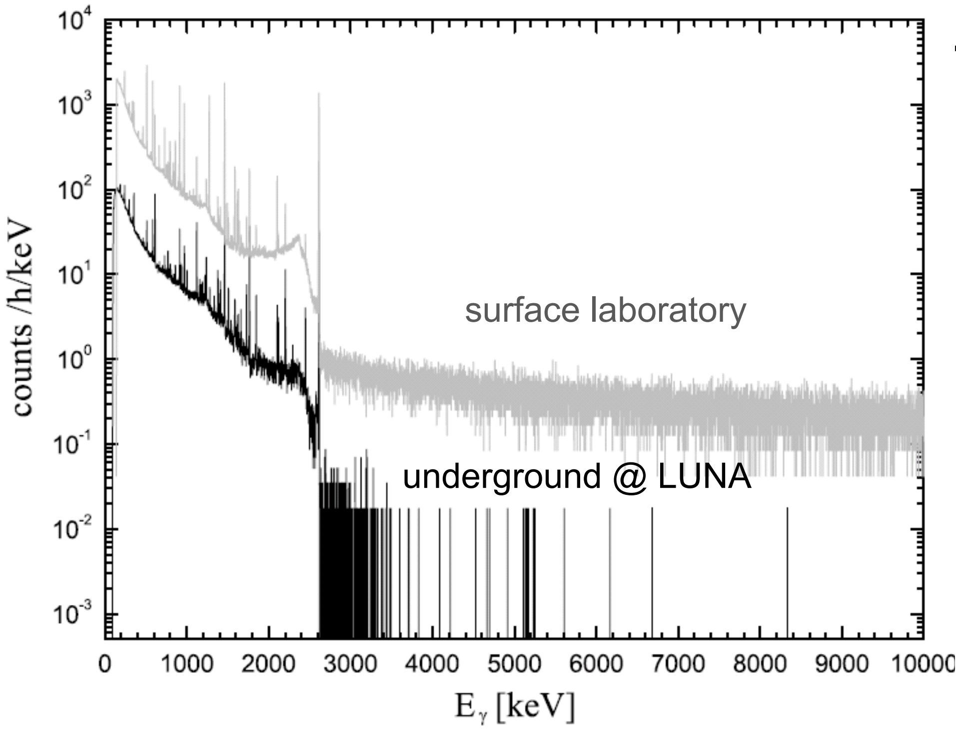
Hungary (Atomki Debrecen)

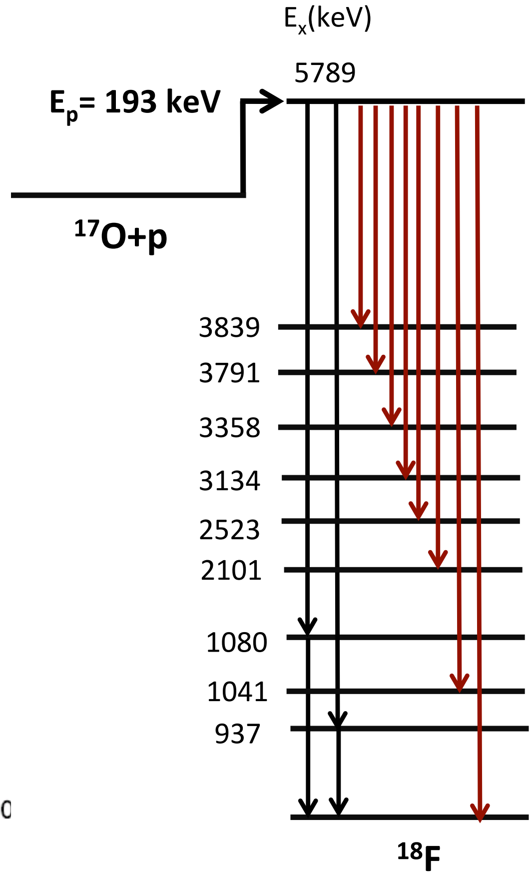
UK (Edinburgh)

the $^{17}O(p,\gamma)^{18}F$ reaction in Classical Novae

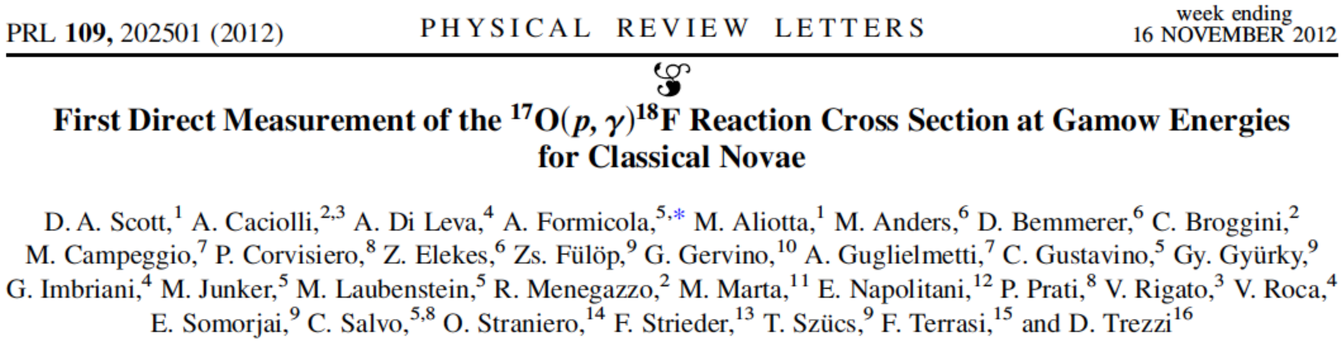


4 orders of magnitude background suppression





Black = Previously Observed
Red = First Observation



PRL **109,** 202501 (2012) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2012

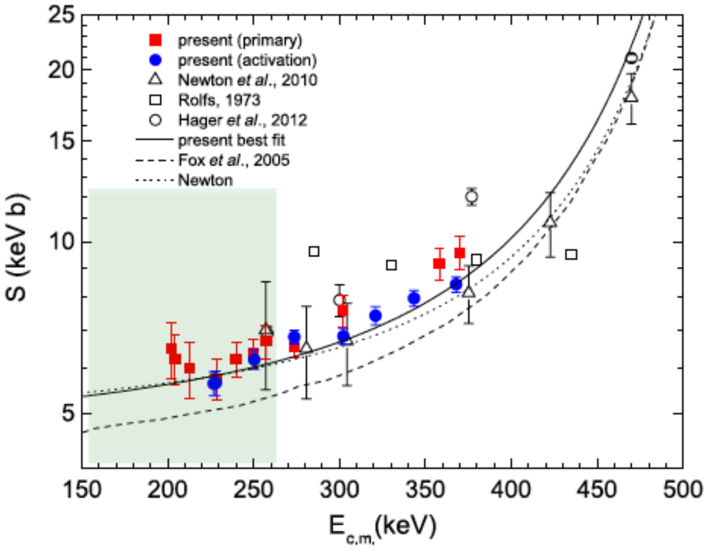
First Direct Measurement of the $^{17}O(p,\gamma)^{18}F$ Reaction Cross Section at Gamow Energies for Classical Novae

