Study of excited states in proton-rich nuclei by resonant elastic scattering

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Content

- The elastic scattering method
  - Direct kinematics
  - Inverse kinematics
    - The method
    - The choice of the target
- On-line spectra and data analysis
  - From raw spectra …
  - … to a theoretical analysis (the R-matrix method)
- The Louvain-la-Neuve ISOL facility
  - Recent highlights in Nuclear Astrophysics and Nuclear Spectroscopy
  - Typical experimental conditions
- Some applications of the elastic scattering method
  - Determination of the ^{7}Be+p scattering lengths
  - Spectroscopy of ^{19}Na excited states by ^{18}Ne+p
  - The ^{11}N excited states revisited by a new ^{10}C+p experiment
- Conclusions and Perspectives

The elastic scattering method in direct kinematics

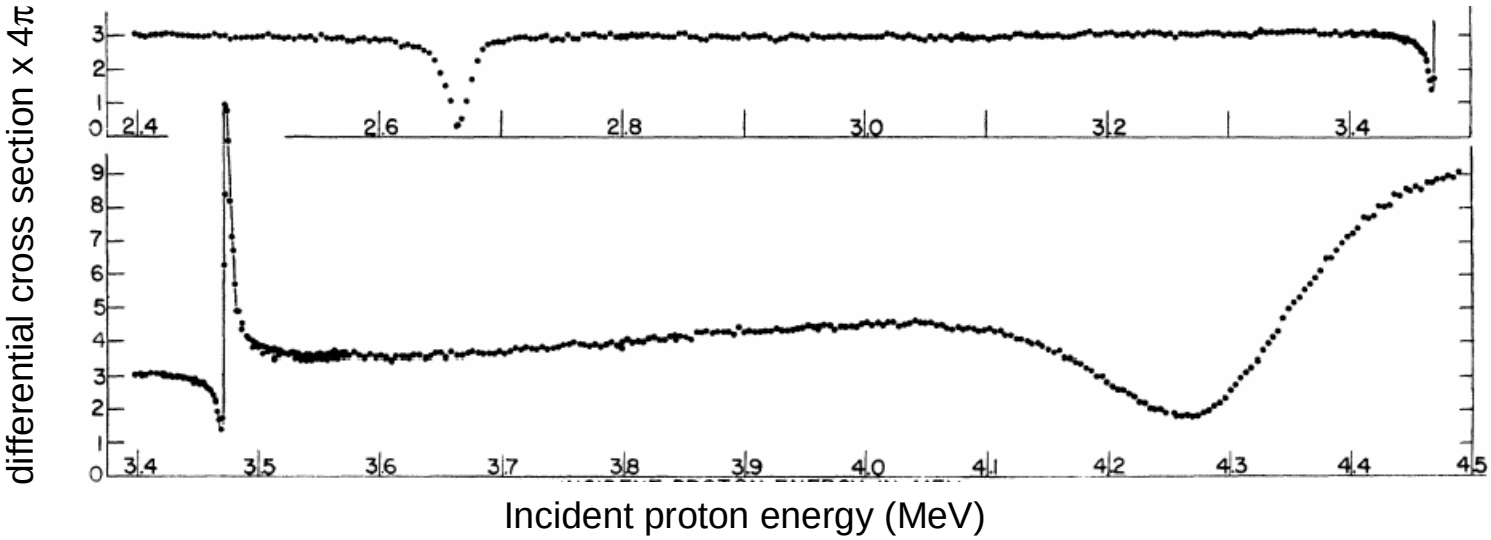
- Elastic scattering of light particles (p, d, α…) using direct kinematics by varying the energy of the light particle in steps of a few keV is a well known technique.
- The first study of an unstable nuclei (^{17}F) was carried out at the Wisconsin electrostatic generator in the early 50's by scattering of protons on a ^{16}O target

PHYSICAL REVIEW VOLUME 84, NUMBER 1 OCTOBER 1, 1951

The Elastic Scattering and Capture of Protons by Oxygen*

R. A. LAUBENSTEIN,† M. J. W. LAUBENSTEIN,† L. J. KOESTER,‡ AND R. C. MOBLEY
University of Wisconsin, Madison, Wisconsin

(Received June 18, 1951)



The elastic scattering method in inverse kinematics (I)

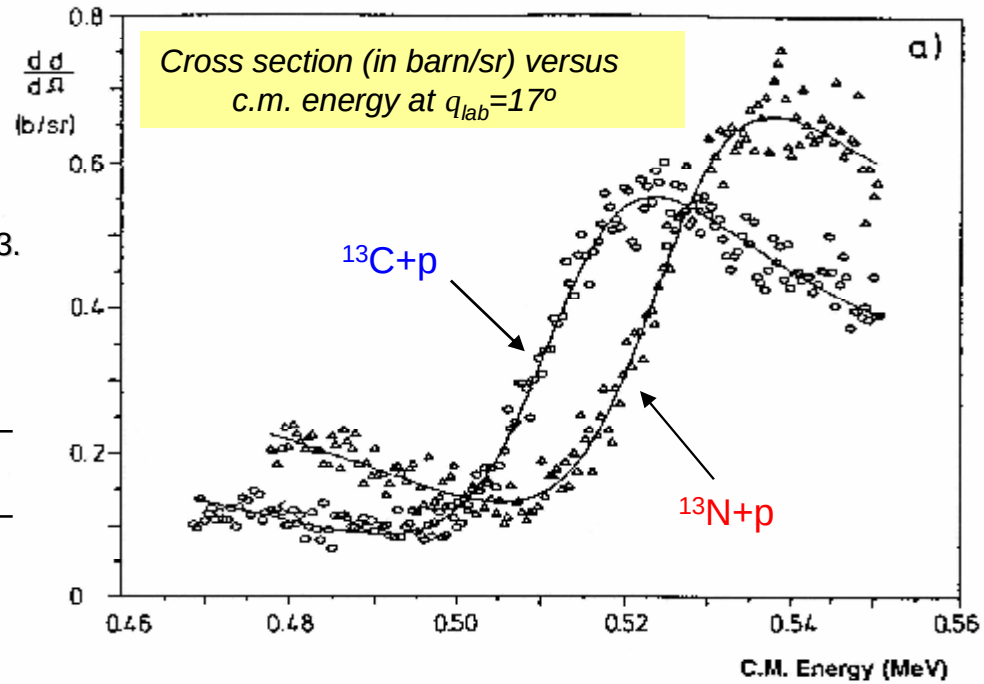
- With the acceleration of the first radioactive beam at Louvain-la-Neuve (1990), it was necessary to develop a technique to study in one step low-energy resonances using:
  - Projectile: a RIB of a few 10^6 - 10^7 pps (should be enough)
  - Target: a proton-rich foil of very simple handling

- The first elastic scattering experiment in inverse kinematics with a stable and a RIB and a quantitative analysis, was performed in 1991 at Louvain-la-Neuve:

"One-step energy scanning of wide low lying 1^- resonances in ^{13}C+p and ^{13}N+p scattering"

