Nuclear reactions for astrophysics

experimental activities in NPI CAS and collaborations

Jaromir Mrazek

EUROPEAN UNION
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Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Outline

- Indirect methods
  - Asymptotic Normalization Coefficients
  - Trojan Horse Method

- project SPIRAL2-CZ and
- nuclear reactions with astrophysical context in GANIL/SPIRAL2 and IPN Orsay

Experimental environment in NPI CAS

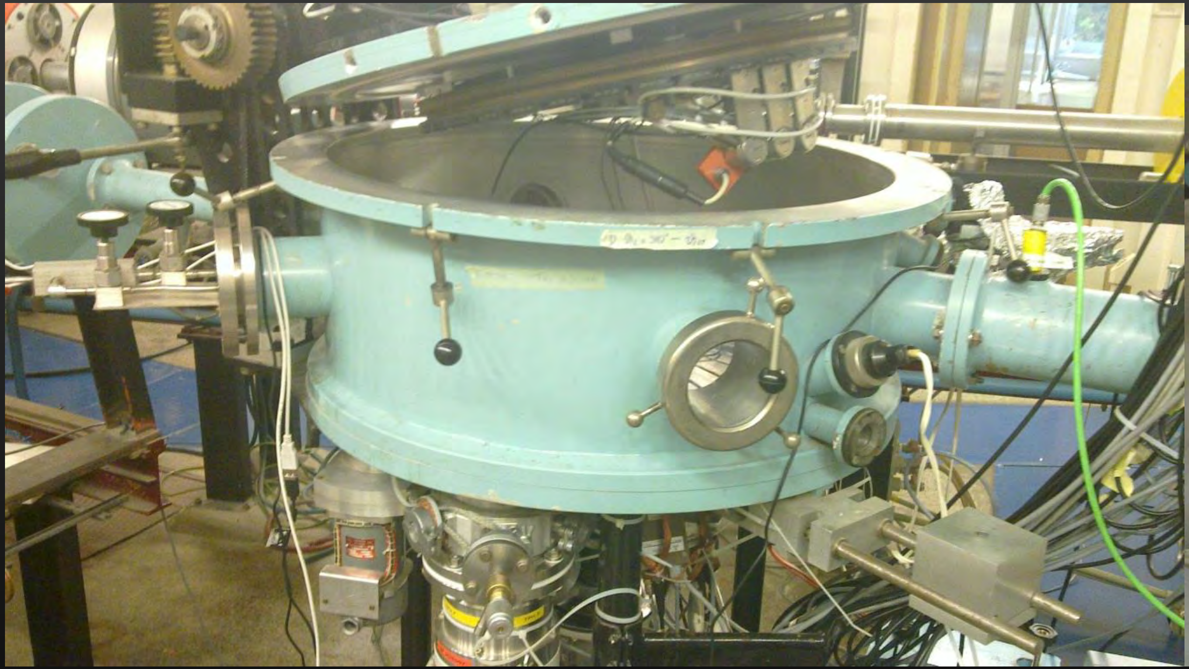
U120M cyclotron

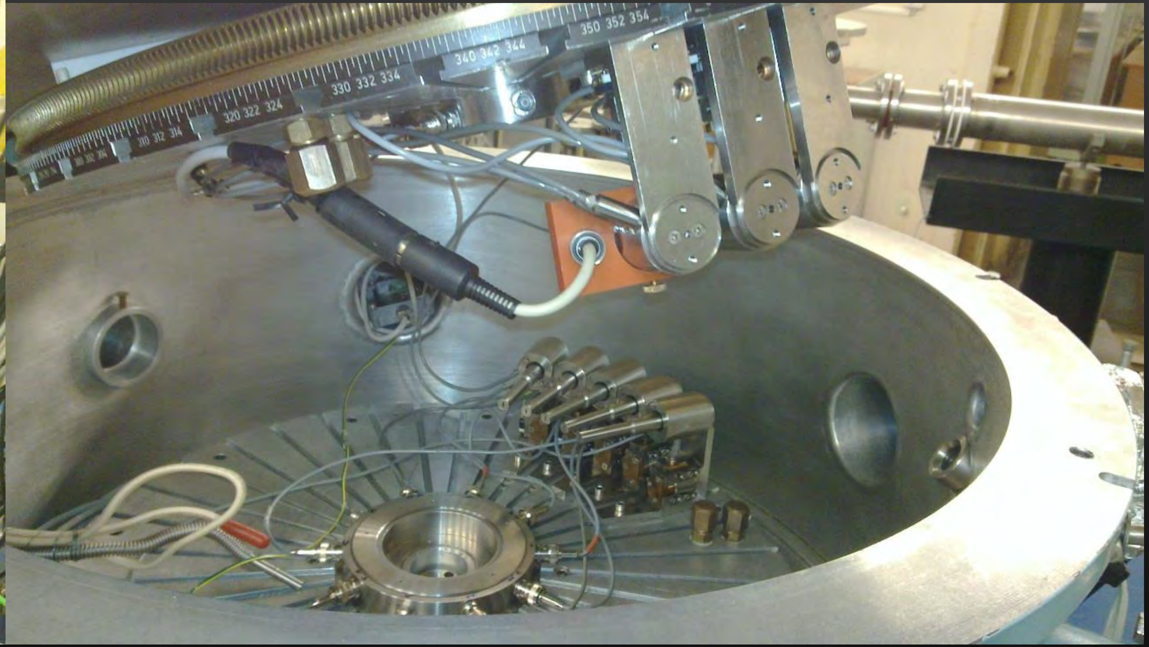
(talk of J.Dobes and J.Stursa this morning)