D. A. Scott,[1] A. Caciolli,[2,3] A. Di Leva,[4] A. Formicola,[5,*] M. Aliotta,[1] M. Anders,[6] D. Bemmerer,[6] C. Broggini,[2]
M. Campeggio,[7] P. Corvisiero,[8] Z. Elekes,[6] Zs. Fülöp,[9] G. Gervino,[10] A. Guglielmetti,[7] C. Gustavino,[5] Gy. Gyürky,[9]
G. Imbriani,[4] M. Junker,[5] M. Laubenstein,[5] R. Menegazzo,[2] M. Marta,[11] E. Napolitani,[12] P. Prati,[8] V. Rigato,[3] V. Roca,[4]
E. Somorjai,[9] C. Salvo,[5,8] O. Straniero,[14] F. Strieder,[13] T. Szücs,[9] F. Terrasi,[15] and D. Trezzi[16]

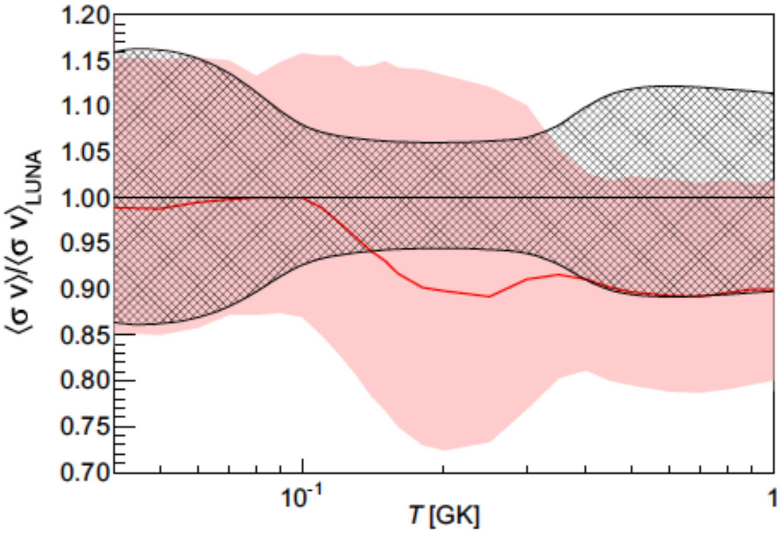
(LUNA Collaboration)

(see also: Di Leva et al. PRC 89 (2014) 015803)

first measurement within Gamow window



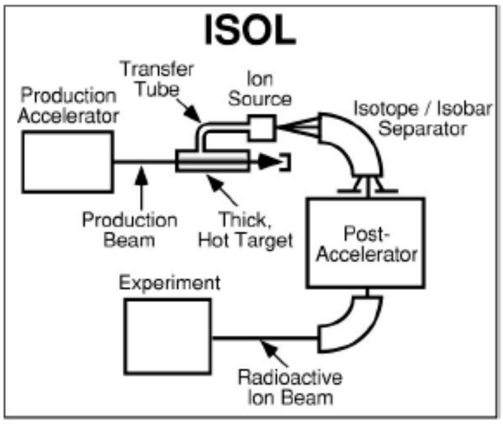
reaction rate: factor of 4 reduction

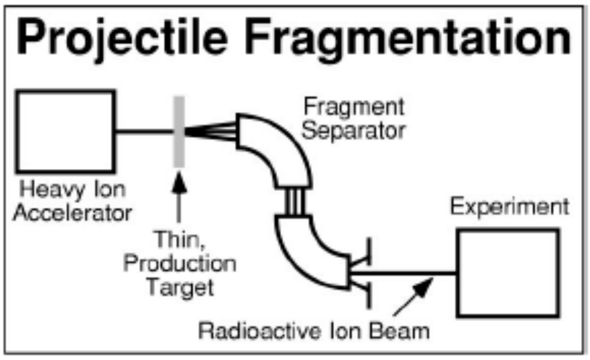


UNSTABLE BEAM EXPERIMENTS

RIB production methods

➢ Isotope Separation on Line (ISOL)	(CERN, LLN, ORNL, TRIUMF)
➢ Projectile Fragmentation (PF)	(GANIL, GSI, MSU, RIKEN)
➢ in-flight production	(ANL, Notre Dame, TAMU)
➢ batch mode production	(suitable for long-lived species)
➢ …	





☺ excellent quality
high purity
high intensities

☹ limited number of species
different production for different species
limited to nuclei with $t_{1/2} \geq 1$s (allow for diffusion)

☺ independent from chemical properties
no limitations on $t_{1/2}$ (fast separation)

☹ typical beam energies too high for NA
poorer beam quality (energy, size)
possible beam contaminations

M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

targets

H targets

solid CH_2 target (plastic material)

☺	☹
simple to handle dx ~ 50 - 1000 μg cm^{-2}	hydrogen depletion non uniformity melting problems deuterium contamination

He targets

solid implanted target

☺	☹
simple to handle	low concentration (n ~ 10^{15} - 10^{17} atoms cm^{-2})

window-confined gas target

☺	☹
higher concentration (depending on pressure)	background reactions (e.g. on window materials)

windowless gas target

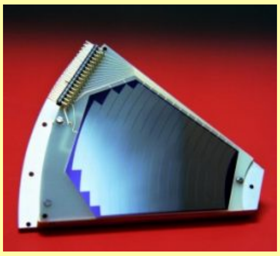
☺	☹
higher concentration almost background free no physical degradation	differential-pumping system high pumping speeds

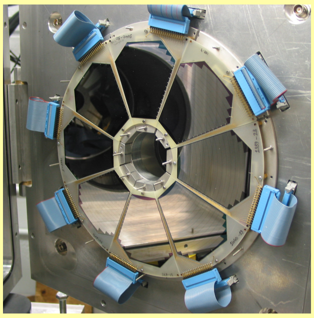
Detectors for RIB Experiments

- low beam intensities:
  - large area ⇒ large solid angle coverage
  - high number of channels ⇒ dedicated electronics
- radioactive decay of beam:
  - high segmentation ⇒ reduce sensitivity to background
  - good modularity ⇒ different configurations possible

"LEDA" type

16 strips in θ
300 mm or
500 mm

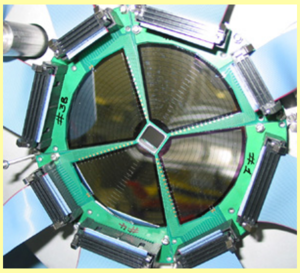


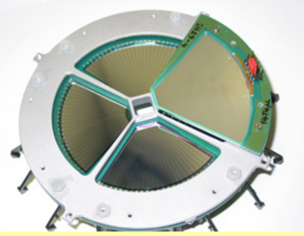


Solid angle:
10% of 4π

"CD" type

16 strips x 4
DSSD
50 mm or 500
mm





4 x PAD

1.5 mm

T. Davinson et al.: NIM A 454 (2000) 350-358

NUCLEAR DATA NEEDS

reactions involving:	cross-section dependence:	knowledge required:
A < 30	individual resonances nuclear properties	excitation energies spin-parity & widths decay modes
A > 30	statistical properties Hauser-Feshbach calculations	masses level densities part. separation energy

- very large amount of reactions in various astrophysical sites
- not feasible to study all reactions involved
- experimental constraints wherever possible

experimental approaches

reaction types and experimental techniques

- DIRECT APPROACHES
  - radiative capture reactions
  - transfer reactions

- INDIRECT APPROACHES
  - resonant elastic scattering
  - transfer reactions
  - time-inverse reactions
  - coulomb dissociation
  - ...