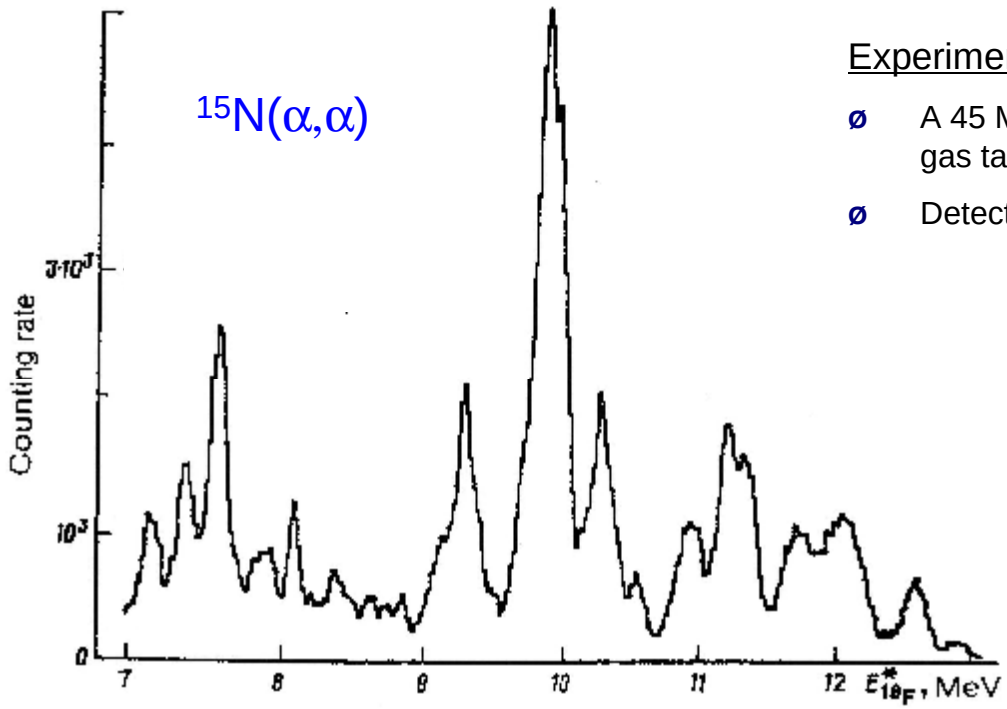
Th. Delbar et al., Nucl. Phys. A542 (1992) 263.

	Resonant energy (keV)	Resonance width (keV)
p + ^{13}C	513.0 ± 1.0	33.7 ± 1.0
p + ^{13}N	526.0 ± 1.0	37.0 ± 1.1



The elastic scattering method in inverse kinematics (II)

- In another context, a similar technique was used at the Kurchatov Institute at Moscow using a very thick ^{4}He gas target and stables beams of ^{12}C and ^{15}N to study α-cluster states in ^{16}O and ^{18}F.



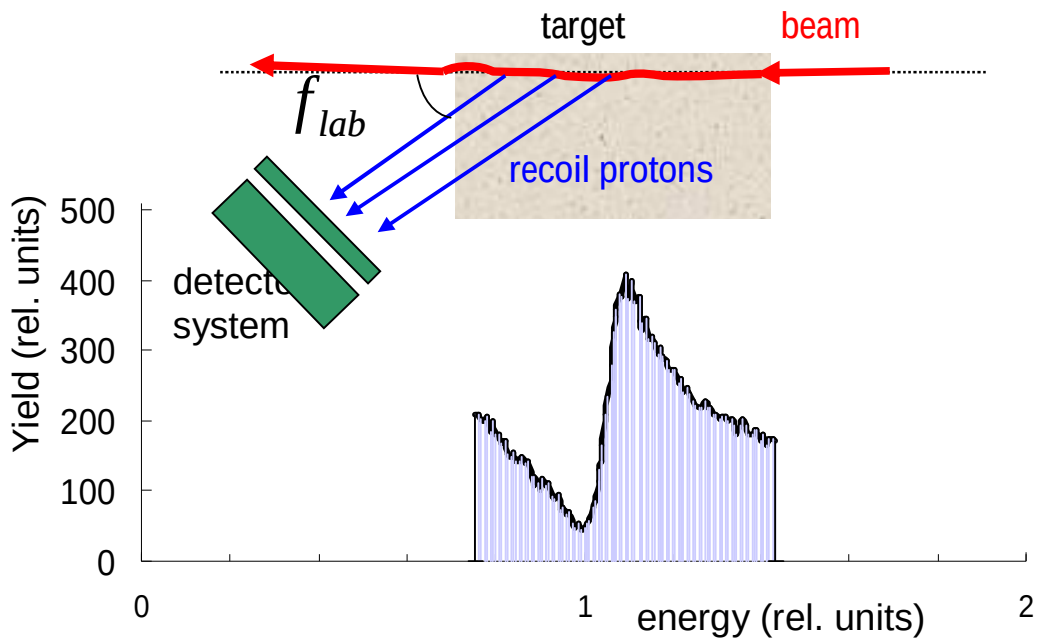
Experimental conditions:

- A 45 MeV ^{15}N beam on a very thick gas target (beam stopped)
- Detection at laboratory angle of ~ 5º

K. Artemov et al., Sov. J. Nucl. Phys. **52** (3), September 1990

The method

Typical spectrum for a ℓ=0 resonant state



Main features

- Inverse kinematics: large laboratory proton energy

$$E_{p,lab} = E_{cm}\frac{4A}{A+1}\cos^2\phi_{lab}$$

- Interference effects are reflected in the spectrum shape:

$$\left(\frac{d\sigma}{d\Omega}\right)_{clas} = |f_N + f_C|^2$$

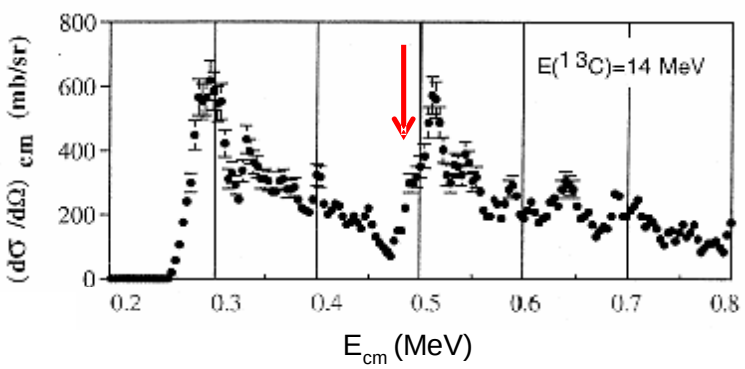
- Beam **à** important energy loss in the target **à** spectacular changes in the recoil proton spectra
- Recoil protons **à** negligible energy loss in the target **à** sensitivity to presence of a resonant state
- Proton spectra **à** information on the resonance energy, orbital momentum, and proton width

The choice of the target

- A very thick target, that will stop the beam, can be used to obtain a general overview of a nuclei level scheme

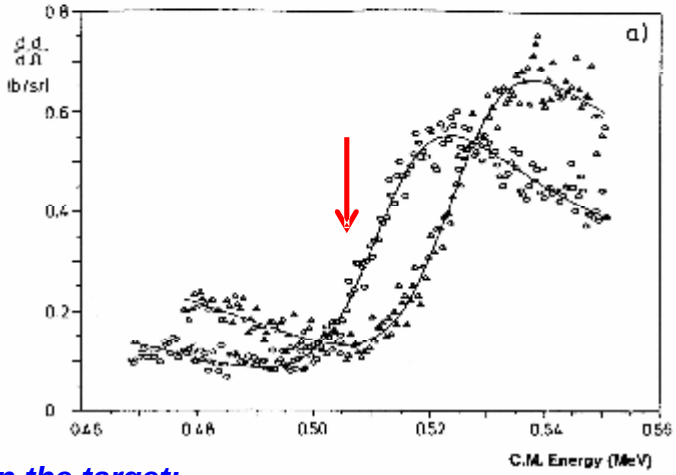
Example: $^{13}C(p,p)$ using a ^{13}C beam

