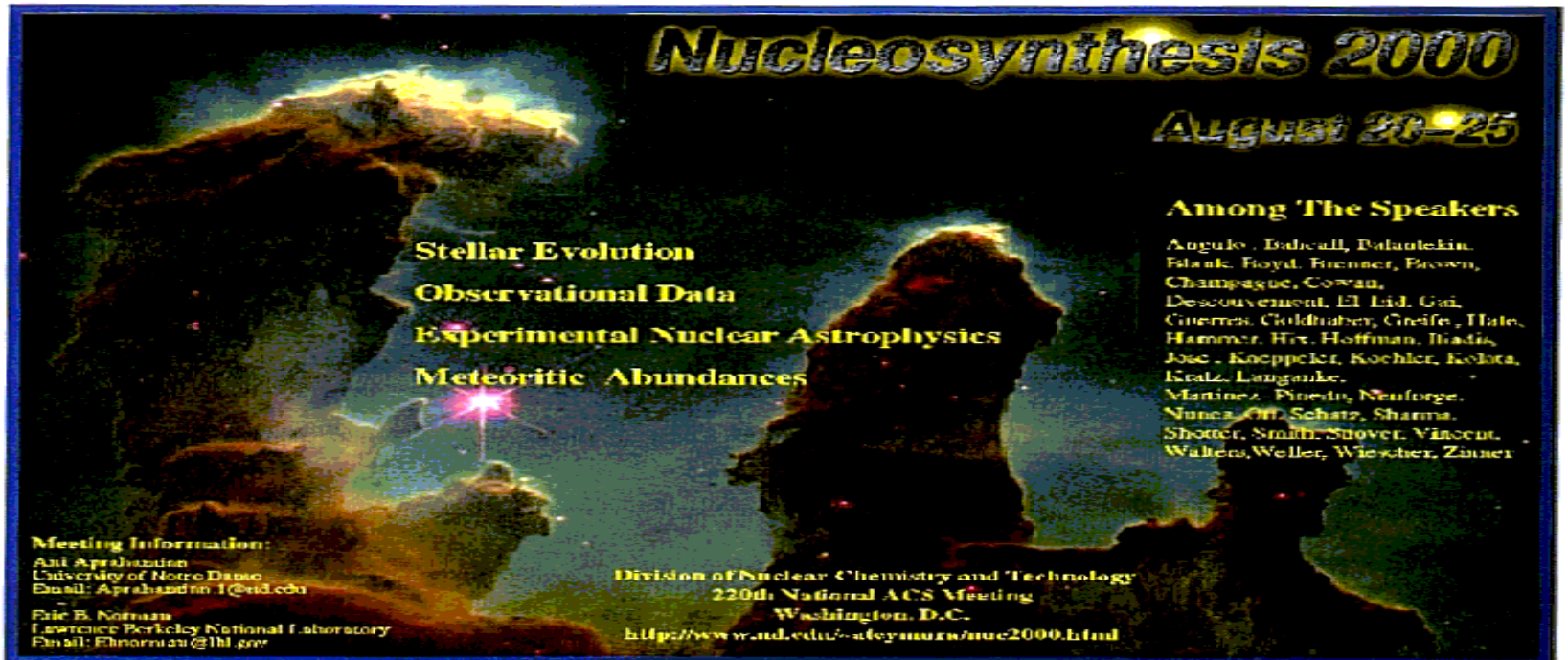

Nuclear astrophysics with radioactive beams at Louvain–la–Neuve

C. Angulo

Nuclear Astrophysics with Radioactive Beams at Louvain-la-Neuve

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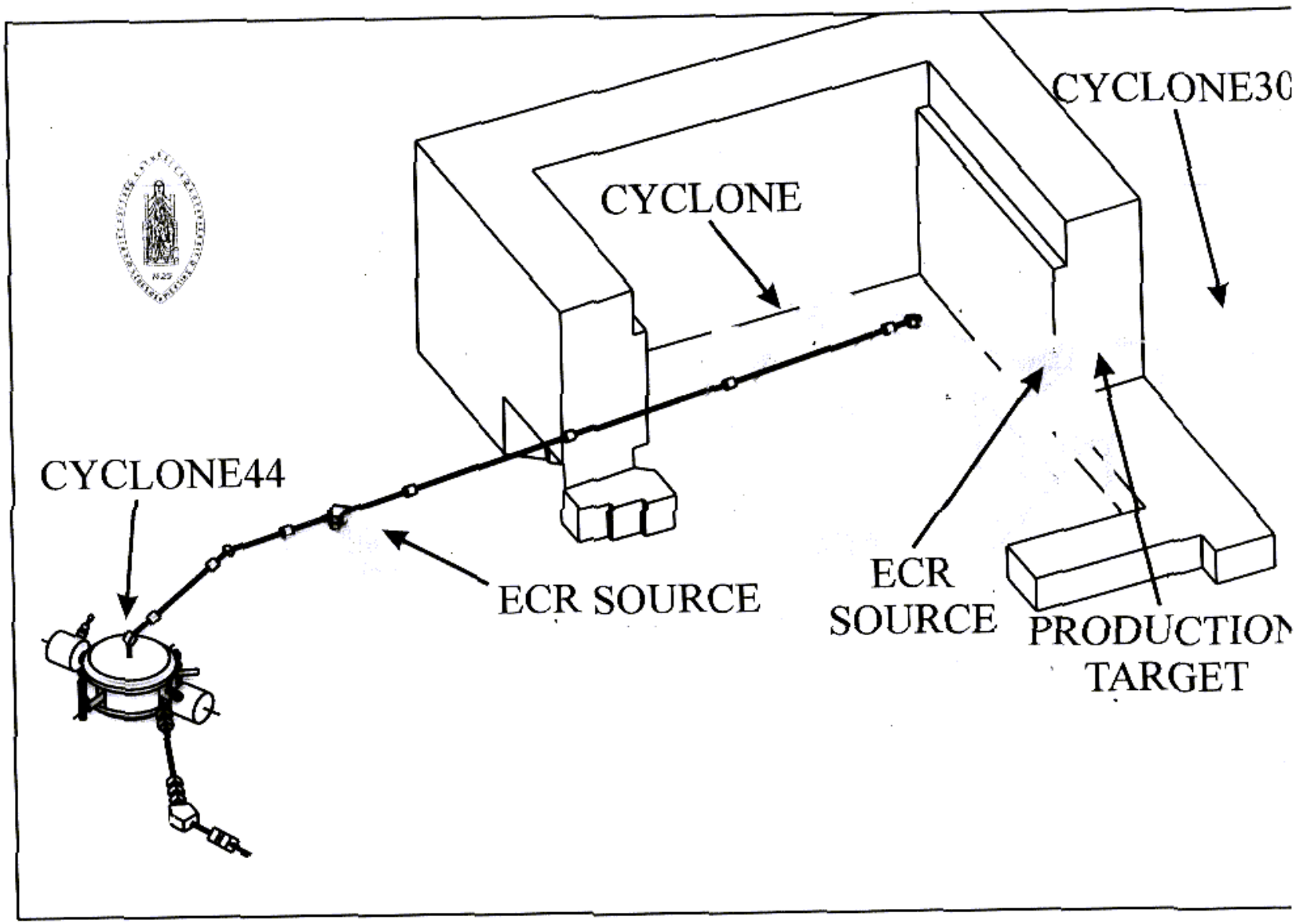
Nucleosynthesis 2000
Washington, 21- 23 August 2000