DIRECT APPROACHES

RADIATIVE CAPTURE

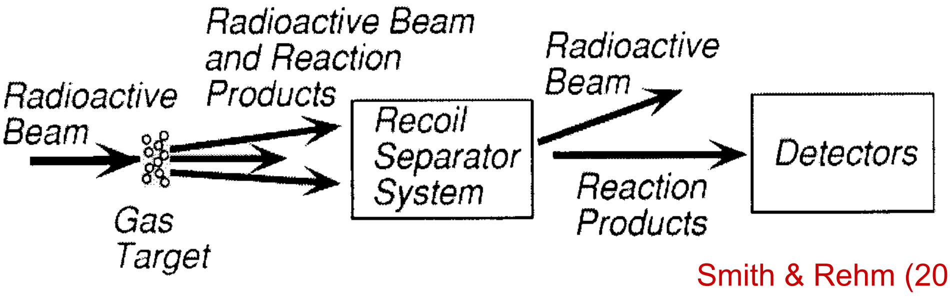
$X(p,\gamma)Y$
$X(\alpha,\gamma)Y$ } among the most common reactions in nuclear astrophysics

- heavy recoil detection

inverse kinematics ⇒ forward peaked emission ($\theta \sim 1^o$)
⇒ detection efficiency ~ 100%

BUT: high suppression factors required (10^{10}-10^{15})

RIB intensities ~ 10^7 ions/s



Smith & Rehm (2001)

examples:

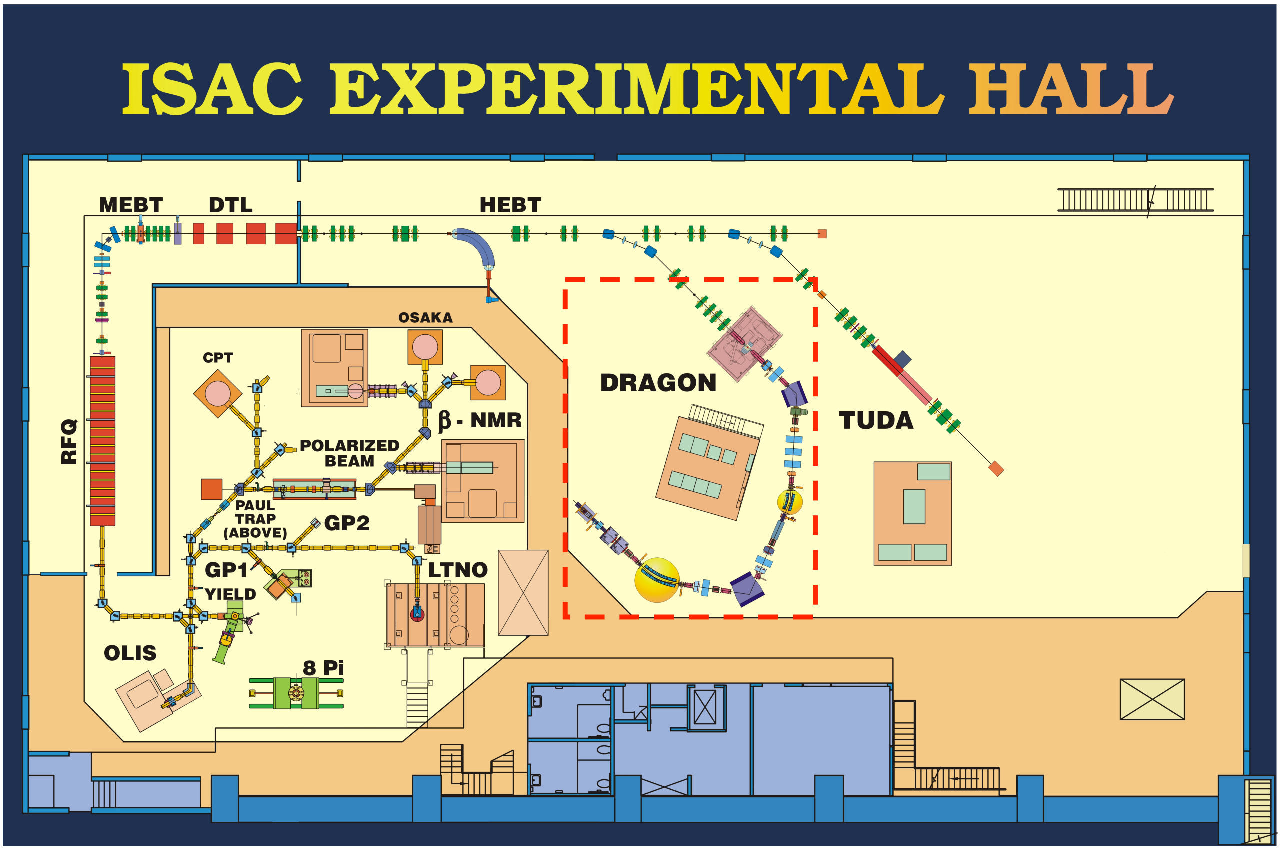
$^{21}Na(p,\gamma)^{22}Mg$, $^{15}O(\alpha,\gamma)^{19}Ne$ @ DRAGON – TRIUMF