… on a 20 µm target

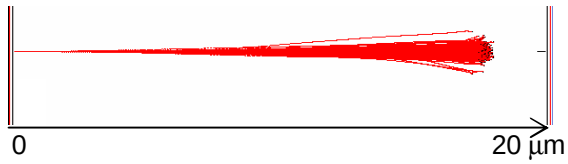


- A thinner target must be used if precise information on energy, width and spin of one or of a few states are searched

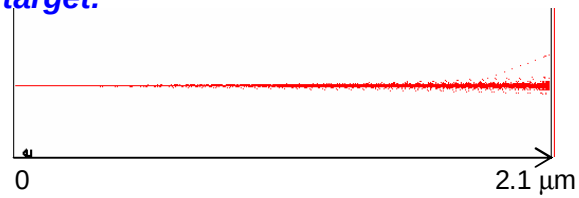
… or on a 2.1 µm target



Energy straggling of the beam in the target:



SRIM2003



Do not swat a fly with a hammer!

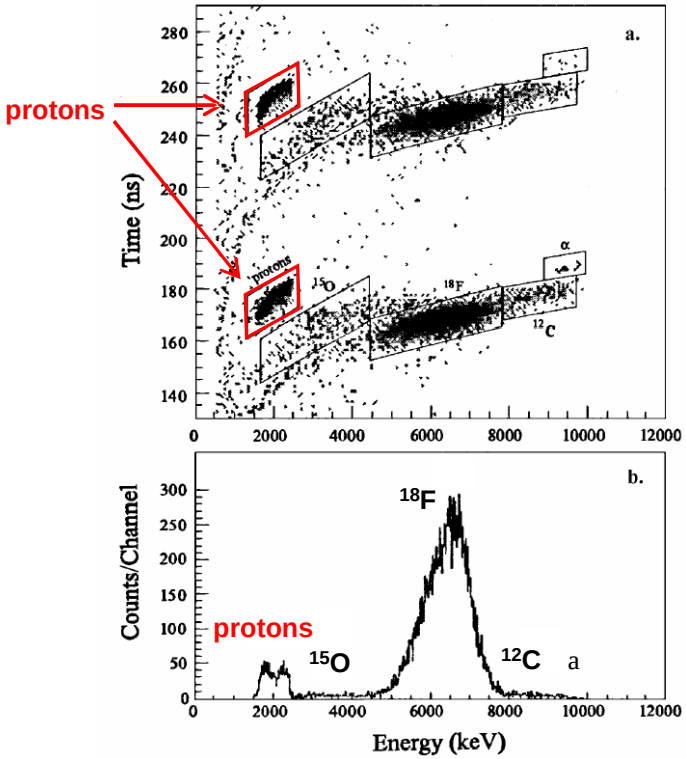
The target thickness must be adapted to

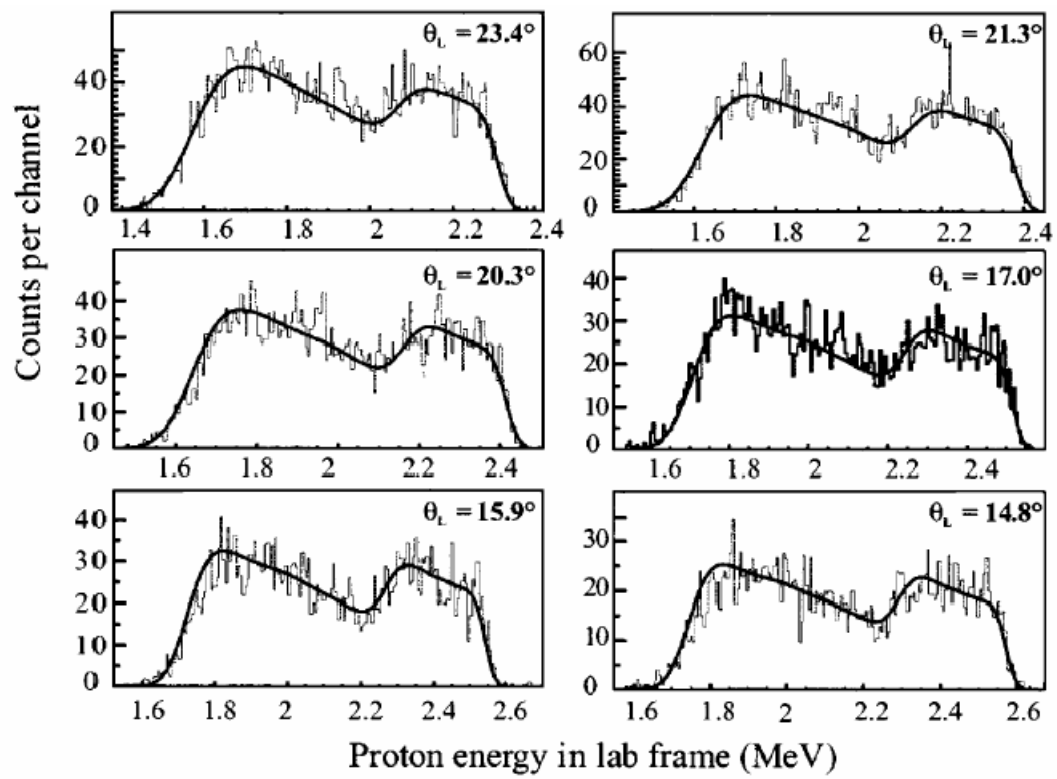
- the experimental goal
- the experimental conditions: beam energy, detection angle…

On-line spectra and data analysis: (i) from raw spectra…

An example: $^{1}H(^{18}F,p)^{18}F$

J.S. Graulich et al., Phys. Rev. C63, 011302(R)(2000).





Limitations

- The energy resolution is limited: the <u>resonance widths</u> must be larger than a few keV
- Above a certain large value of the width, the spectra are independent of the energy resolution
- For very thick targets, only the detection at small angles is appropriate

… to the theoretical analysis

The R-matrix formalism

A.N. Lane and R.G. Thomas, Rev. Mod. Phys. 30 (1958) 257-353.