U120M can deliver p, d, 3He and 4He beams with energy approx. 10-40 MeV

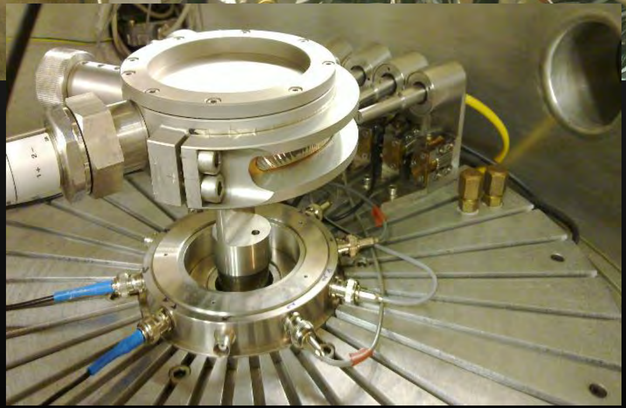
at intensities up to 20 nA in the experimental hall 102

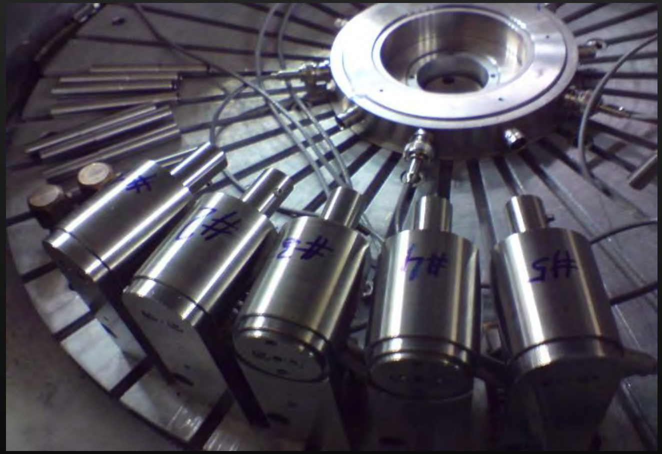
Experimental environment in NPI CAS

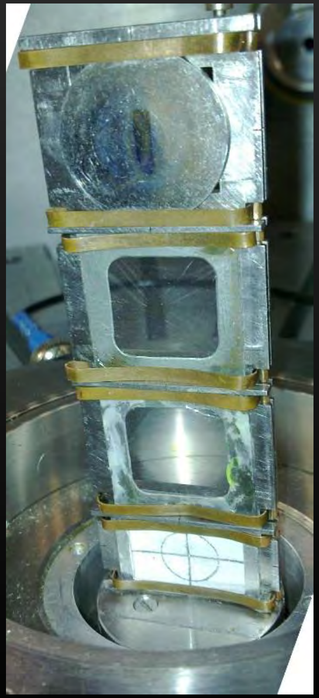




Typical experimental ANC setup in NPI







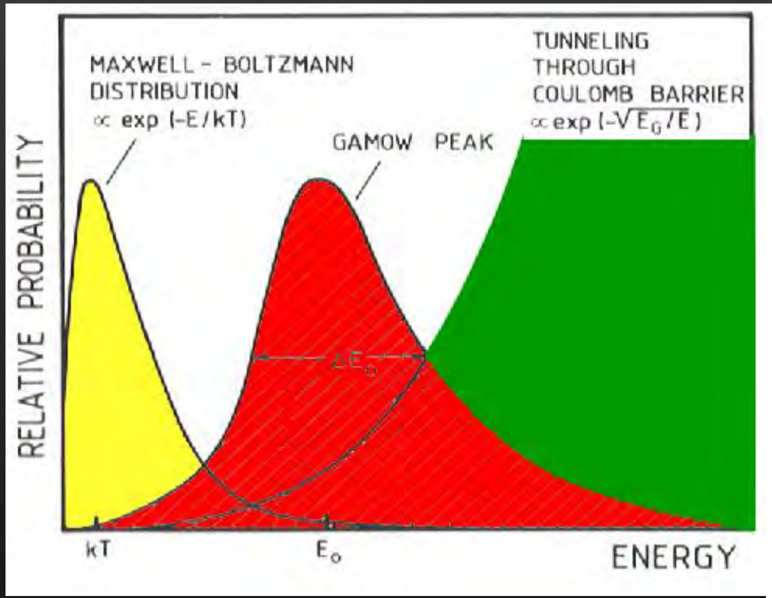
Why indirect?