Louvain-la-Neuve Radioactive Beam Facility

- CYCLONE110, CYCLONE30
- CYCLONE44 **(new) (E = 0.2 – 0.8 MeV/nucleon)**
- ARES **(new)** (**Astrophysics** REcoil **Separator**): **coupled to CYC44**
- LEDA (**Louvain-Edinburgh Detector** Array)

APPLICATIONS

- Research in the field of particle accelerators
- Development of medical, technological and industrial applications of accelerators
- Chemistry, medicine, and isotope production
- Nuclear structure
- NUCLEAR ASTROPHYSICS


CYCLONE30
CYCLONE
CYCLONE44
ECR SOURCE
ECR
SOURCE
PRODUCTION
TARGET

New equipment at LLN

CYCLONE44

Energy constant K [MeV] = 44

Energy Range [MeV/A] = 0.2 – 0.8

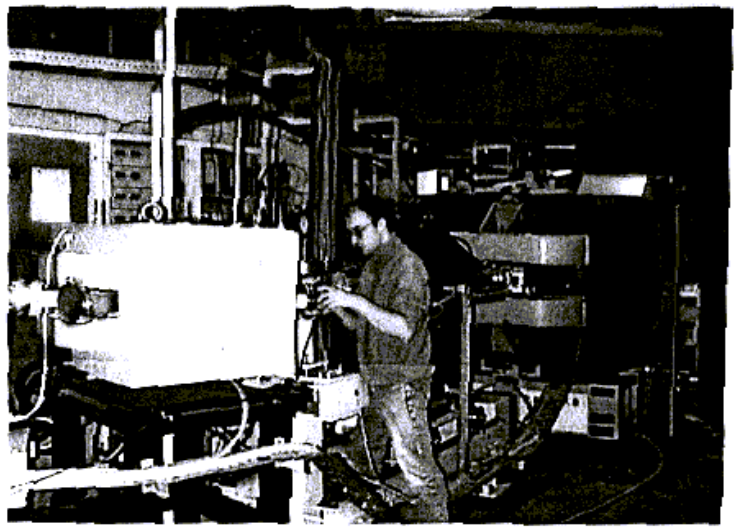
Particle accelerated M/Q = 4 to 14

ARE

A recoil separator for the measureme

of (p,γ) and (α,γ) reactions with stab

and radioactive bean



Radioactive Ion Beams available at the CRC

Ion	$T_{1/2}$	q	Intensity [pps]	Energy range [MeV]
^{6}He	0.8 s	1+	9×10^{6}	5.3 – 18
		2+	3×10^{5}	30 – 73
^{7}Be	53 days	1+	1×10^{7} (*)	5.3 – 15.7
^{11}C	20 min	1+	1×10^{7}	6.2 – 10
^{13}N	10 min	1+	4×10^{8}	7.3 – 8.5
		2+	3×10^{8}	11 – 34
		3+	1×10^{8}	45 – 70
^{15}O	2 min	2+	6×10^{7}	10 – 29
^{18}F	110 min	2+	1×10^{6}	11 – 24
^{18}Ne	1.7 s	2+	6×10^{6}	11 – 24
		3+	4×10^{6}	24 – 36, 45 – 55
^{19}Ne	17 s	2+	2×10^{9}	11 – 23
		3+	1.5×10^{9}	23 – 38, 45 – 50
		4+	8×10^{8}	60 – 93
^{35}Ar	1.8 s	3+	2×10^{6}	20 – 28
		5+	1×10^{5}	50 – 79