The differential cross section ⟺ The collision matrix U_l ⟺ The R-matrix $R(E)$ / The phase shift δ_l

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{1}{4k^2}\left|\sum_\ell (2\ell+1)(1-U_\ell)P_\ell(\cos(\theta))\right|^2 \qquad U_\ell = \frac{I(ka)}{O(ka)}\frac{1-L^\star R(E)}{1-LR(E)} = \exp(2i\delta_\ell)$$

With the R-matrix for λ poles defined as: $R(E) = \sum_\lambda \frac{\gamma_\lambda^2}{E_\lambda - E}$

Pole parameters (calculated or formal)	≠	Resonance parameters (observed or experimental)
$E_\lambda, \gamma_\lambda^2, \Gamma_\lambda$		$E_R, \gamma_R^2, \Gamma_R$

The usual procedure to related these quantities is not direct

An alternative parameterization to easily switch between "formal" and "experimental" parameters is developed in C. Angulo and P. Descouvemont, Phys. Rev. C61 (2000) 064611
(A generalization of this procedure is in C.R. Brune, Phys. Rev. C 66 (2002) 044611)

Non-exhaustive list of elastic scattering experiments

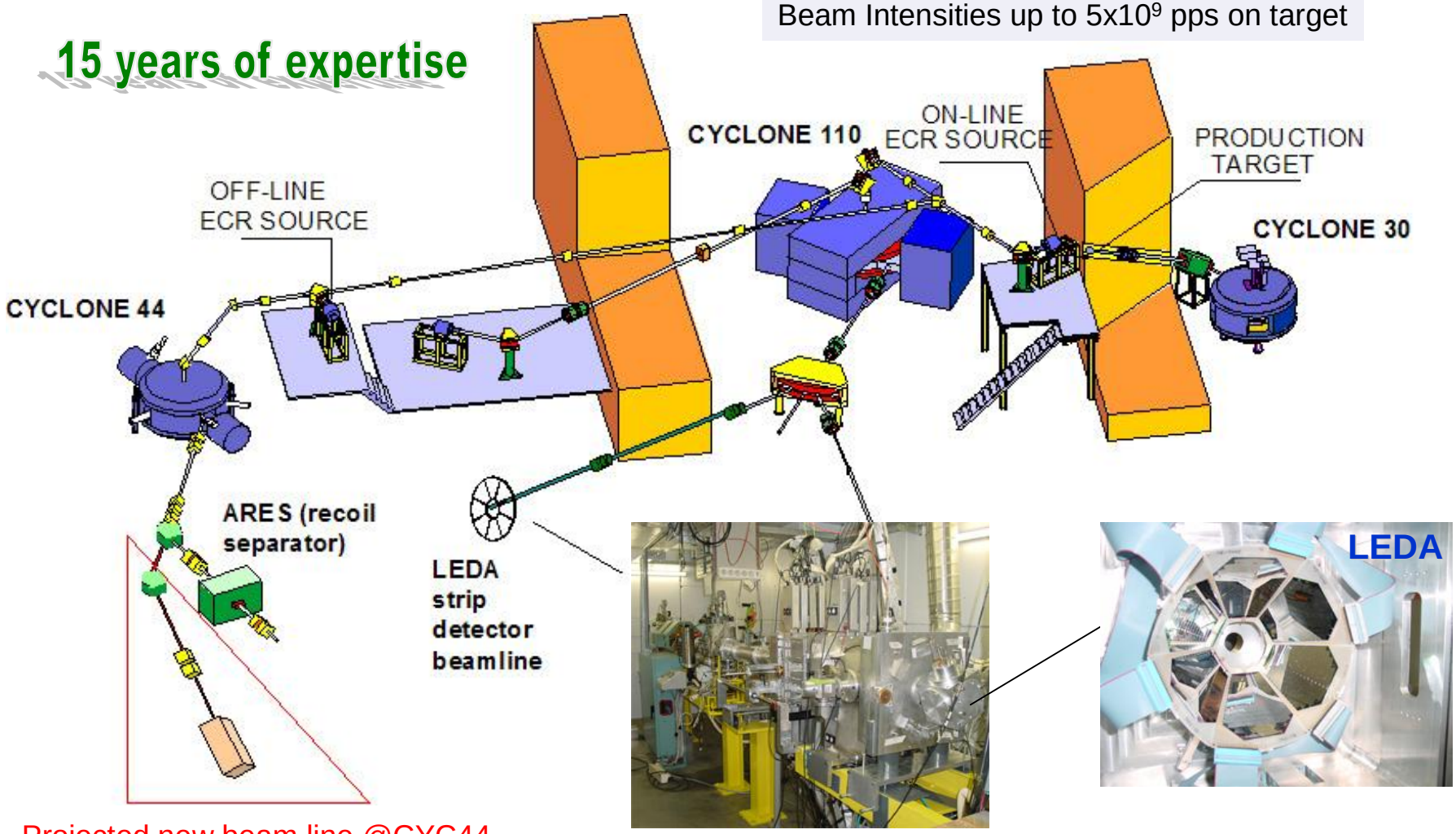
Nucleus	System	Facility
^{11}N	$^{10}C + p$	MSU, GANIL, CRC
^{12}N	$^{11}C + p$	LBNL, RIKEN, CRC
^{14}N	$^{13}C + p$	CRC
^{14}O	$^{13}N + p$	CRC
^{18}Ne	$^{17}F + p$	ORNL
^{19}Ne	$^{18}F + p$	ORNL, CRC
^{19}Na	$^{18}Ne + p$	CRC, SPIRAL
^{21}Mg	$^{20}Na + p$	TRIUMF
^{22}Mg	$^{21}Na + p$	TRIUMF
8B, scat. lengths	$^{7}Be + p$	CRC, Notre-Dame