the experiment

first direct measurements of **^{21}Na(p,γ)^{22}Mg** @ TRIUMF – Canada

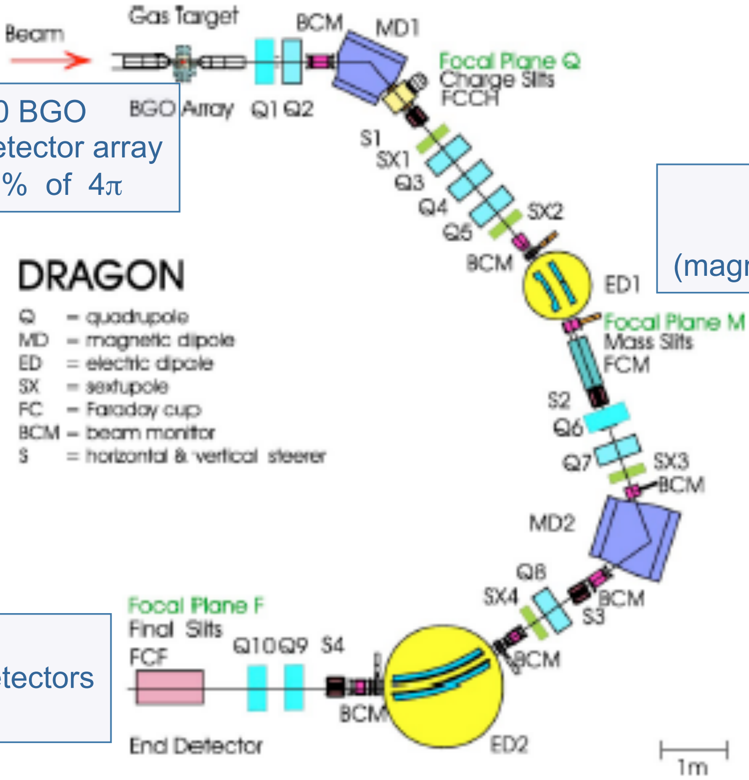
S. Bishop et al.: Phys Rev Lett 90 (2003) 162501(4)

J.M. D'Auria et al.: Phys Rev C 69 (2004) 65803(16)



the DRAGON facility

Detector of **R**ecoils **A**nd **G**ammas **O**f **N**uclear reactions



differentially pumped
window-less
gas target (~ 12cm)

30 BGO
γ-ray detector array
~ 90% of 4π

(start)

two-stage
recoil separator
(magnetic and electric dipoles)

(stop)

DSSSD
double sided silicon strip detectors
for recoil detection

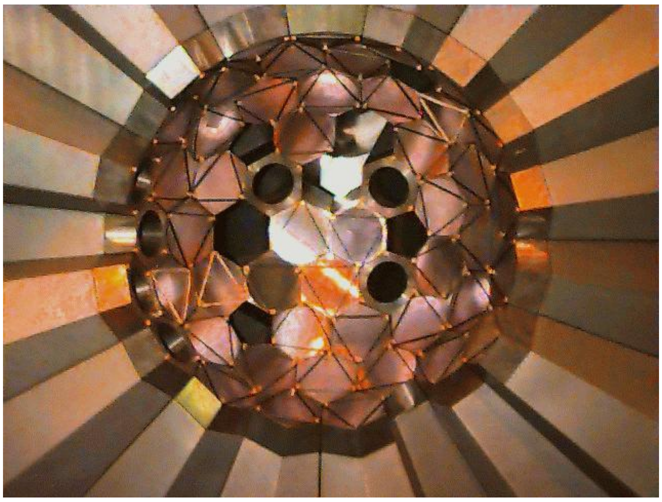
see: J.M. D’Auria et al., Nucl Phys A 701 (2002) 625 and D. Hutcheon et al., NIM A 498 (2003) 190 for details

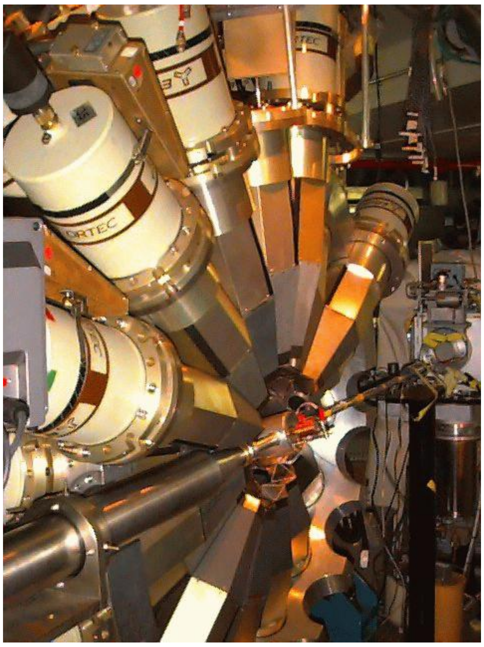
- γ-ray detection

low efficiency ⇒ ~ 4π coverage needed

γ-ray background induced by β^+ beam decay

gammasphere





100 HPGe detector array

absolute efficiency: 9% for 1.33 MeV γ ray

example: **$^{22}Na(p,\gamma)^{23}Mg$** @ ANL

- delayed decay measurements

example:

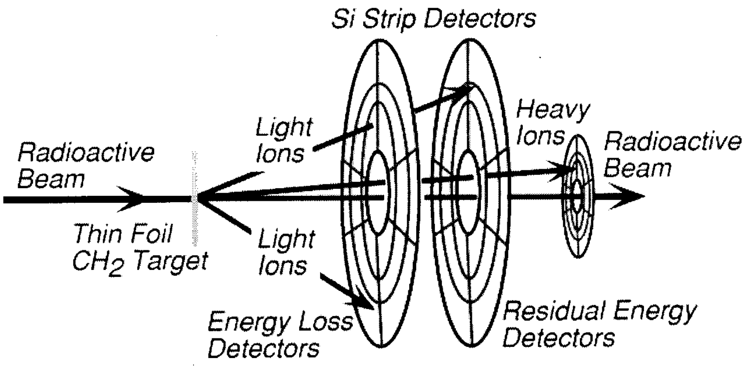
$^{19}Ne(p,\gamma)^{20}Na(\beta^+)^{20}Ne^*(\alpha)^{16}O$ @ Louvain-la-Neuve

TRANSFER REACTIONS mainly X(p,α)Y and X(α,p)Y

- light-heavy nuclei coincidence

silicon strip detector arrays ⇒ large solid angle coverage (e.g. LEDA)

RIB intensities ~ 10^5 ions/s



examples:

^{18}Ne(α,p)^{21}Na	@ LLN	Groombridge et al.: Phys Rev C 66 (2002) 55802(10)
	& TRIUMF	TUDA collaboration
^{18}F(p,α)^{15}O	@ ORNL	Bardayan et al.: Phys Rev C 63 (2001) 65802(6)
		Bardayan et al.: Phys Rev Lett 89 (2002) 262501(4)
^{14}O(α,p)^{17}F	@ GANIL	Aliotta et al.