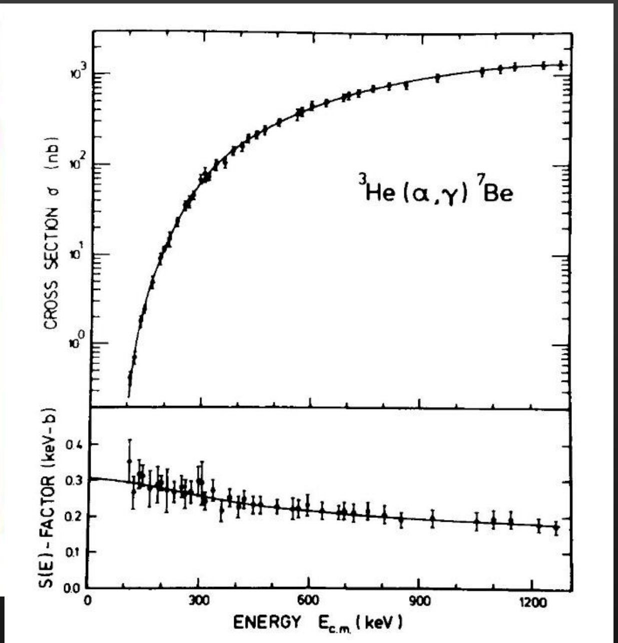
Ractions typically at low energies

Energies of Gamow peak

in Sun and AGB stars typically tens or 100 keV

explosive scenarios e.g. $p+^{28}Si$ 380 keV





Astrophysical S factor

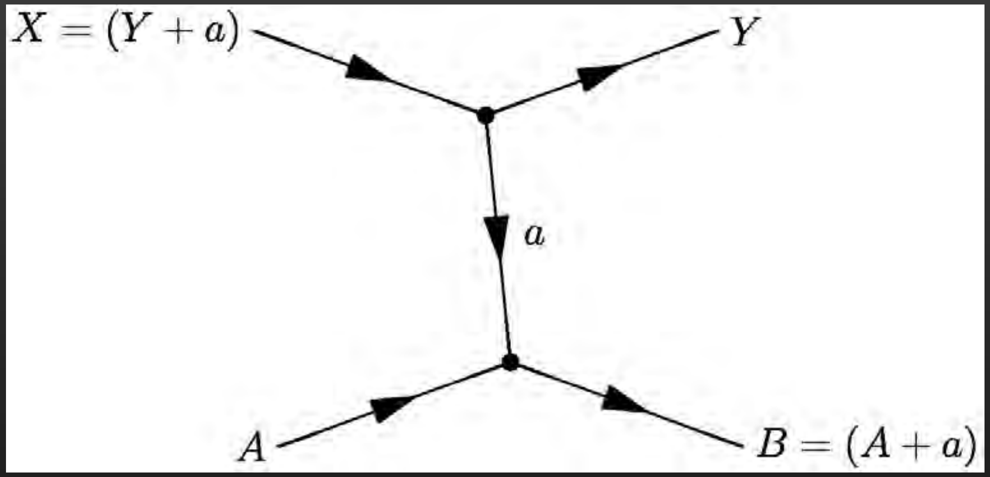
$$S(E) = \sigma(E)\,E\,\exp(2\pi\eta)$$

Sommerfield factor $\eta = Z_1 Z_2 e^2/(\hbar v)$

Indirect methods in NPI CAS

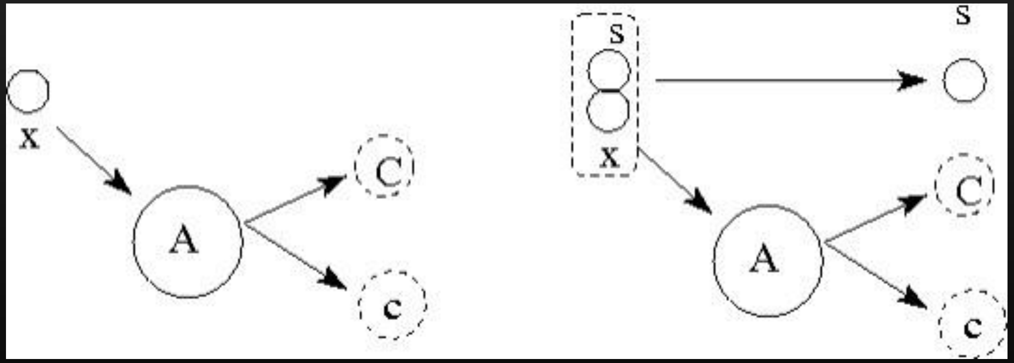
Asymptotic Normalization Coefficients (ANC)

- study a direct binary reaction in peripheral conditions
- determine the nuclear vertex constant(s) X+A→Y+B
- extract a x.s of direct radiative capture a + A → B + gamma



Trojan Horse method (THM)

- study a ternary reaction at exact conditions
- determine x+A → C + c behavior around E_{trsh}



ANC principles

The method comes from DWBA technique

DWBA amplitude is given by:

$$M(E_i, \cos\theta) = \sum_{M_a} \langle \chi_f^{(-)} I_{Aa}^{B} | \Delta V | I_{Ya}^{X} \chi_i^{(+)} \rangle$$

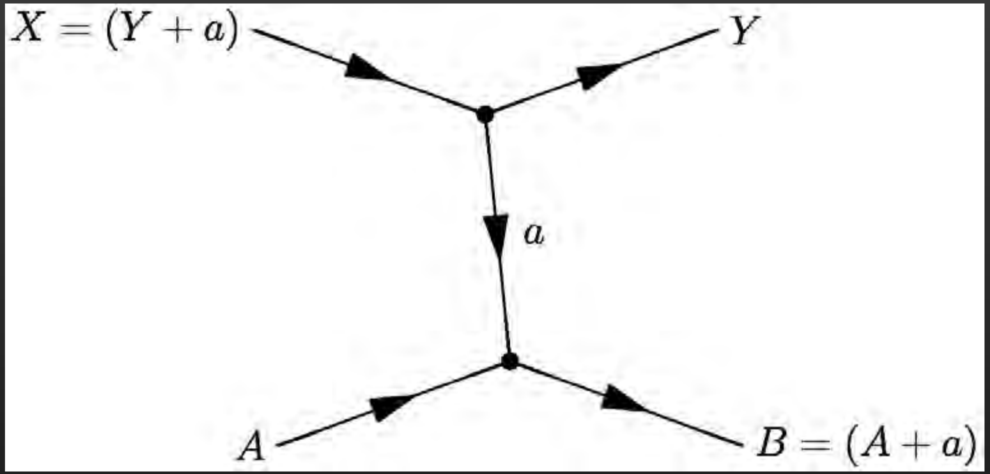
$$I^{\alpha}_{\beta\gamma l_\alpha j_\alpha}(r_{\beta\gamma}) = S^{1/2}_{\beta\gamma l_\alpha j_\alpha} \phi_{n_\alpha l_\alpha j_\alpha}(r_{\beta\gamma})$$

DWBA cross section:

$$\sigma^{DW}_{l_B j_B l_x j_x} \sim |M(E_i, cos\theta)|^2$$

experimental cross section and spectroscopic factors:

$$\frac{d\sigma}{d\Omega} = \Sigma_{j_B j_x} S_{Aa l_B j_B} S_{Ya l_x j_x} \sigma^{DW}_{l_B j_B l_x j_x}$$



Radial overlap function is approximated by a model wave function of the bound state

Spectroscopic factors – model dependent

But IF nuclear interior is not much involved ...