The Louvain-la-Neuve RIB ISOL facility

Production and acceleration of isobarically pure and intense low energy RIB's

Beam Intensities up to $5x10^9$ pps on target

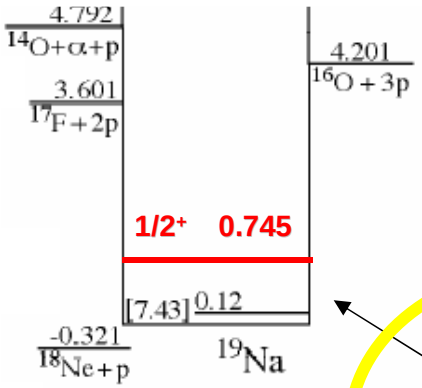
15 years of expertise

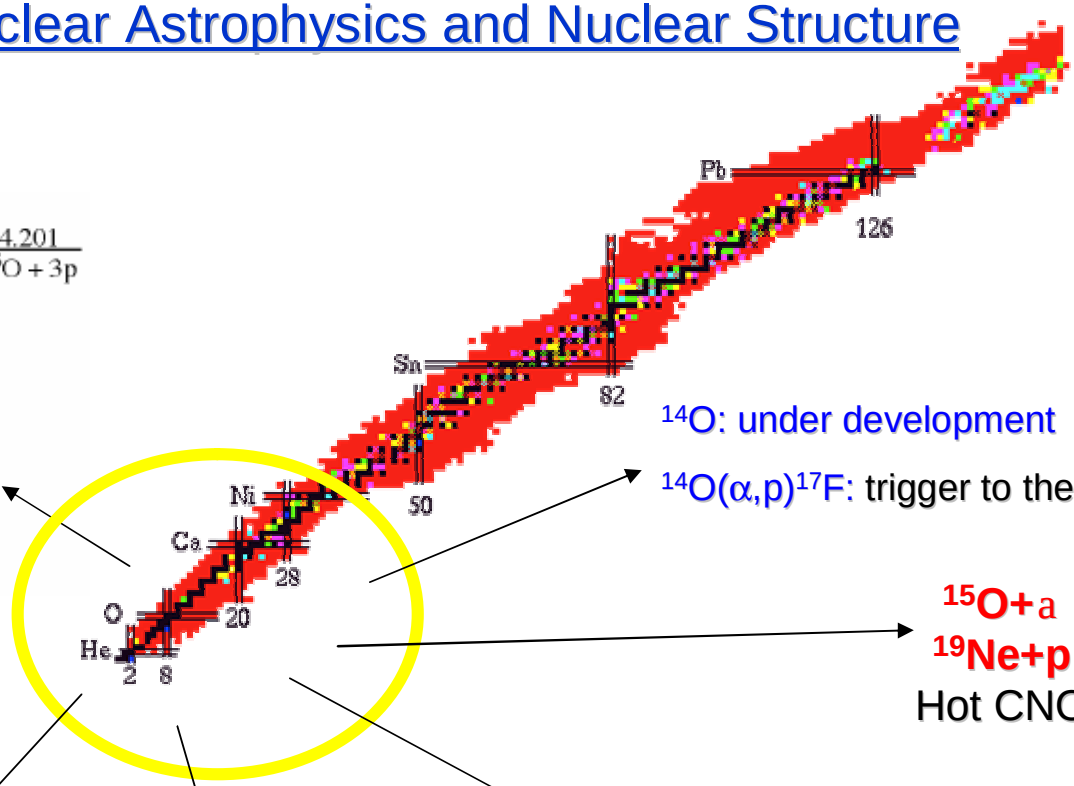


Projected new beam line @CYC44

Recent highlights in Nuclear Astrophysics and Nuclear Structure

^{18}Ne+p:
Drip line nucleus
^{19}Na



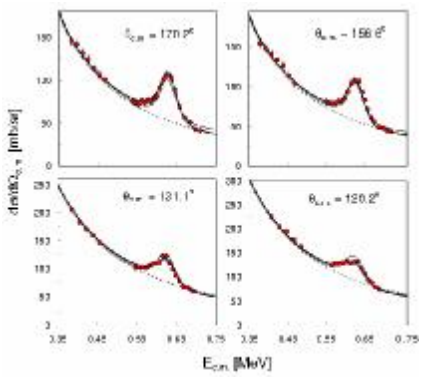


^{14}O: under development

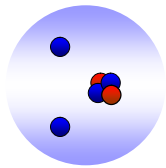
^{14}O(α,p)^{17}F: trigger to the rp process

^{15}O+a
^{19}Ne+p
Hot CNO

^{7}Be+p: Charge symmetry and nuclear astrophysics



^{6}He



- Effect of halo
- Study of ^{5}H and ^{7}He

^{18}F(d,p)^{19}F(a)^{15}N

Novae γ-ray emission

Typical experimental conditions at Louvain-la-Neuve

- Low-energy isobarically pure radioactive beams of intensities from 10^5 pps ($^{10}C^{2+}$) to 5×10^9 pps ($^{19}Ne^{3+}$)
- Self-supporting targets (CH_2, CD_2, ^9Be, ^7Li…) and gas cells
- Strip detectors covering up to 10% of 4π:

  LEDAS, the **L**ouvain-la-Neuve **E**dinburgh **D**etector **A**rrayS

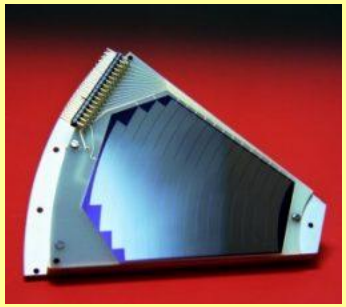
  A very efficient detector system largely used in many laboratories worldwide

  (ex. TUDA at TRIUMF is a LEDA-type system)

"LEDA" type

16 strips in θ

300 μm or 500 μm

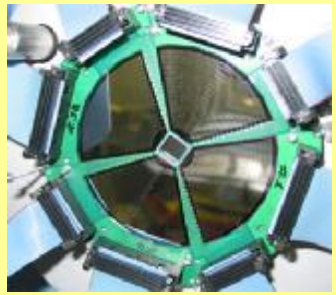


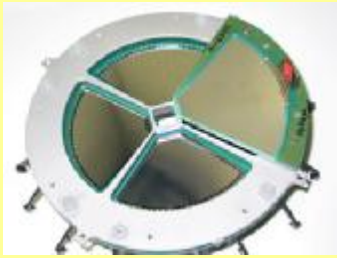
Solid angle: 10% of 4π

"CD" type

16 strips x 4 DSSD

50 μm or 500 μm





4 x PAD

1.5 mm

The ^{7}Be+p elastic scattering @ Louvain-la-Neuve

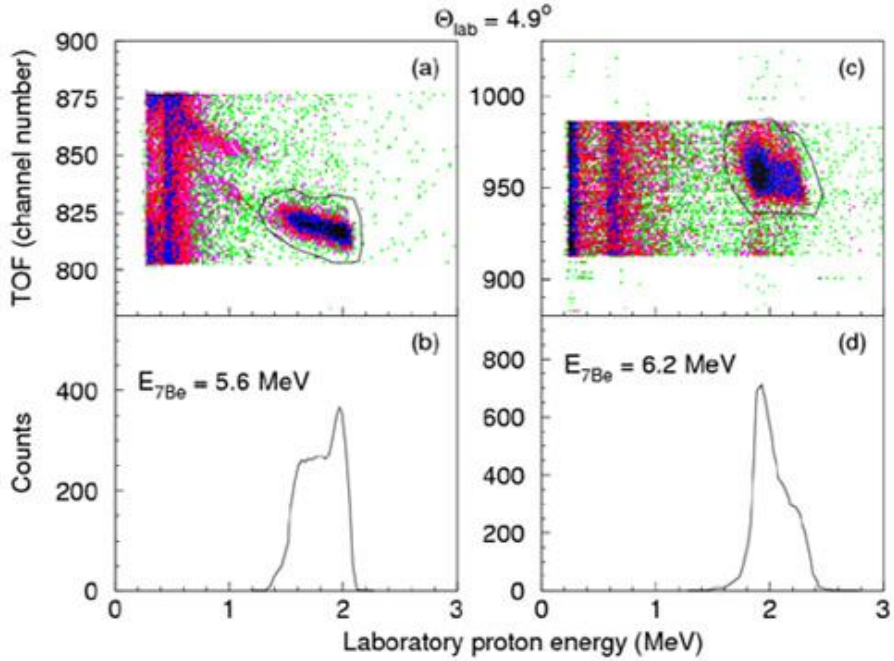
C. Angulo et al., Nucl. Phys. A 716 (2003) 211-229

- First experimental determination of the $\ell=0$ scattering lengths of the ^{7}Be+p system
- Applications to the ^{7}Be(p,γ)^{8}Be S-factor and charge symmetry of mirror systems