(*) with 10% of the activity in the source

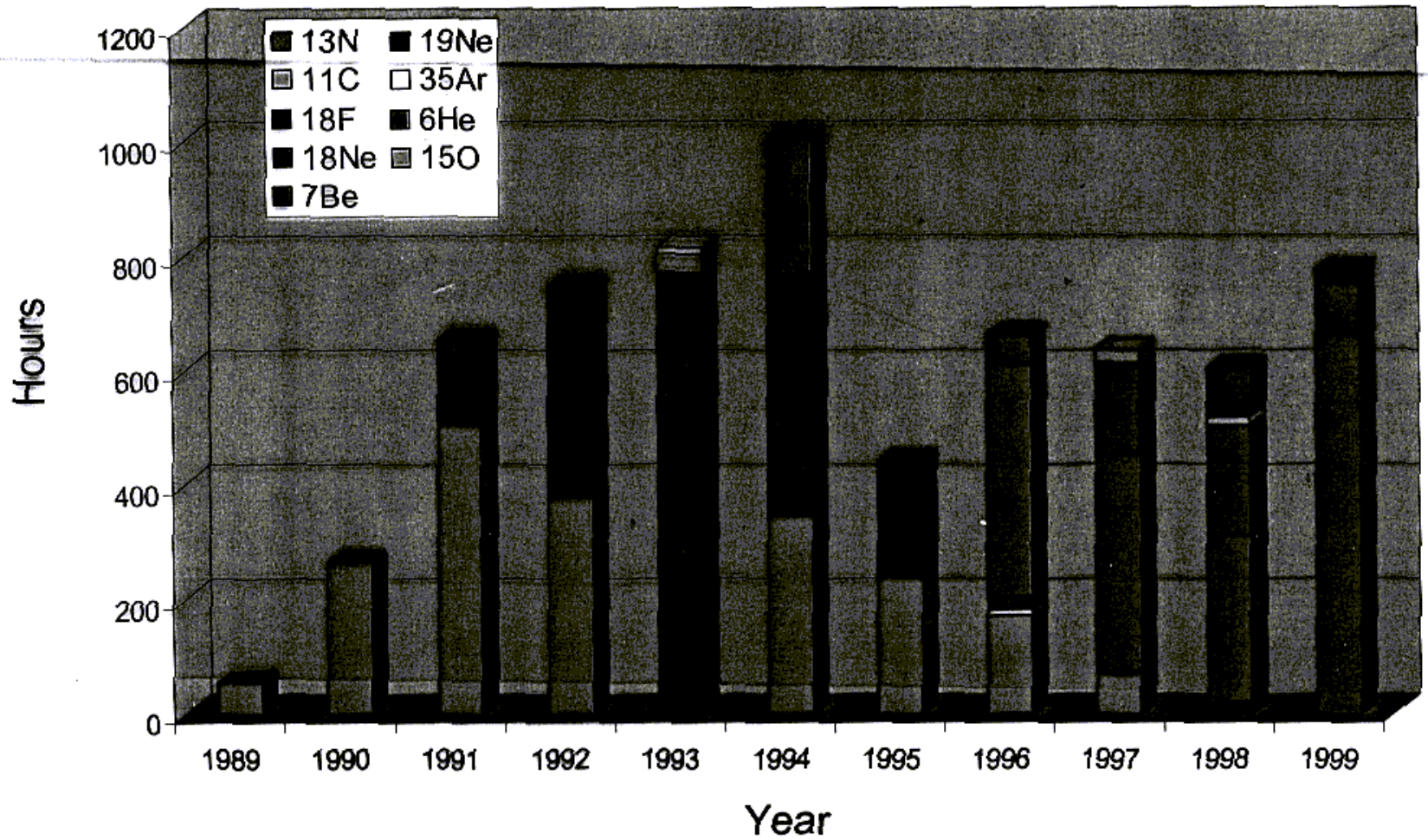
INTENSITY after acceleration !!

^{37}Ar is produced but not accelerated

^{14}O in developpement.

^{7}Be / ^{15}O continues.

Use of Radioactive Ion Beams at LLN



Nuclear Astrophysics

~~Recent experiments:~~

Hot CNO Cycle (Edinburgh-Catania-LLN):

$^{18}F(p,\alpha)^{15}O$ $^{18}Ne(\alpha,p)^{21}Na$ $^{18}Ne(d,p)^{19}Ne^{*}$

In progress:

CNO and hot CNO cycles (ARES - stable and radioactive beams)

$^{19}F(p,\gamma)^{20}Ne$ $^{19}Ne(p,\gamma)^{20}Na$ $^{11}C(p,\gamma)^{12}N$

$^{7}Be(\alpha,\gamma)^{11}C$ $^{15}O(\alpha,\gamma)^{19}Ne$ ...

Neutrino problem (UConn-LLN): $^{7}Be(p,\gamma)^{8}B$

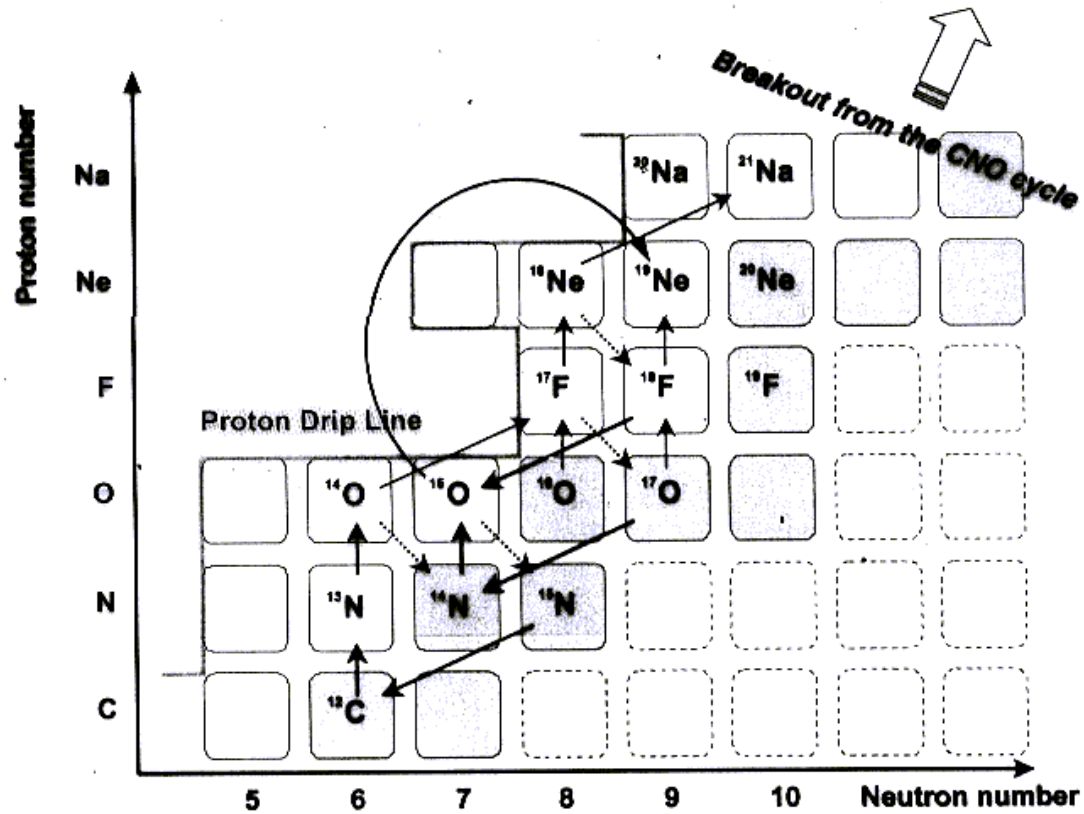
The hot CNO cycle

Most of the star's energy is believed to come from the conversion of H into He through the CNO cycle