ANC principles

$$I^{\alpha}_{\beta\gamma l_\alpha j_\alpha}(r_{\beta\gamma}) = S^{1/2}_{\beta\gamma l_\alpha j_\alpha}\phi_{n_\alpha l_\alpha j_\alpha}(r_{\beta\gamma})$$

Radial Overlap function in asymptotic behavior

For peripheral reaction:

- C is ANC
- b is a single particle ANC

$$I^{\alpha}_{\beta\gamma l_\alpha j_\alpha}(r_{\beta\gamma}) \xrightarrow{r_{\beta\gamma}>R_N} C^{\alpha}_{\beta\gamma l_\alpha j_\alpha}\frac{W_{-\eta_\alpha,l_\alpha+1/2}(2\kappa_{\beta\gamma}r_{\beta\gamma})}{r_{\beta\gamma}}$$

$$\phi_{n_\alpha l_\alpha j_\alpha}(r_{\beta\gamma}) \xrightarrow{r_{\beta\gamma}>R_N} b_{\beta\gamma l_\alpha j_\alpha}\frac{W_{-\eta_\alpha,l_\alpha+1/2}(2\kappa_{\beta\gamma}r_{\beta\gamma})}{r_{\beta\gamma}}$$

$$\frac{d\sigma}{d\Omega} = \Sigma_{j_B j_x}(C^B_{Aal_Bj_B})^2(C^X_{Yal_xj_x})^2\frac{\sigma^{DWBA}_{l_Bj_Bl_xj_x}}{b^2_{Aal_Bj_B}b^2_{Yal_xj_x}} = \Sigma_{j_B j_x}(C^B_{Aal_Bj_B})^2(C^X_{Yal_xj_x})^2R_{l_Bj_Bl_xj_x}$$

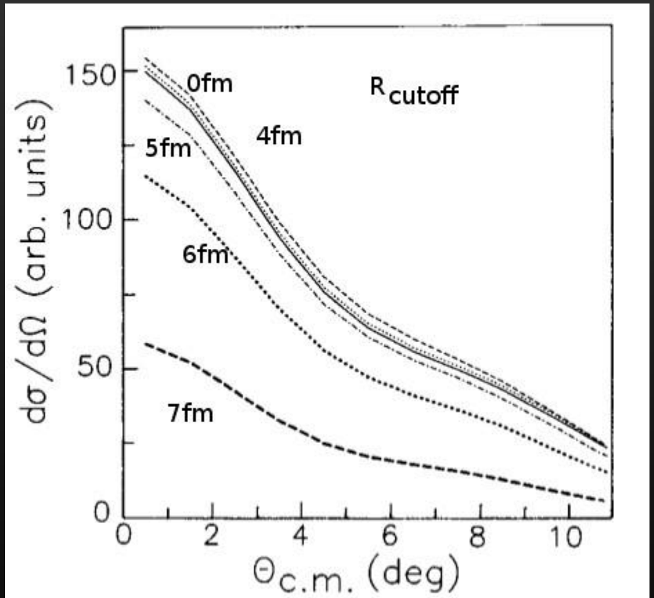
And – for **peripheral** reaction - $R_{l_Bj_Bl_xj_x}$ is nearly independent of b^2

Reaction peripherality

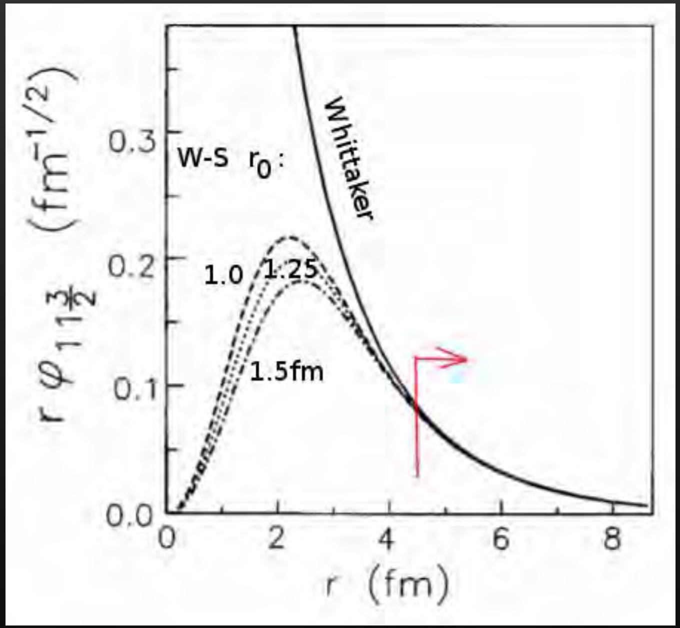
Example from ^{9}**Be(p,gamma)**^{10}**B** *Mukhamedzhanov ,PhysRev56,1302*

To verify a peripherality of the reaction in experimental conditions, several checks are done.

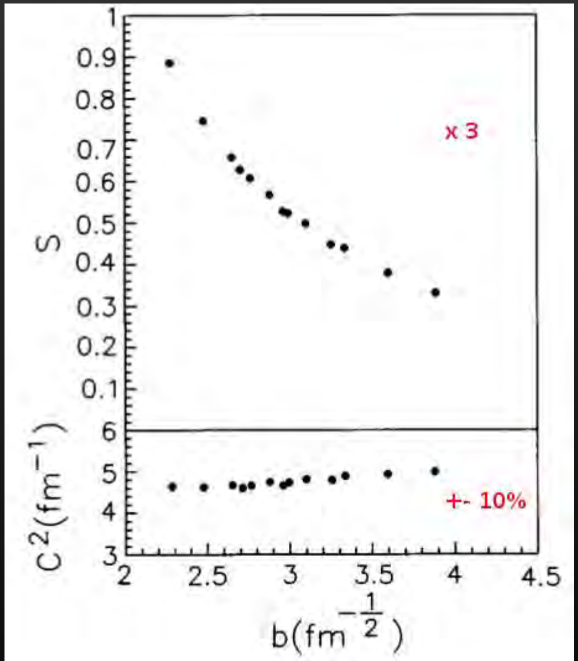
- optical potentials were deduced first from the angular distributions



DWBA xs.behaviour without interior(R_{cutoff})