Experimental conditions

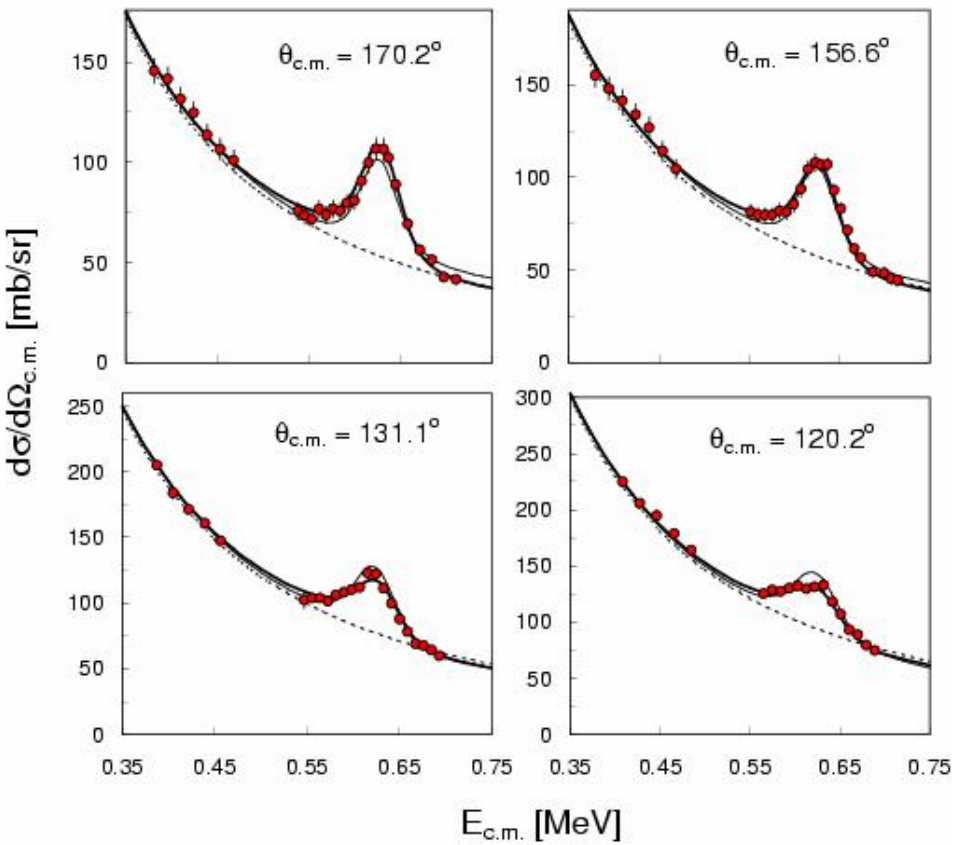
- ^{7}Be @ 4.4, 5.7 and 6.3 MeV with averaged intensity ~ 3 x 10^6 pps
- A very stable beam during 9 days
- Target: 270 μg/cm^2 polyethylene foil
- LEDA system, Mylar foils to stop the scattered ^{7}Be and ^{12}C

Typical TOF and energy spectra



The ^{7}Be+p elastic scattering @ Louvain-la-Neuve

- R-matrix analysis of $\sigma(\theta)$ for energies $E_{c.m.}$ = 0.35 – 0.7 MeV for 20 angles.
- No channel spin mixing included (a good approximation: Fred Barker, private communication)
- Sensitivity tested with respect to the channel radius, the effective range, and the energy straggling



Results

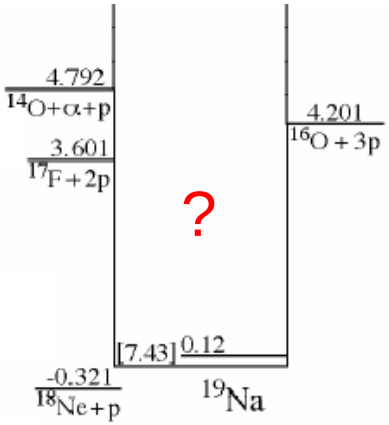
Parameter	Present	Literature	Charge symmetry
a_{01} [fm]	25 ± 9	---	2 to 3
a_{02} [fm]	-7 ± 3	---	-7 to -11
E_R [keV]	634 ± 5	632 ± 10	
G_R [keV]	31 ± 4	37 ± 5	

Astrophysical consequences are weak but not negligible if one considers the precision needed in solar models

- New ^{7}Be+p experiment at CRC to confirm these results

Spectroscopy of ^{19}Na by ^{18}Ne+p elastic scattering @ Louvain-la-Neuve

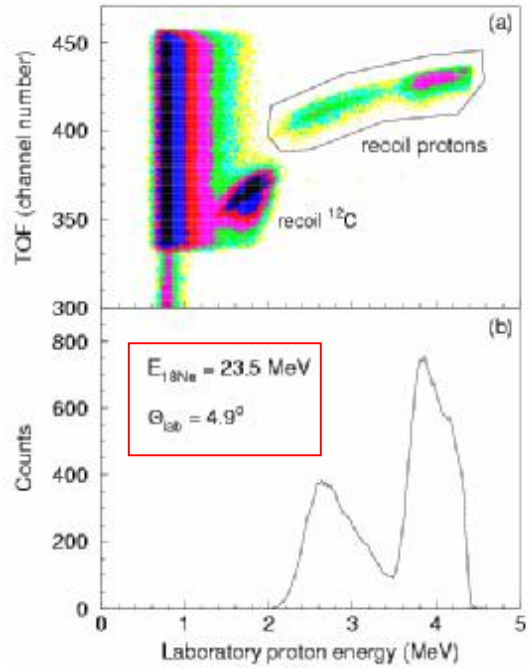
C. Angulo et al., Phys. Rev. C67 (2003) 014308



- The level scheme of the drip line nucleus ^{19}Na is practically unknown
- It is proton unstable by -321 keV with its first excited state at ~ 120 keV above the ^{18}Ne+p threshold

Ideal candidate for an elastic scattering experiment using the low energy ^{18}Ne beam at Louvain-la-Neuve