INDIRECT APPROACHES

RESONANT ELASTIC SCATTERING

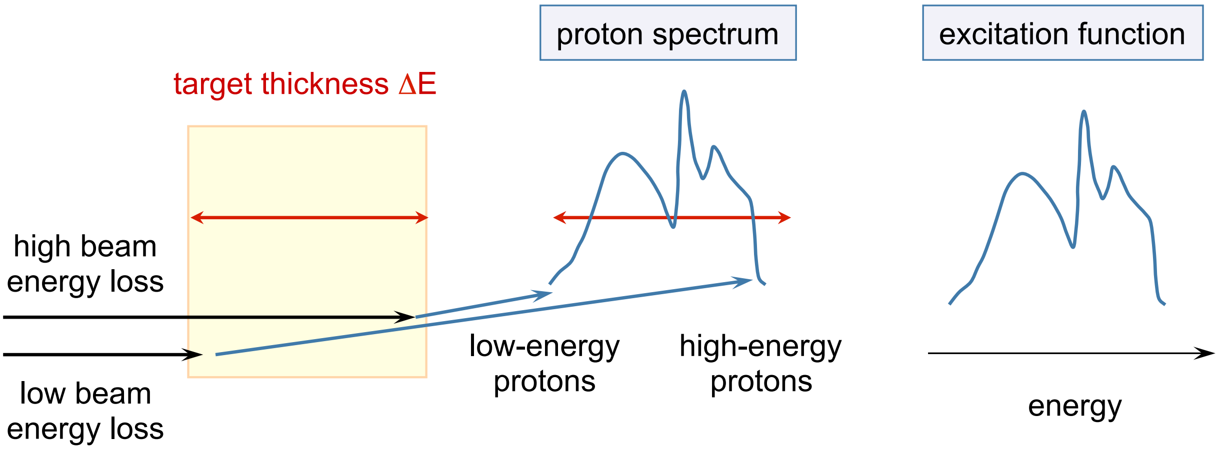
typically X(p,p)X

⇒ investigate resonance properties of compound nucleus

the method

Laubestein et al.: PR 84 (1951) 12

inverse kinematics + suitably thick target (eg $(CH_2)_n$) + proton detection



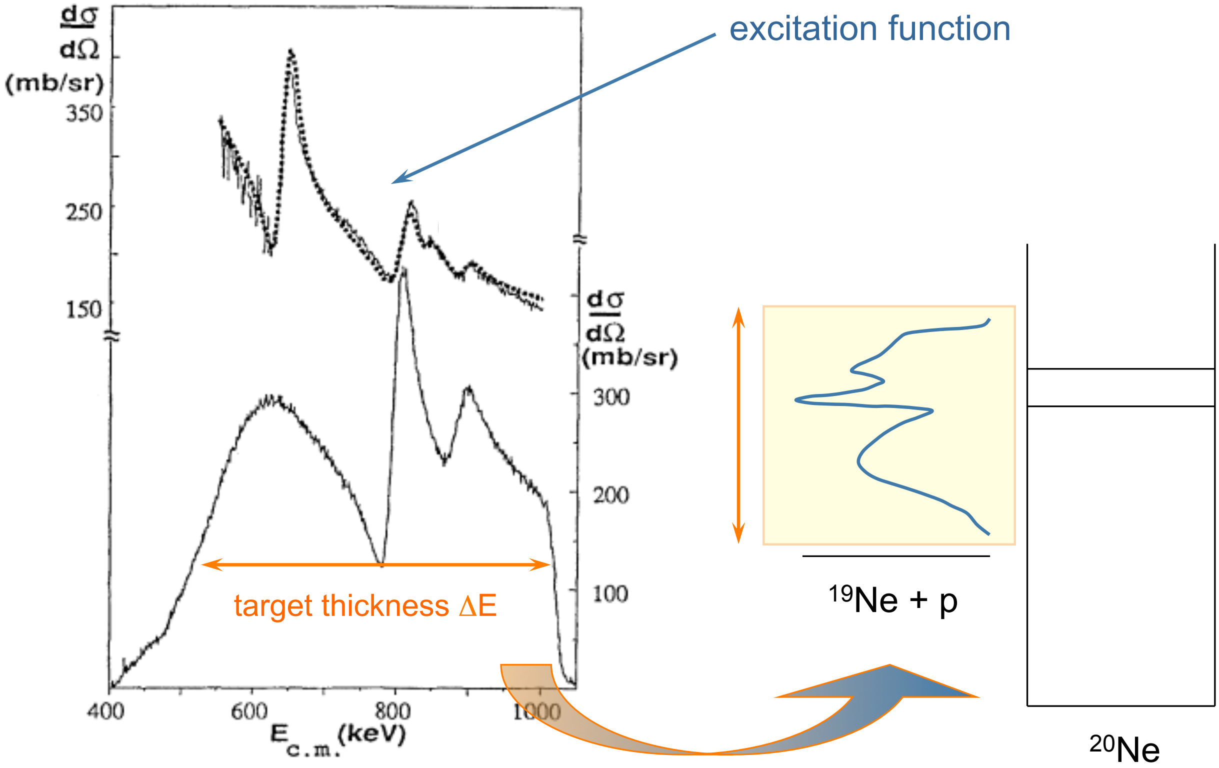
protons undergo little energy loss, little kinematics variation, little straggling ➡ retain information on resonance shape

a real case

$^{19}Ne(p,p)^{19}Ne$

<u>resonant elastic scattering</u>

Coszach et al.: Phys Rev C 50 (1994) 1695



excitation function

target thickness ΔE

$^{19}Ne + p$

^{20}Ne

resonant elastic scattering

relevance

R-matrix analysis to:

- locate resonance state ⇒ E_r
- determine partial widths ⇒ Γ_p
- determine spins ⇒ J

advantage

resonant elastic scattering has high cross sections

RIB intensities ~ 10^3 ions/s

limitations

<u>requirement:</u> proton width $\Gamma_p \geq 1$ keV due to current limits in detection energy resolution

progressively harder at lower energies due to increase in Rutherford cross section and decrease in resonance widths because of penetrability effects

examples: ^{11}C(p,p) & ^{7}Be(p,p) @ LLN
^{21}Na(p,p) @ TUDA - TRIUMF

TRANSFER REACTIONS

RIB intensities ~ 10^4 ions/s

e.g. X(d,p)Y

⇒ investigate (n,γ) reactions for *s*- (or *r*-)*process*

TIME-INVERSE REACTIONS

e.g. Coulomb dissociation

⇒ investigate (x,γ) radiative capture reactions

MASS & LIFETIME MEASUREMENTS

… and much more…

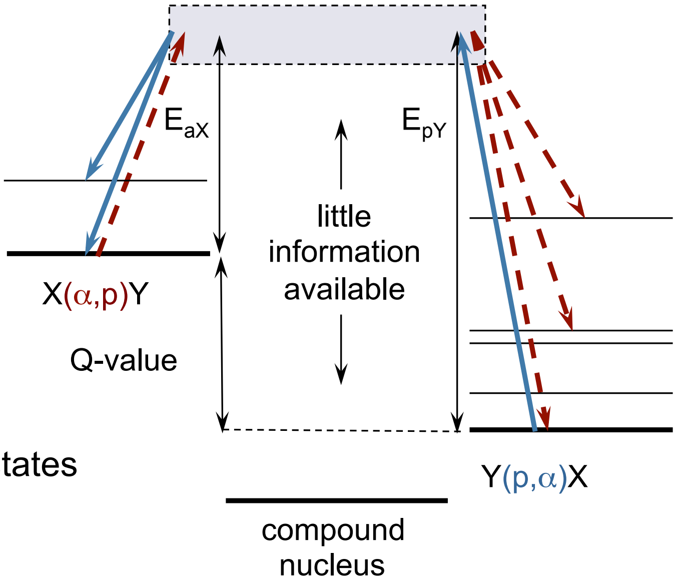
Time-reverse approach for (α,p) reactions

the methodology

time-reversed approach: X(α,p)Y ⇔ Y(p,α)X

detailed-balance theorem

$$\frac{\sigma_{\alpha X}}{\sigma_{pY}} = \frac{m_p m_Y}{m_a m_X}\frac{E_{pY}}{E_{aX}}\frac{(2J_p+1)(2J_Y+1)}{(2J_a+1)(2J_X+1)}$$



direct approach: spin-less particles
⇒ populate only natural parity states

indirect approach: no selectivity

However! kinematic selection on transitions between ground states
⇒ ensure only natural parity states have been populated