At high temperatures, the creation of heavier elements starts, competing the radioactive decay:

the hot CNO cycle

→ ***Rapid proton capture or rp process***



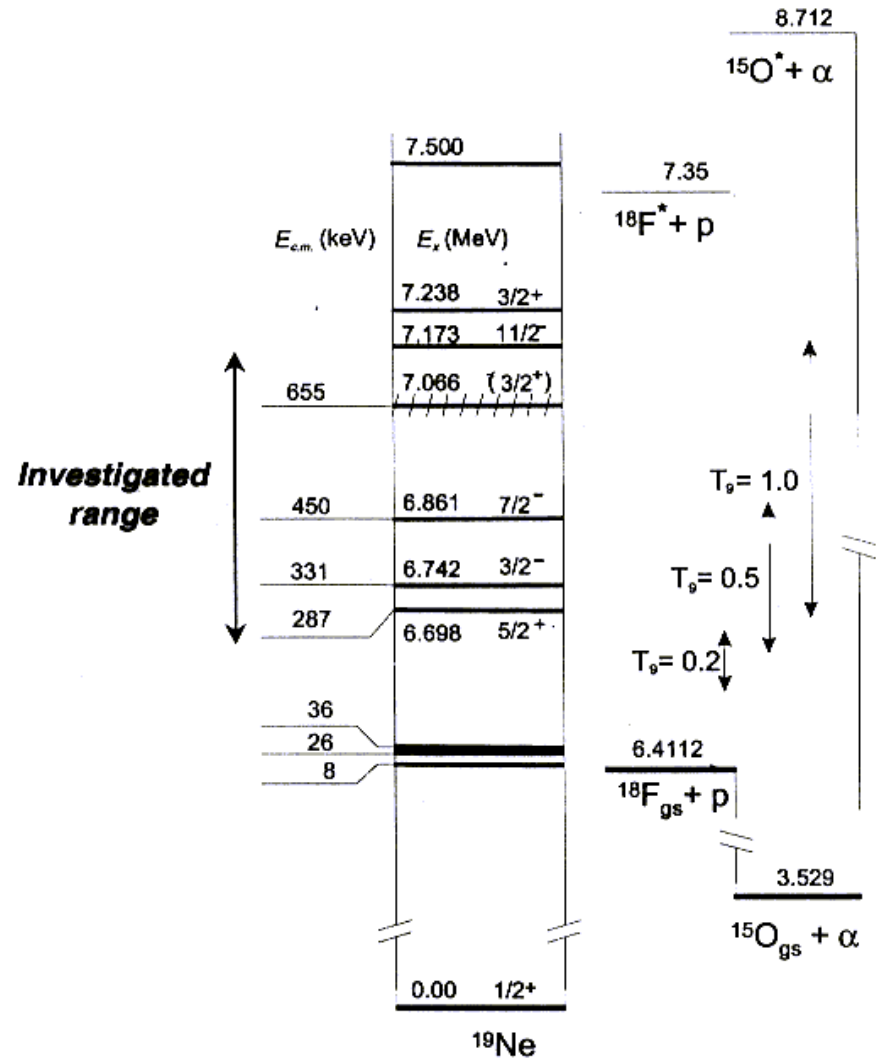
The 7.07 MeV resonant state in ^{19}Ne revisited

- New measurements:
  ^{18}F(p,α)^{15}O reaction and ^{18}F(p, p) scattering using ^{18}F radioactive beam and $(CH_2)_n$ targets

- Energy range:
  E_{cm} = 250 – 740 keV above the ^{19}Ne threshold

- Improvements:
  - **Better statistics**
  - **Less energy loss corrections**

(J.S. Graulich, PhD, July 2000)



Previous results (I)

- *Two measurements with ^{18}F radioactive beams*

- **Argonne (Phys. Rev. C25 (1995) R460)** **$H(^{18}F,\alpha)^{15}O$**

  $\Gamma_t = 13.6 \pm 4.6$ keV $\omega\gamma = 2.1 \pm 0.7$ keV $E_x = 7064 \pm 7$ keV

- **LLN (Phys. Lett. B353 (1995) 184)** **$H(^{18}F,\alpha)^{15}O$** **$H(^{18}F,p)^{18}F$**

  $\Gamma_t = 37 \pm 5$ keV $\omega\gamma = 5.6 \pm 0.6$ keV $E_x = 7048 \pm 15$ keV