Example of TOF and energy spectra



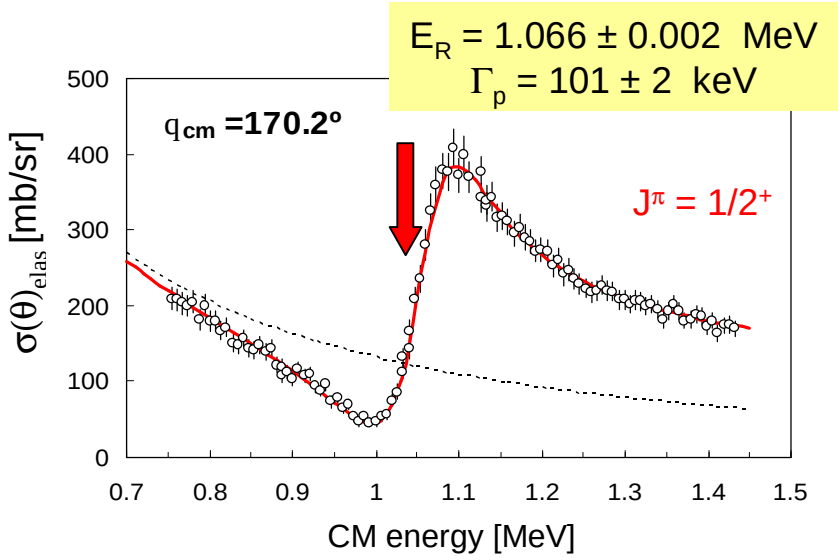
Experimental conditions

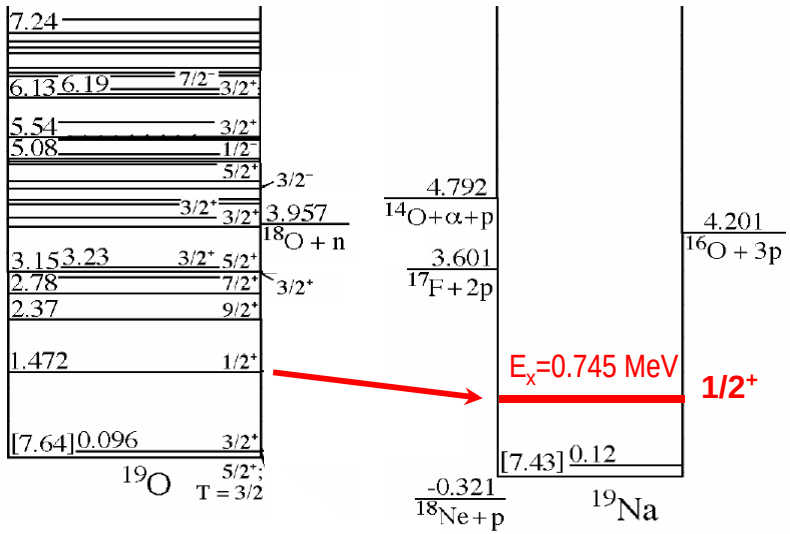
- ^{18}Ne beam @ 21, 23.5 and 28 MeV
- Averaged beam intensity on target: 4 ×10^6 pps
- Running time: ~ 3 days/energy (excellent statistics)
- Target: 520 mg/cm^2 of polyethylene foil
- LEDA system: data for 20 angles for E_{cm} = 0.3 - 0.8 MeV

Spectroscopy of ^{19}Na by ^{18}Ne+p elastic scattering @ Louvain-la-Neuve

C. Angulo et al., Phys. Rev. C67 (2003) 014308

- R-matrix fits: only 2 parameters, data for 20 angles, χ^2 minimization
- <u>First observation</u> of the second excited state in ^{19}Na. It has a large Coulomb shift, Δ_c = 0.73 MeV

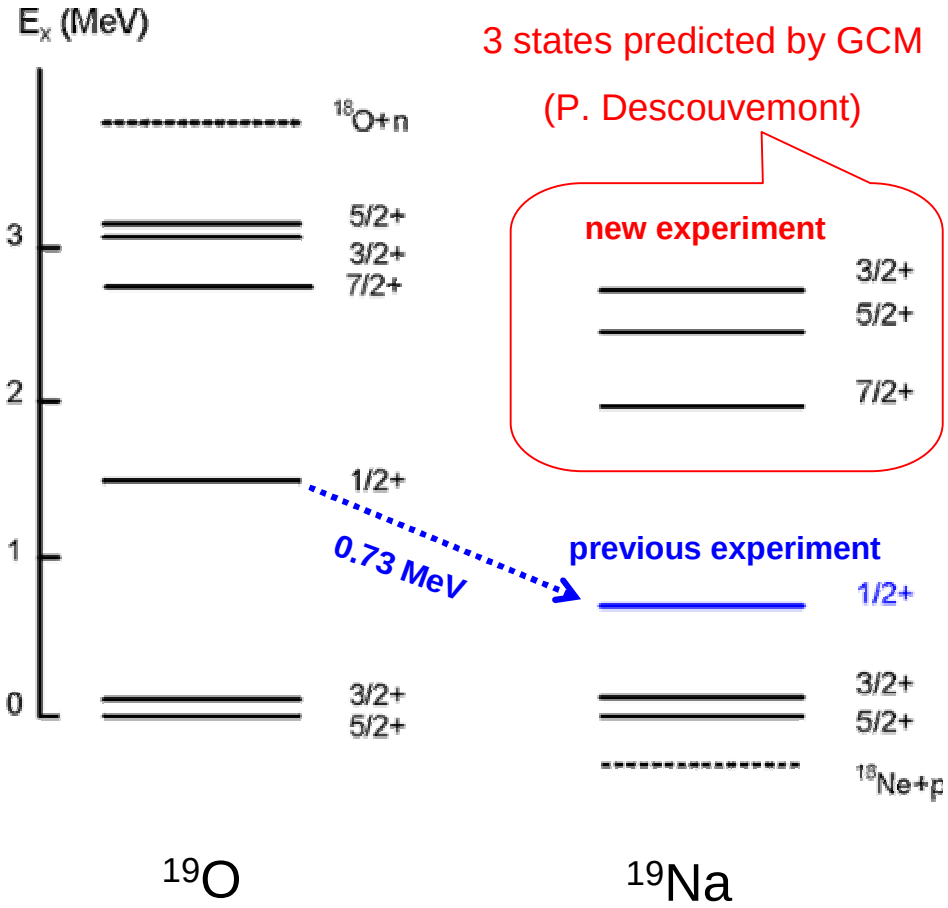




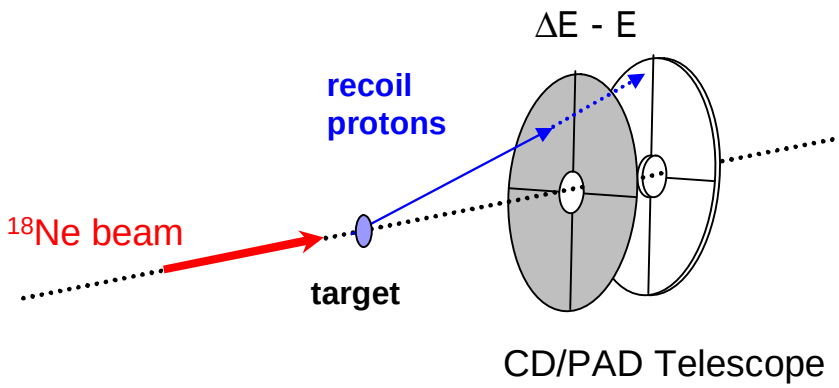
$\theta_p^2 = 23\%$ typical of a single particle state

very large Coulomb shift (0.73 MeV) between the 1/2$^+$ states in the mirror nuclei ^{19}O and ^{19}N

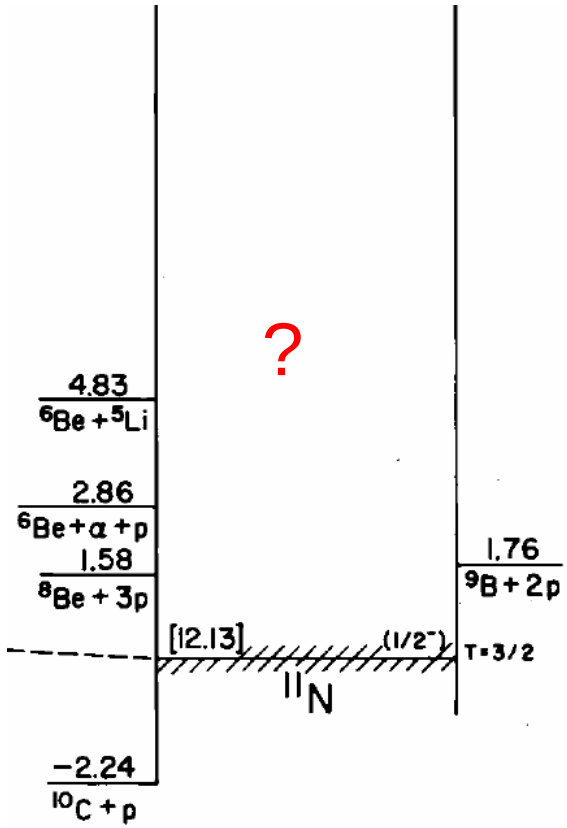
Spectroscopy of ^{19}Na by ^{18}Ne+p elastic scattering @ Louvain-la-Neuve