Radial bound state wavefunctions for different r_0



Dependence of Sfactor and C on single particle ANC

Radiative capture reactions in CNO cycle

$^{13}C + p \leftrightarrow {}^{14}N$

$^{14}N + p \leftrightarrow {}^{15}O$

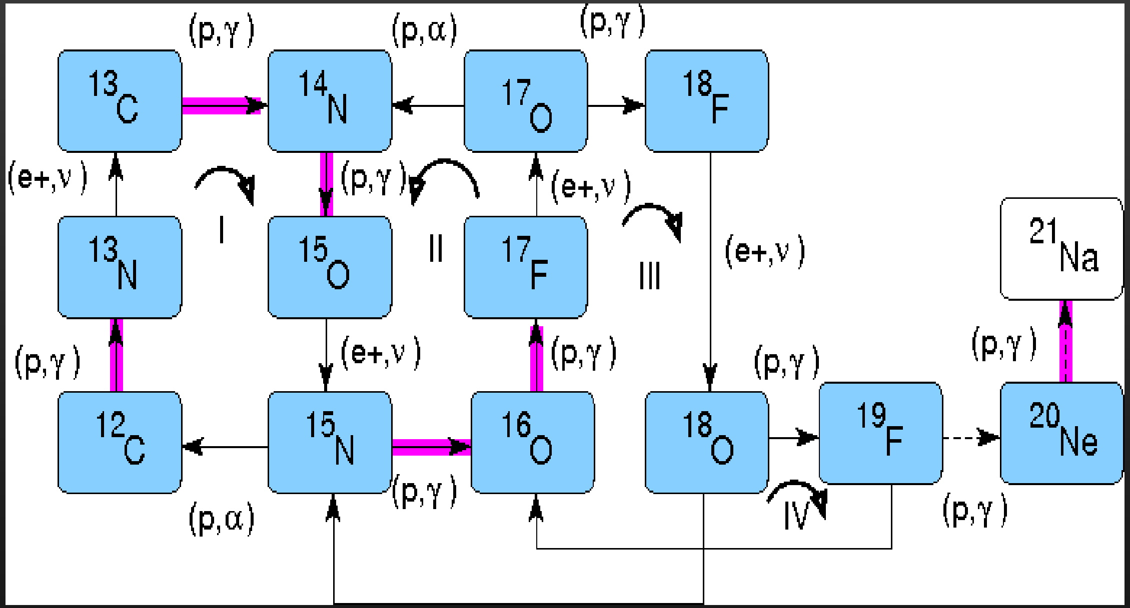
$^{16}O + p \leftrightarrow {}^{17}F$

$^{15}N + p \leftrightarrow {}^{16}O$

$^{14}C + n \leftrightarrow {}^{15}C$

$^{13}C + n \leftrightarrow {}^{14}C$

$^{20}Ne + p \leftrightarrow {}^{21}Na$

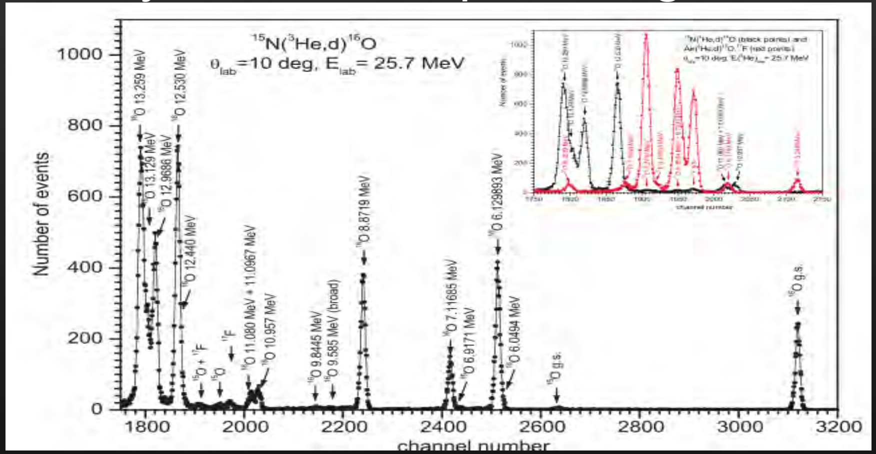


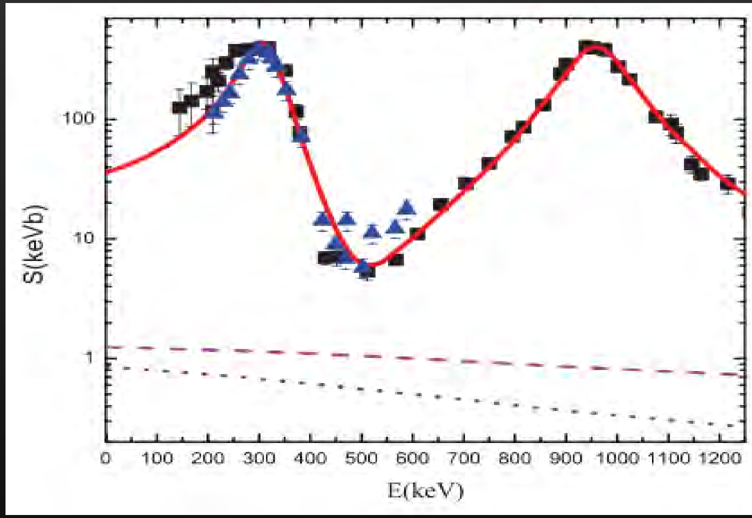
ANCs Measured using (^{3}He,d) in NPI Rez and (d,p)

$^{15}N(p,gamma)^{16}O$

measured with $^{15}N(^{3}He,d)^{16}O$

- CN cycle transform to CNO II, CNO III
- dominated by resonant capture to g.s. through two J=1- resonances