  $l = 0$ $J^\pi = 3/2^+$ favored

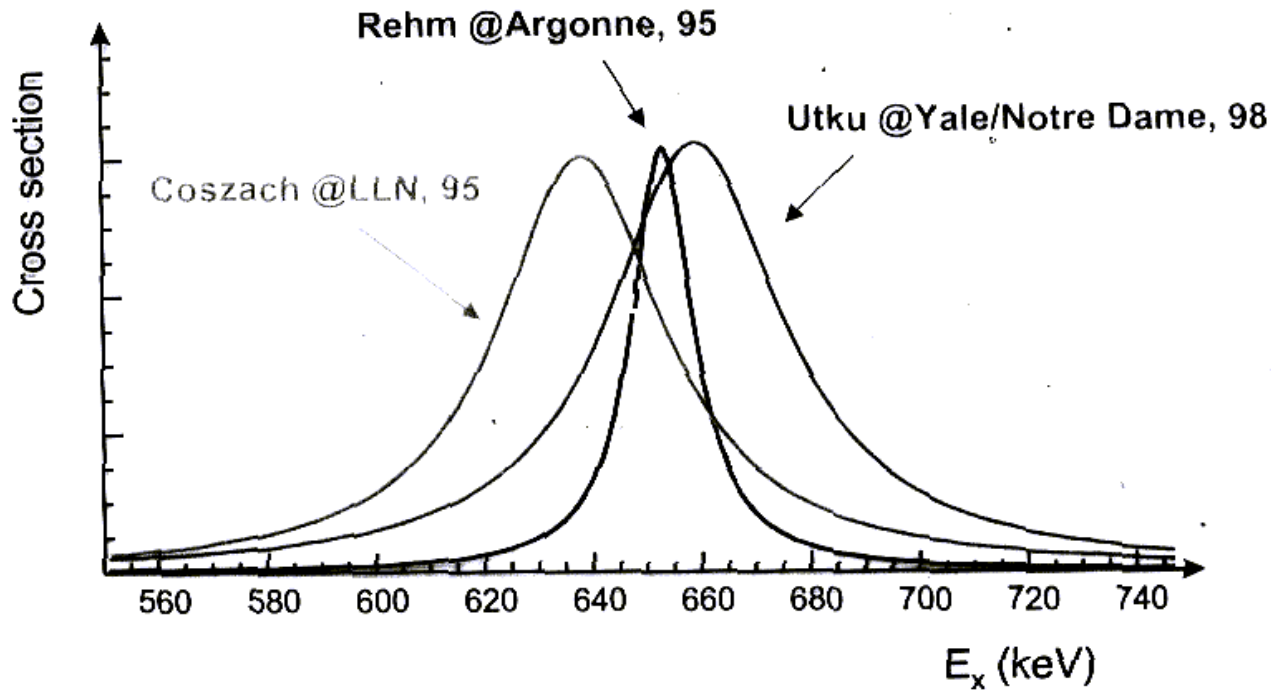
- *A measurement with stable beams*

- **Yale/Notre Dame (Phys. Rev. C57 (1998) 2731)** **$^{19}F(^3He,t)^{19}Ne \rightarrow (\alpha)^{15}O$, $\rightarrow (p)^{18}F$**

  $\Gamma_t = 39 \pm 10$ keV $\Gamma_p/\Gamma_\alpha = 0.58 \pm 0.06$ $E_x = 7070 \pm 7$ keV

This state dominates the rate over most of the temperature domain relevant to H burning in explosive enviroments

Previous results (II)



A collaboration with the Positron Tomographie Laboratory - UCL

1. Production of ^{18}F:

- Using a 15 MeV proton beam from CYCLONE30 on water enriched in ^{18}O
- After 2 hours: 1 Curie → 3.5×10^4 ^{18}F nuclei
- Chemical separation: ^{18}F extracted as CH_3F (50% efficiency)
- CH_3F is cooled, condensed and transported to the ionization source

2. Ionisation:

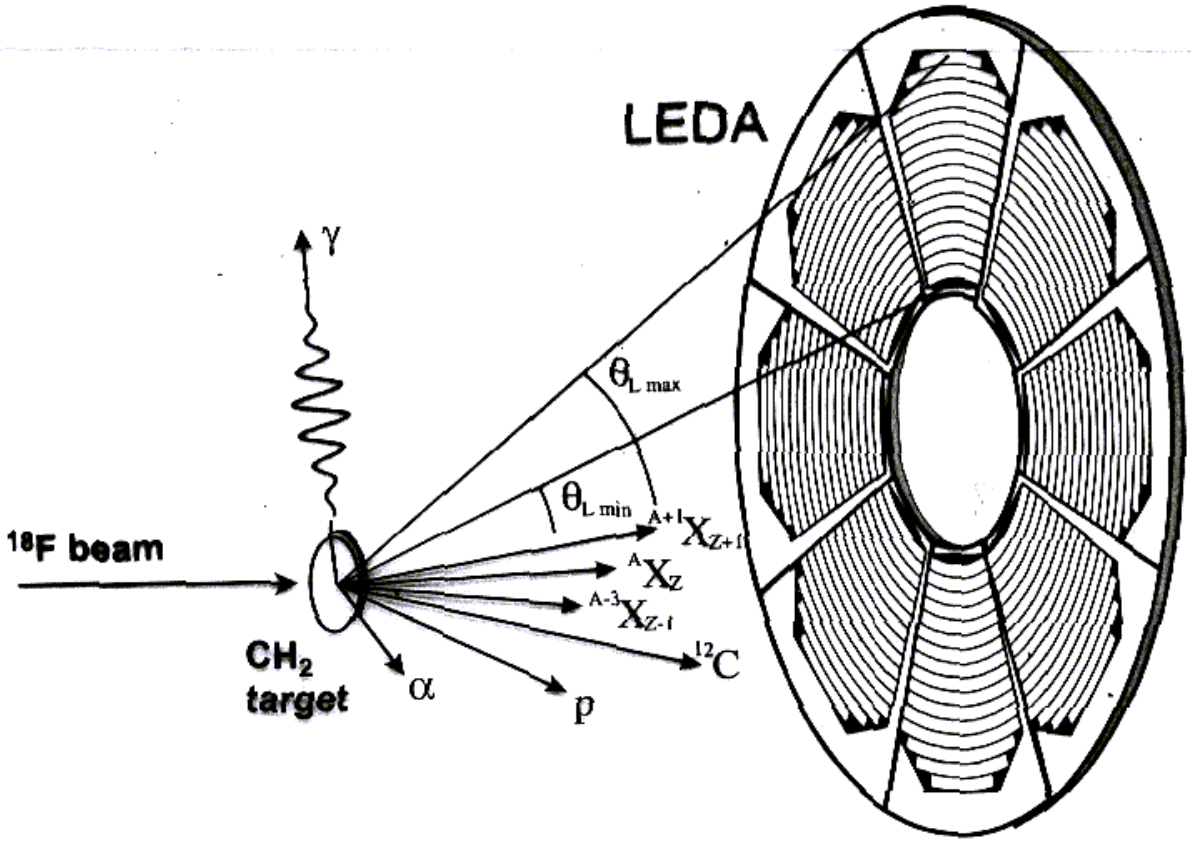
- CH_3F introduced and ionised in the ECR source (0.5% efficiency)
- $^{18}F^{2+}$ ions selected and extracted (together with the isobarique analogue ^{18}O)