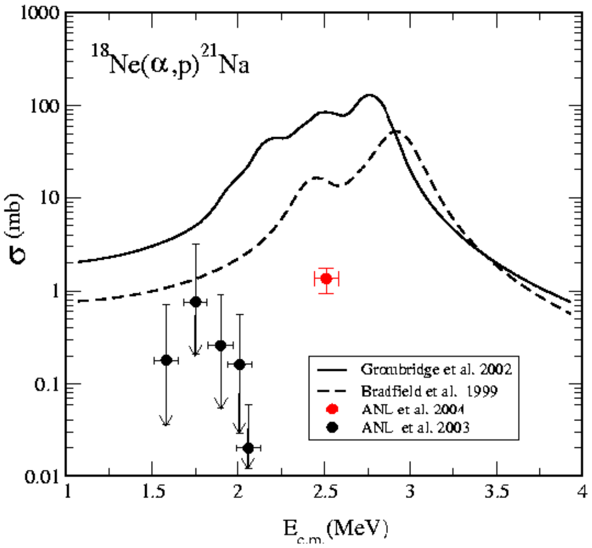
main limitation: only ground-state to ground-state transitions
⇒ lower limit to cross section

the ^{18}Ne(α,p)^{21}Na case

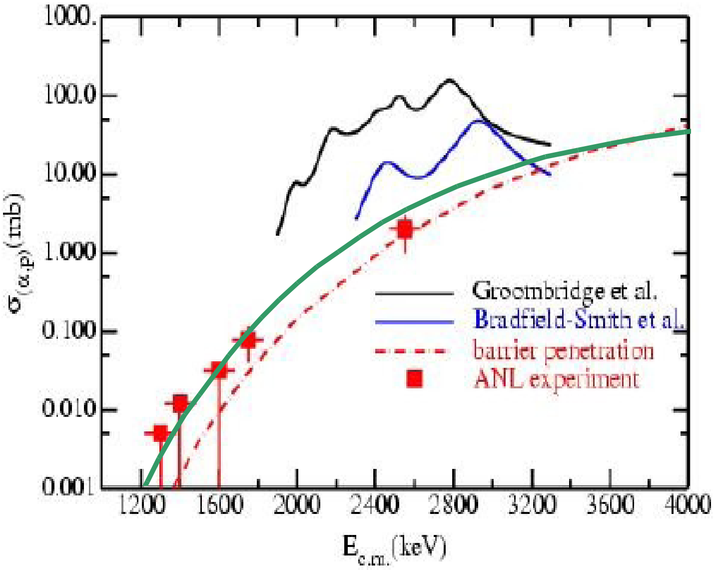
a break-out route from the HCNO cycle in X-ray bursts

^{18}Ne(α,p)^{21}Na : current status

Argonne National Laboratory
Internal Report 2004



Argonne National Laboratory
Internal report 2005



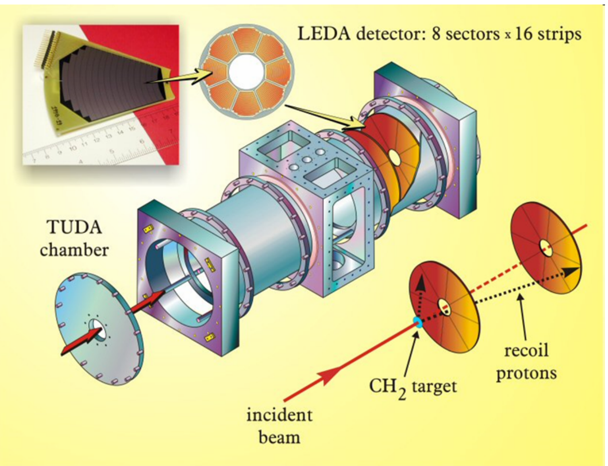
- two direct measurements
- one time-reversed measurement
- theoretical calculation (Hauser-Feshbach)
- large discrepancies remain
- new studies of ^{22}Mg states (up to 12-13 MeV)
  e.g. via ^{24}Mg(p,t)^{22}Mg - Chae (2009); Matic (2009)
- resonant elastic scattering - He (2008, 2009)

$^{21}Na(p,\alpha)^{18}Ne$

Experiment run in August 2009

TRIUMF

TUDA scattering chamber



S1103 Collaboration

University of Edinburgh – University of York - TRIUMF

Experimental setup @ ISAC II

^{21}Na 5^{+} beam

I ~ 5x10^{6} pps

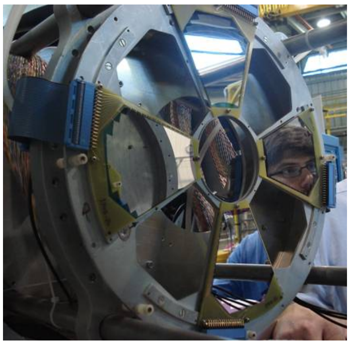
E ~ 5.5 – 3.8 MeV/u

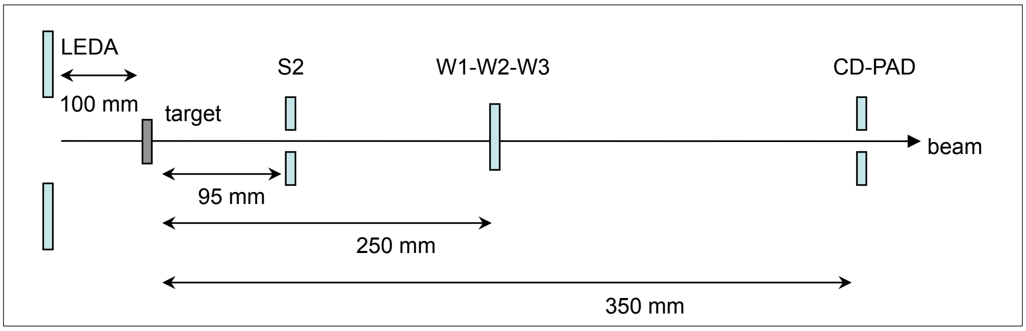
CH$_2$ target

W: protons (alphas)

aim 2
meas elastic proton scattering
(thick rement)