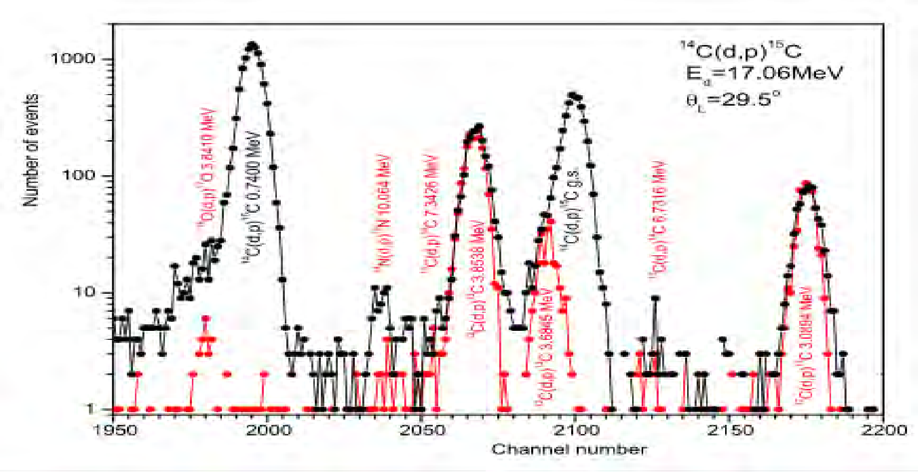
S(0)=36.0 (6.0) keV b … below the previous value 64 (6) NPA235 (1974)
R-matrix fit
rate of leak from CN cycle -
- **one in every 2200 (300) (previously 1200)**

A.M.Mukhamedzhanov et al., PRC78, 015804 (2008)PRC83, 044604 (2011)
LUNA measurement - 39.6 +-2.6 keV b PRC82, 55804 (2010)

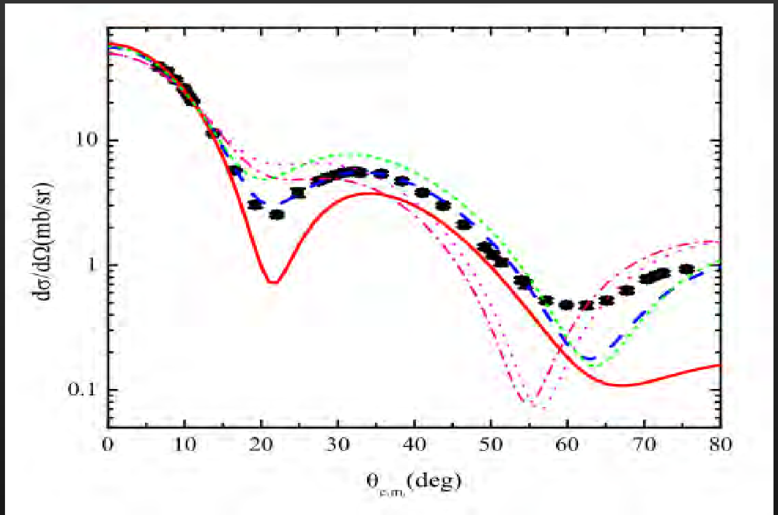
$^{14}C(n,gamma)^{15}C$ skip

using (d,p) reaction

- 'depletes' ^{14}C in inhomogenous big bang models (production A>20)
- depletion of CNO cycle isotopes in AGB stars, seeds for r-process



ang.dist. from trans.to g.s.



- ANC's determined for g.s. and 1st excited state

$C^2_{01/2}$ = 1.64+-0.26 fm $^{-1}$ $C^2_{2\,5/2}$ = (3.55 +- 0.43) 10^{-3} fm^{-1}

- **FR-ADWA** approach decreased the errors (24% → 16%)
- value overlaps with that from **mirror symmetry**,
- older d,p measurement overestimated xs. By 30% at fw angles

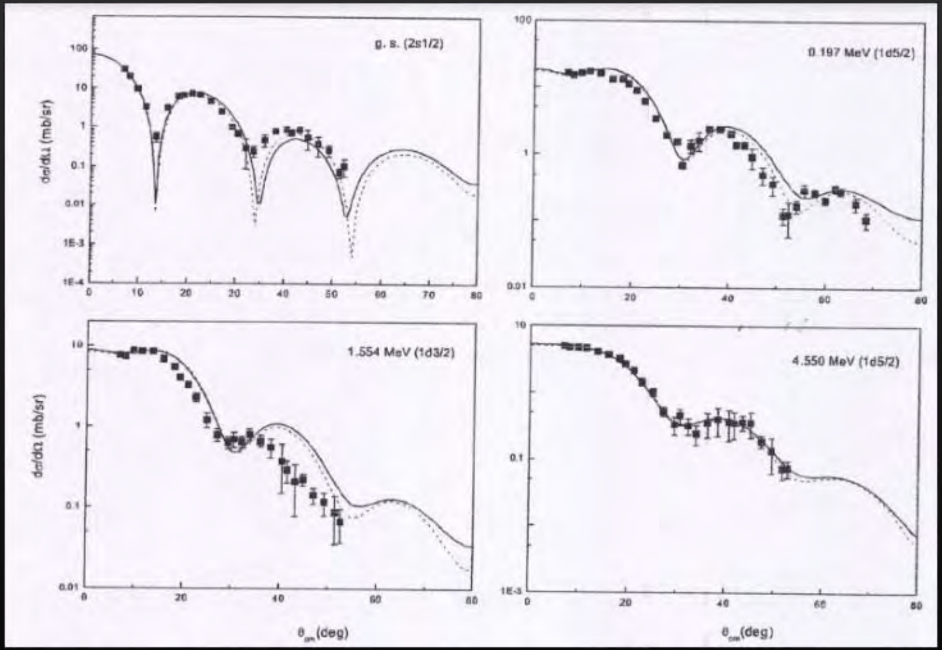
$C^2_{01/2}$	
1.89 +- 0.11	^{15}F mirror
1.48+-0.18	prev.exp.
1.64+-0.03	Coul.dissoc
1.88 +- 0.18	in TAMU (2014)