- New ^{18}Ne+p experiment (LEDA coll.) scheduled at the CRC in December'03 at higher energies using a $^{18}Ne^{4+}$ beam
- Investigation of the ^{18}Ne + p elastic and inelastic scattering



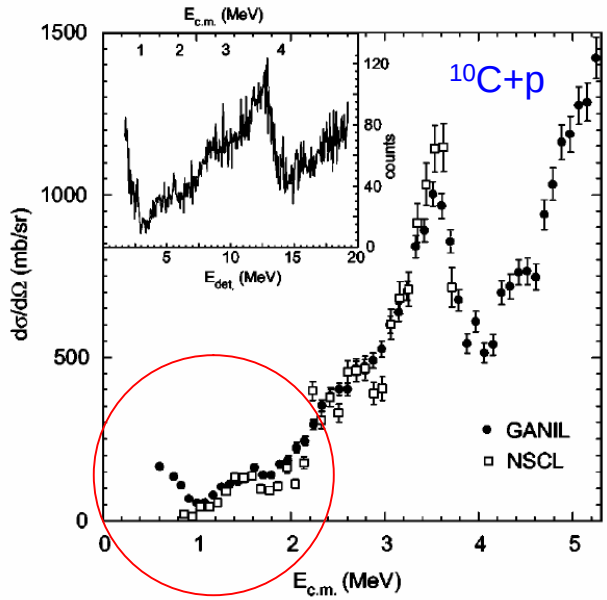
Spectroscopy of ^{11}N



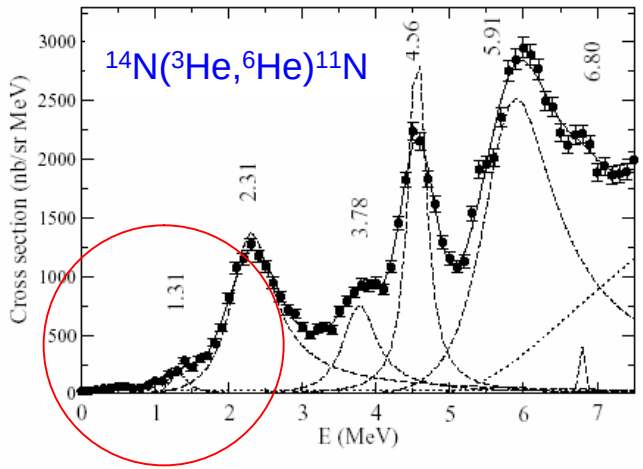
Level scheme from:

http://www.tunl.duke.edu/nucldata/

K. Markenroth et al., Phys. Rev. C62 (2000) 034308.



V. Guimarães et al., Phys. Rev. C67 (2003) 064601.



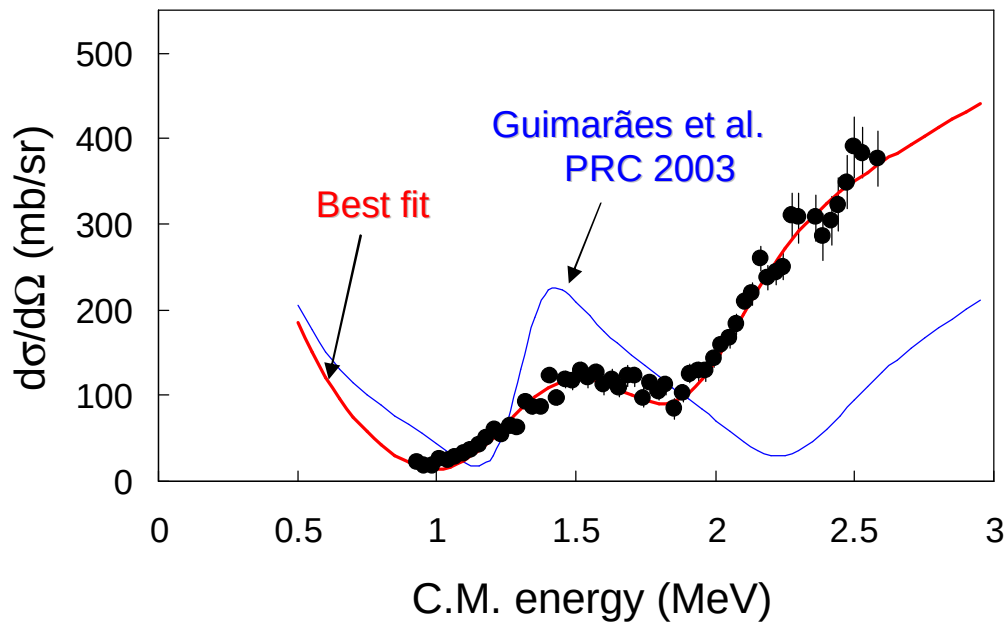
The ^{11}N revisited by a new ^{10}C+p experiment

- Experiment performed end of June 2003
- Goal: study the lower energy states, in particular the ground state of ^{11}N ($1/2^+$)
- 6 days of running time using:
  - New $^{10}C^{2+}$beam @ 25.5 and 32 MeV, beam intensity ~ 6000 to 10000 pps
  - A 1.5 mg/cm^2 CH_2 target
  - ΔE-E detector (CD + PAD): 16 angles
- Several broad states observed
- An R-matrix analysis is undergoing

Example:
R-matrix fit for θ_{cm} = 163.8º
(channel radius a= 6 fm):

- 3 resonant states included
- Best fit: $\chi^2/N = 1.2$
- Resonance parameters in fair agreement with Markenroth et al. and calculations (Fortune, Barker, Descouvemont, …)
- But in disagreement with Guimarães et al.

Preliminary results



Conclusions and Perspectives

- The proton (and alpha) elastic scattering is a powerful tool for the study of exotic nuclei
- The choice of the target, and other experimental conditions, are crucial for the success of the technique
- The analysis of the cross section using a physically based formalism, like the R-matrix method, is a fundamental step to obtain meaningful resonance parameters

New investigations at Louvain-la-Neuve

- ^{19}Ne by ^{15}O+α (in October 2003) – first experiment with a ^{15}O beam
- ^{5}H by ^{6}He + ^{7}Li (in November 2003)
- ^{19}Na by ^{18}Ne(p,p) and ^{18}Ne(p,p') (in December 2003)
- ^{16}F by ^{15}O+p (in preparation for 2004)

A new beam of ^{14}O is being developed for nuclear astrophysics and nuclear spectroscopy of light nuclei, in particular to investigate the ^{14}O(α,p)^{18}F reaction: a possible trigger to the astrophysical rp process

Collaborators (nuclear physics and nuclear astrophysics)

- LEDA collaboration (Louvain-la-Neuve and Edinburgh)
- PNTPM, Brussels
- INFN Catania
- LPC Caen
- KULeuven
- CSIC Madrid
- Kurchatov Institute Moscow
- CEA Saclay
- Universities of: Birmingham, Connecticut, Huelva, York, Notre-Dame, Sevilla, …
- Ruder Boskovic Inst. Zagrev
- ….

CRC is a European Large Scale Facility

Partner in EURONS – FP6

www.cyc.ucl.ac.be