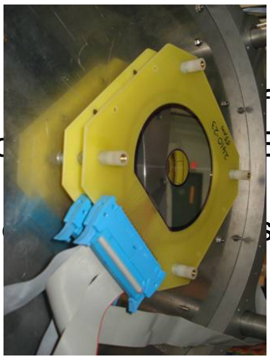
LEDA: RBS on Au spot



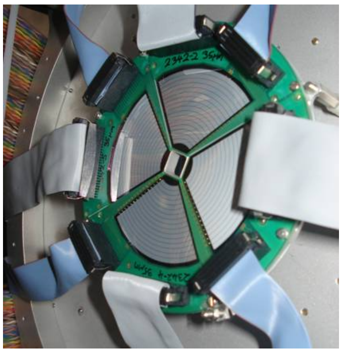


aim 1): measure for ^{18}Ne+alpha
particle ic E-E technique
(thin targ s)

S2 detector:
alpha particles



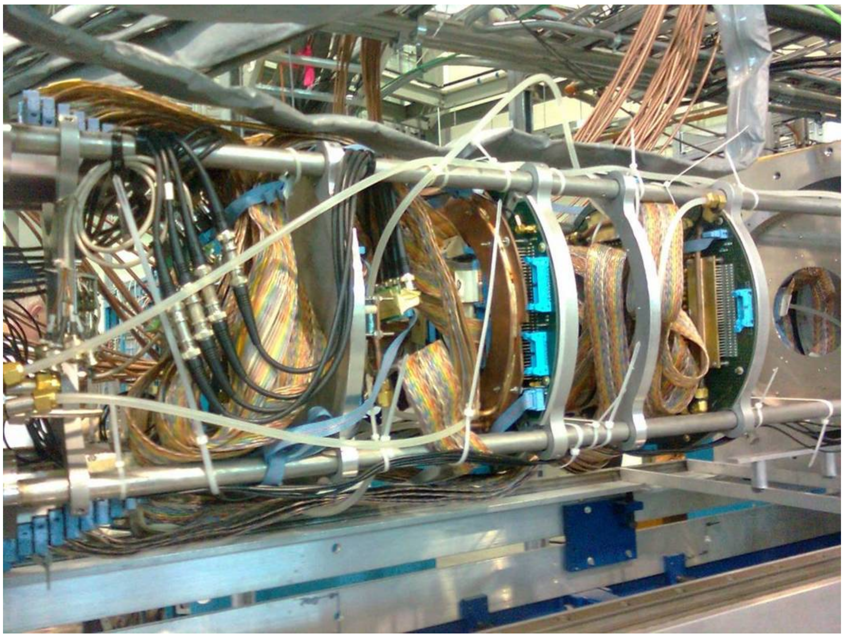
CD-PAD:
heavy ions
^{18}Ne, ^{21}Na



~420 individual channels

largest number ever of silicon detector channels in TUDA

a messy situation…

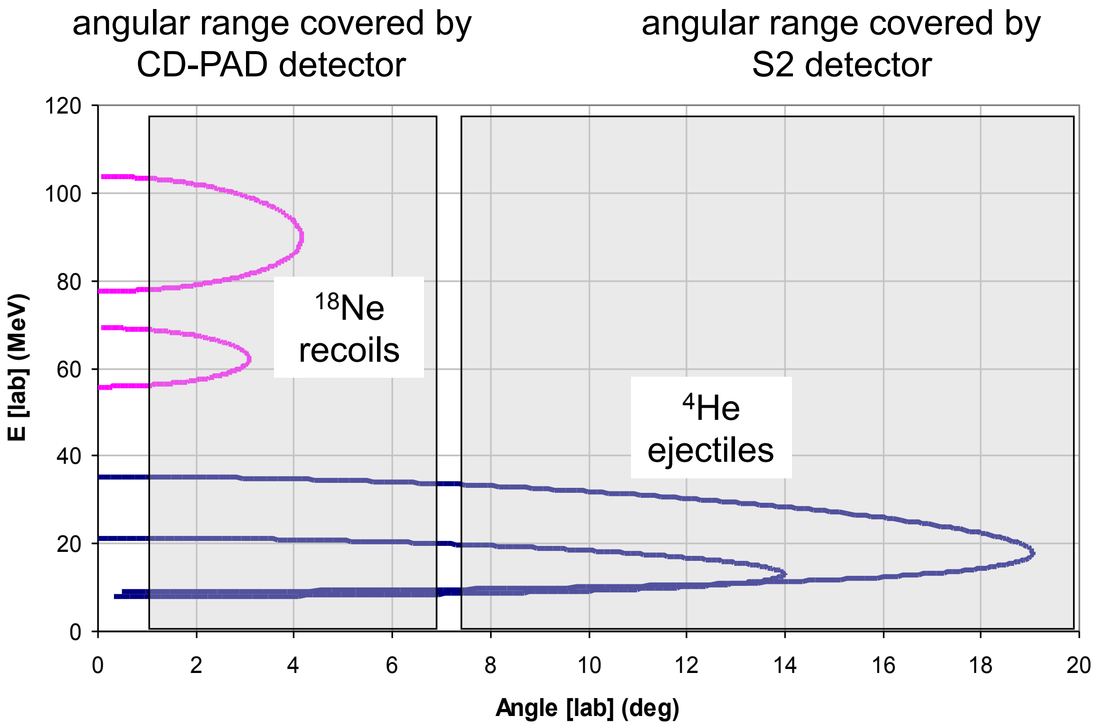


Philip Salter working hard…

kinematics curves

^{21}Na(p,α)^{18}Ne   kinematics at E_{beam} = 115 – 80 MeV

inverse kinematics ⇒ forward focussed reaction products

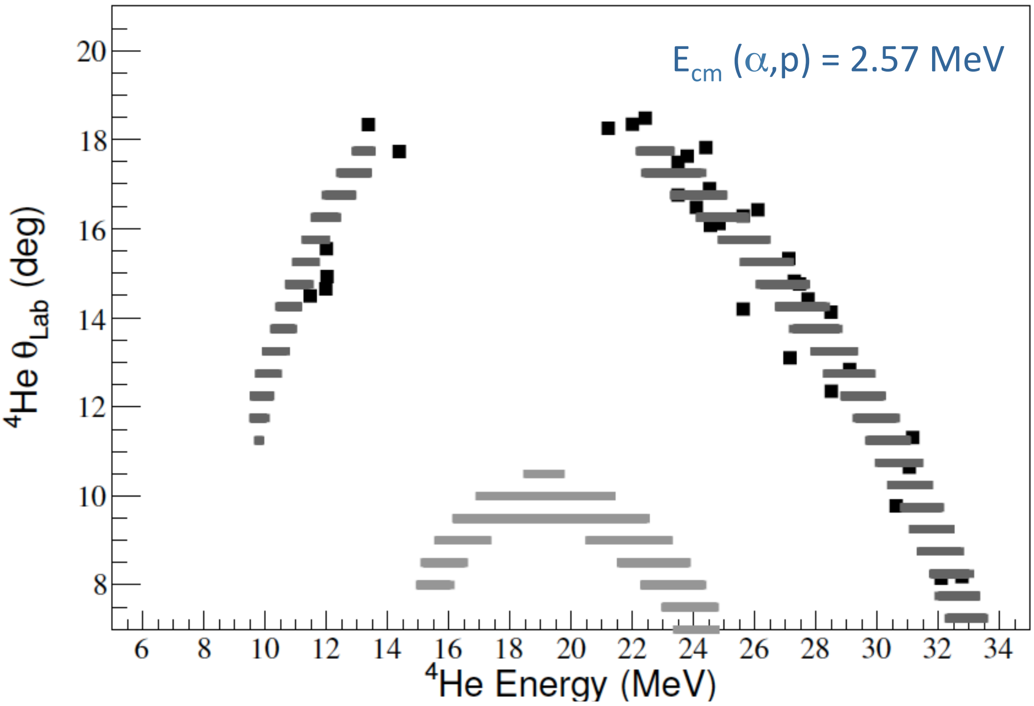


particle identification by ΔE-E and total energy reconstruction
distinguish gs-gs transition from gs to 1.89 MeV in ^{18}Ne

Our Results

alpha kinematics loci (experimental and simulated)

alpha particles in coincidence with 18Ne in CD-PAD



Salter *et al*. PRL 108 (2012) 242701

distinguish gs-gs transition from gs to 1.89 MeV in ^{18}Ne

no events observed to first excited state of 18Ne

PRL **108,** 242701 (2012) PHYSICAL REVIEW LETTERS week ending 15 JUNE 2012

Measurement of the ^{18}Ne(α, p_0)^{21}Na Reaction Cross Section in the Burning Energy Region for X-Ray Bursts