^{18}O(p,gamma)^{19}F

various ratios of oxygen isotopes can be observed in C.Ch. grains

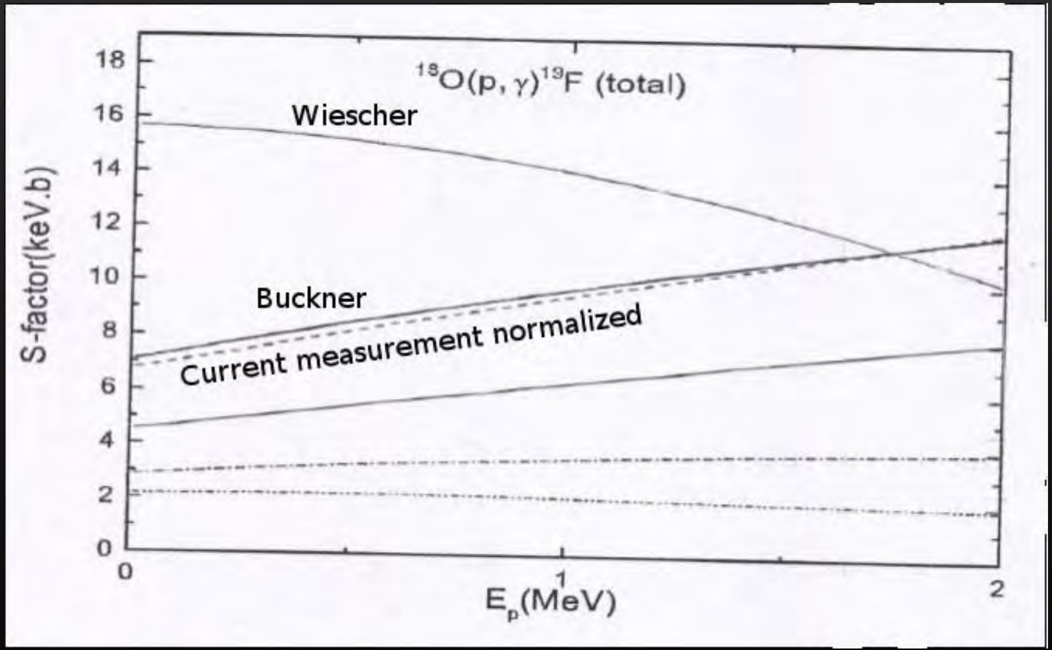
- depletion reaction of ^{18}O in AGB stars

12 levels analyzed



S-factor – earlier disagreement

Wiescher et al. x Buckner et al. = prefered



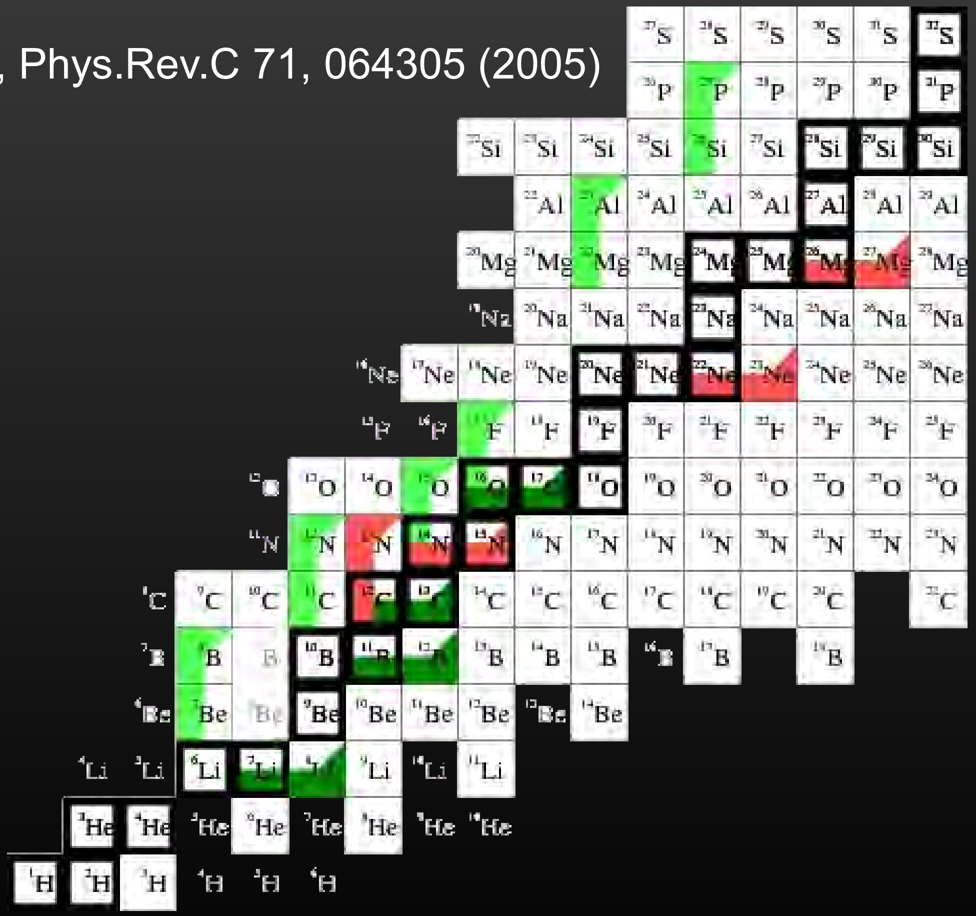
courtesy of Vaclav Burjan

ANC for mirror nuclei

N.K.Timofeyuk et al., Phys.Rev.Lett 91, 232501 (2003)

Timofeyuk, Descouvemont, Phys.Rev.C 71, 064305 (2005)

$$|C_p/C_n|^2 = \mathcal{R} \approx \mathcal{R}_0 = \left|\frac{F_l(i\kappa_p R_N)}{\kappa_p R_N\, j_l(i\kappa_n R_N)}\right|^2$$



On the sample of mirror cases it was shown, that with few % precision

- microscopic cluster model calculations should be used to deduce mirror ANC,

- or simultaneous use of the above analytical formulae and single-particle estimate.