3. Acceleration:

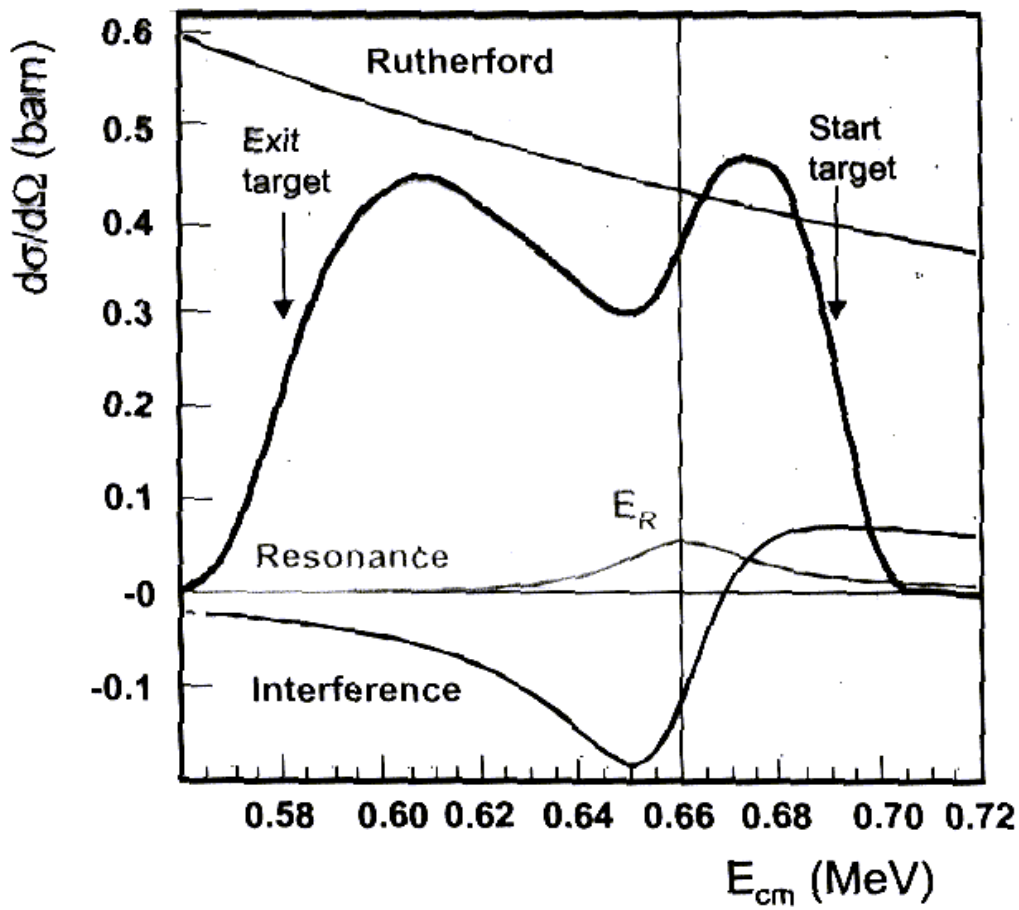
- At CYCLONE110: $^{18}F^{2+}$ and $^{18}O^{2+}$ are accelerated with different trayectories.
- They separated by fine tunning the magnetique field in the extraction (4% acceleration efficiency).

- Thank organizers for inviting me to this meeting
- I'm pleased to represent the R.I.B. facility at LLN.
- For those that never been in BE: LLN is...
- First, I will make a brief introduction of the lab and the available ion beam. Then I will present you the most recent results on n.r. measurements of astrophys. interest

LLN experimental set up

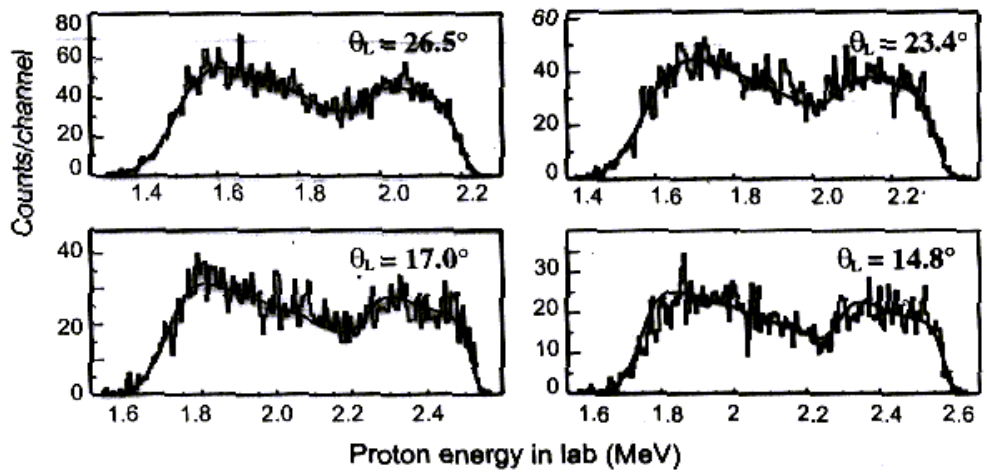


$^{18}F(p,p)^{18}F$ elastic scattering cross section

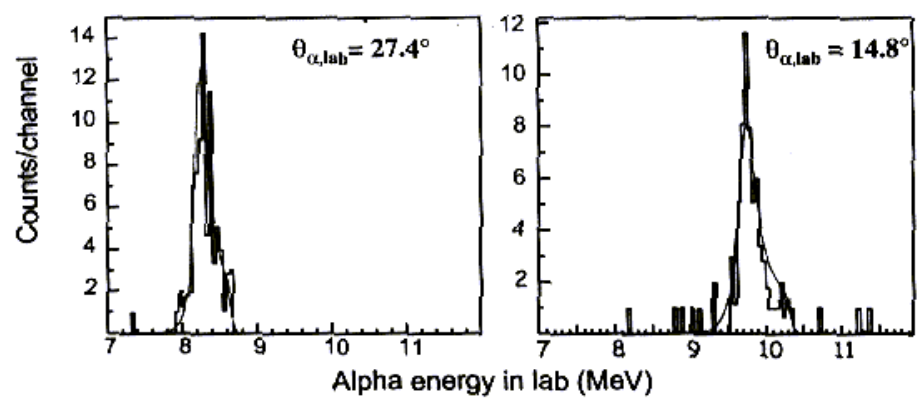


Analysis of the proton and alpha spectra

Adjustement of 8 proton spectra *simultaneously*, *between* θ_{lab} =15° *and* θ_{lab} = 27°



Analysis of the α spectra: comparison angle by angle



Summary of results

For the 7.066 MeV state in ^{19}Ne:

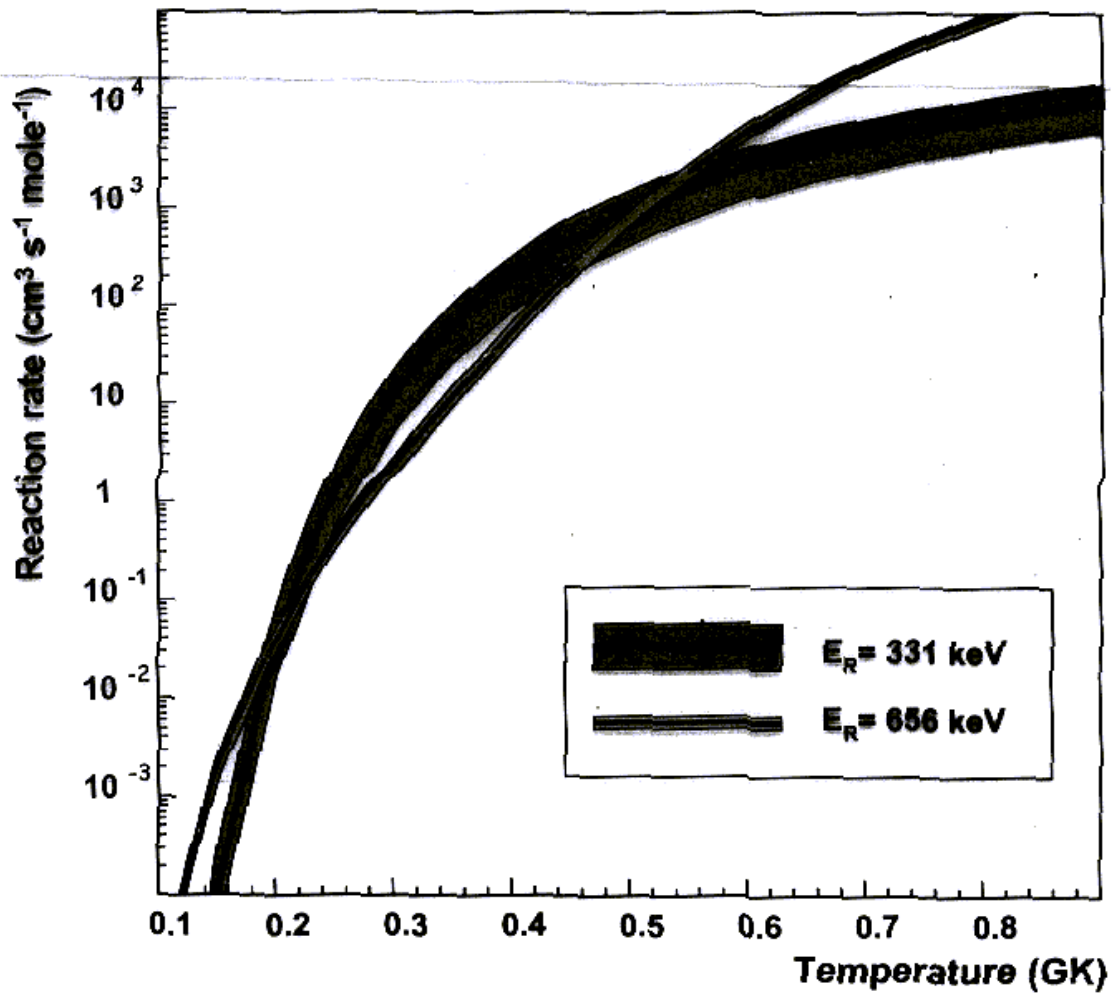
	E_r (keV)	Γ_{tot} (keV)	Γ_p/Γ_{tot}	$\omega\gamma$ (keV)
Proton data:				
$J^{\pi}_R = 1/2^+$	$660 \pm 1 \pm 5$	$34.5 \pm 2.2 \pm 5.0$	$0.873 \pm 0.026 \pm 0.06$	$1.3 \pm 0.3 \pm 0.4$
$J^{\pi}_R = 3/2^+$	$656 \pm 1 \pm 5$	$31.5 \pm 1.9 \pm 5.0$	$0.467 \pm 0.013 \pm 0.06$	$5.2 \pm 0.3 \pm 0.4$
Alpha data:	$659 \pm 1 \pm 5$	$37 \pm 1 \pm 3$		$4.6 \pm 0.1 \pm 0.3$
Global results:	657.5 ± 5.0	34.0 ± 3.6		4.9 ± 0.3

- **Proton data:** $\omega\gamma$ **calculated from** $\omega \times (\Gamma_p\,\Gamma_\alpha)/\Gamma_\alpha$ (ω = 2/6 for (J_R =1/2), ω= 4/6 for (J_R =3/2))
- **Alpha data:** $\omega\gamma$ **obtained from** α**-yield**
- J_R **=1/2 excluded**
- **Global result = averaged of proton data for** J_R **=3/2 and alpha data**

For the 6.742 MeV state in ^{19}Ne:

$E_r = 329 \pm 15$ keV $\qquad \omega\gamma = 4.3 \pm 2.1$ eV

Astrophysics implications



- Scape from the hot CNO cycle: $^{18}F(p,\gamma)^{19}Ne$ is not competitive

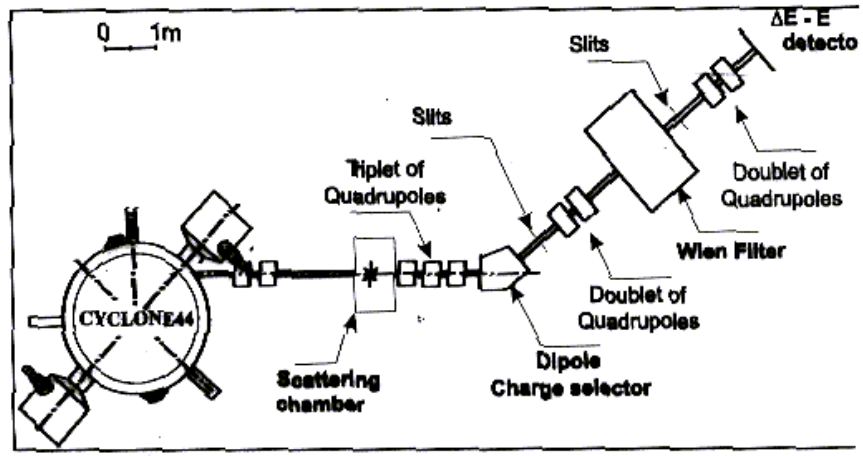
- Novae: the resonant at 331 keV is dominant between 0.2 *and 0.5 GK*