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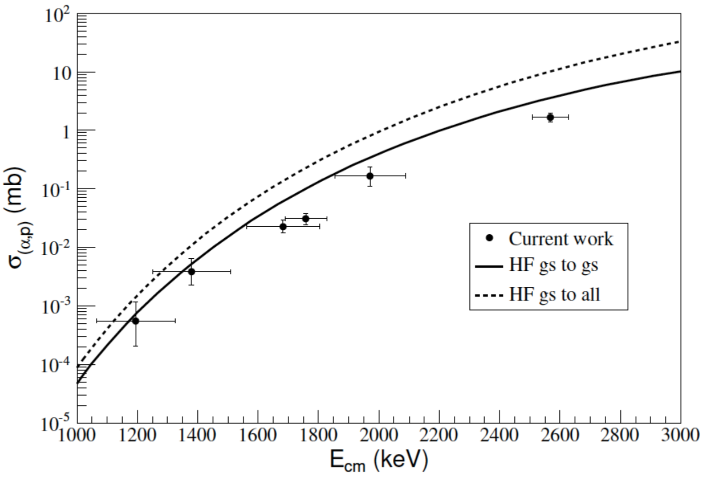
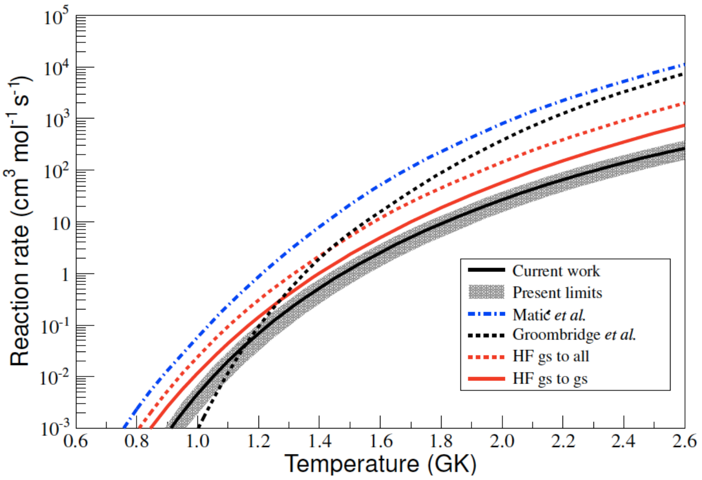
a factor of 2-3 lower than HF_{gs} calculations

lowest energy measurement to date



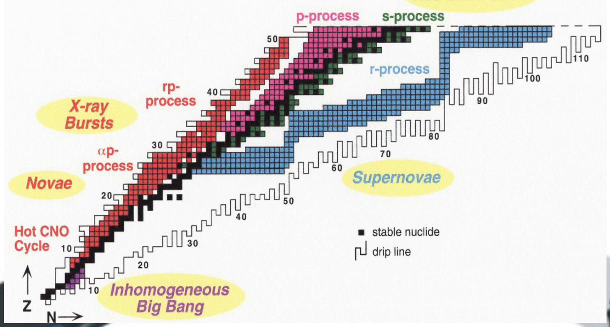
reaction rate: up to factor 40 lower



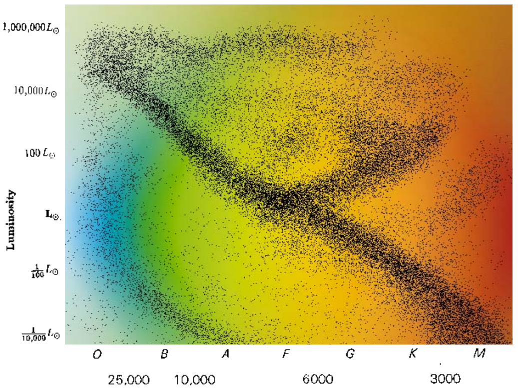
SUMMARY AND OUTLOOK

Our cosmic inheritance

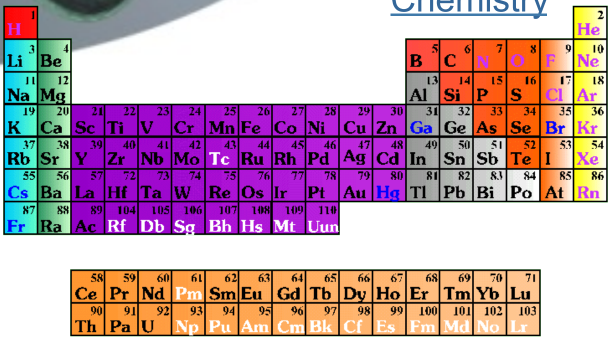
Nuclear Physics



Astrophysics



Chemistry



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

summary & outlook

Experimental Nuclear Astrophysics: very lively research field

stars are huge cauldrons where elements are produced and energy is generated

nuclear reactions take place under many different conditions

- quiescent burning governed mainly by reactions between stable nuclei

  Challenges: low cross sections → underground experiments

- explosive burning governed mainly by reactions with unstable nuclei

  Challenges: limited beams available → need for RIB facilities upgrades

laboratory investigations pose great challenges to experimentalists

variety of approaches and techniques must be used

The End

$^{17}O(p,\gamma)^{18}F$ reaction
sample gamma-ray spectrum