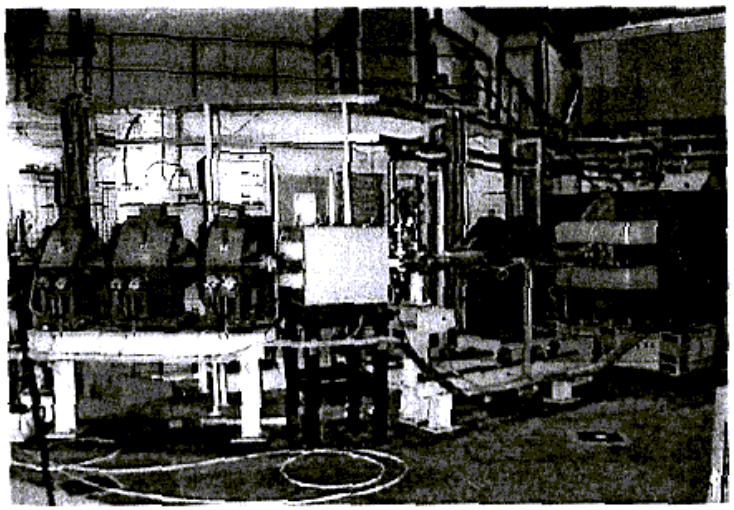
- γ – astronomie: low counting rate, lower quantity of ejected ^{18}F after novae explosions

ARES – a new tool for nuclear astrophysics at LLN

In order to enhace the detection efficiency of reaction cross sections at astrophysical energies:

- *recoil separator ARES, coupled to CYCLONE44*



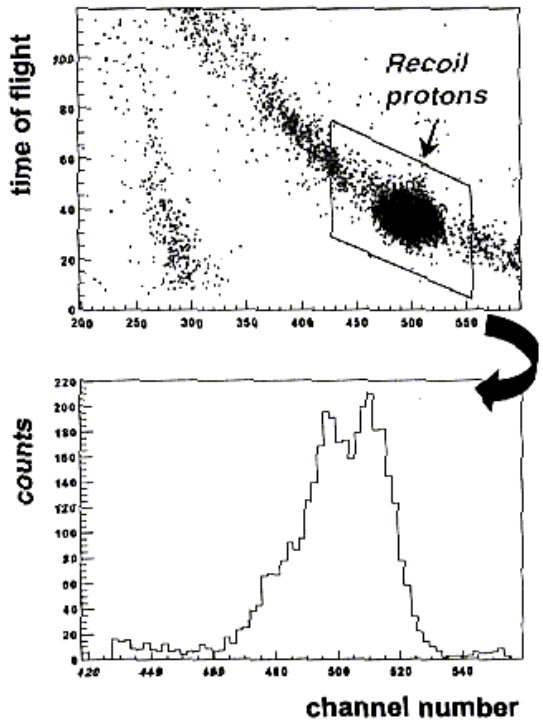


Main components

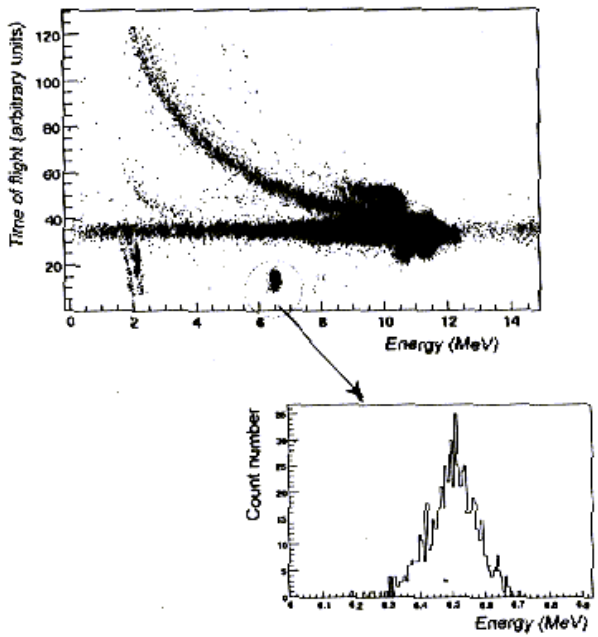
- Dipole Magnet: Selection of the most abundant charged
- *Wien Filter*: Velocity selection between the beam an the product
- ΔE– E detector : Additional separation power
- Scattering chamber – Monitoring beam properties b *detecting recoil protons and scattered ions*

ARES – First results

Using a 9.1 MeV ^{14}N beam, a rejection factor of 7×10^{-11} by tunning ARES to transmit mass 15 in the 5^+ state, to simulate recoils following radiative capture on mass 14



Measurement of the 635 keV resonance in ^{20}Ne using a ^{19}F beam on $(CH_2)_n$.



^4He – implanted targets: Energy vs. TOF spectrum of ^4He implanted target in an Al foil

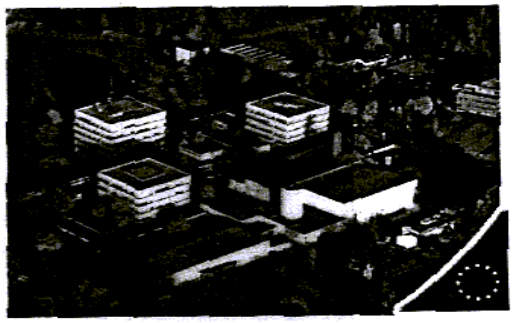
Conclusions and perspectives

Radioactive beams are powerful *tools for the study of* nuclear reactions involved in explosive stellar events

LLN RIB facility

- **New facilities: CYCLONE44, ARES**
- **New radioactive beams**

Groups from Europe and USA take advantage of the LLN RIB facility, which is one of the 10 Large Scale Facilities in Europe supported by the European Commission.



Recent experiments

- **$^{18}F(p,\alpha)^{15}O$, $^{18}Ne(\alpha,p)^{21}Na$, $^{18}Ne(d,p)^{19}Ne^{*}$**
- **ARES: promising results**

FUTURE

- **Inverse kinematics: RIB + ARES + LEDA**
- **Experiments with ^{7}Be, ^{18}O, ^{18}F, ^{19}F, ^{18}Ne, ^{20}Ne...**
- **Beam development : ^{7}Be, ^{14}O, ^{15}O ...**

Louvain-la-Neuve

C. Angulo
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W. Galster
J.S. Graulich
P. Leleux
F. Vanderbist

+ Cyclotron Team

Collaborations

Brussels
Catania
Conneticut
Edinburgh
Leuven
Notre-Dame
Saclay
Zagreb
...