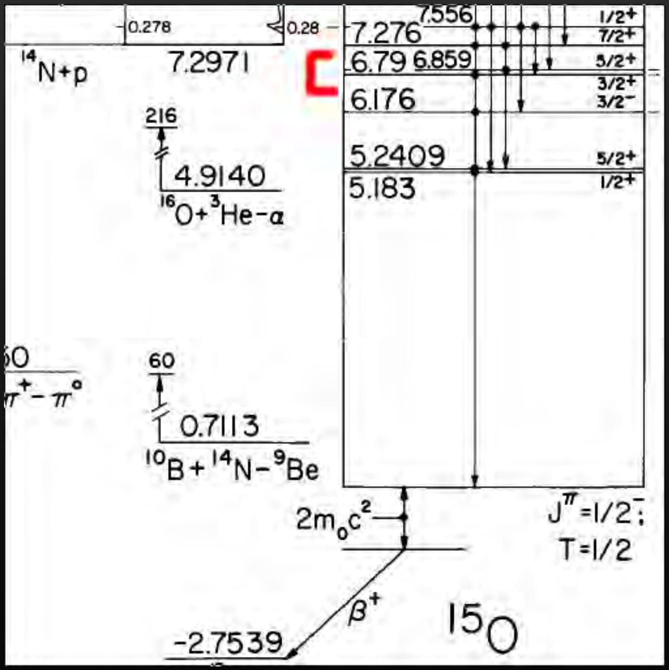
Core polarization effects created 12%.

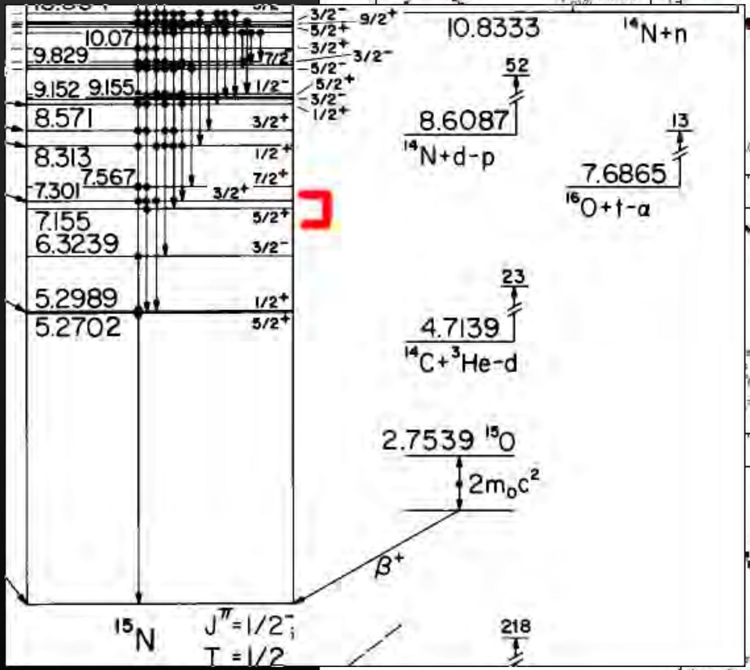
ANC – mirror nuclei

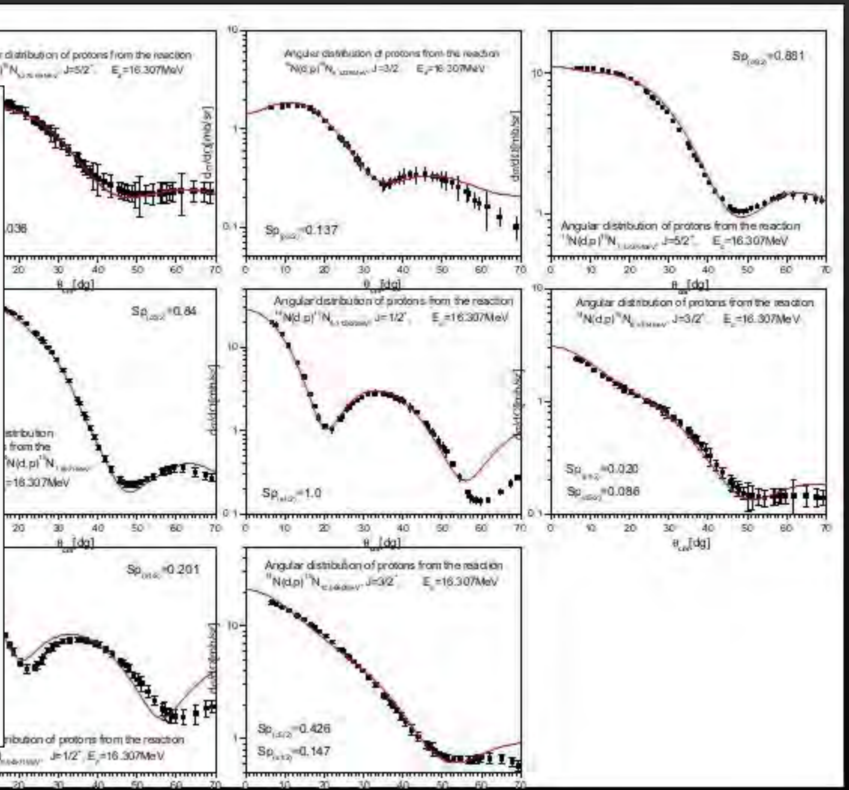
$^{14}N(n,g)^{15}N$ – Yi Xu – postoc in NPI CAS (currently in ELI NP)

Mirror reaction to $^{14}N(p,gamma)^{15}O$ - which is mainly responsible for energy production in CNO cycle

separation of levels 80 keV / 150 keV







ANC – mirror nuclei

^{26}Si(p,g)^{27}P – via mirror ^{26}Mg(d,p) - experiment June 2017

has an impact on amount of observable galactic ^{26}Al

Timofeyuk, Johnson, Mukhamedzhanov – PRL 23 (2003)

- suggestion for study ^{26}Si(p,g), ^{22}Ne(p,g)

Timofeyuk, Descouvemont – Phys.Rev.C71 (2005)

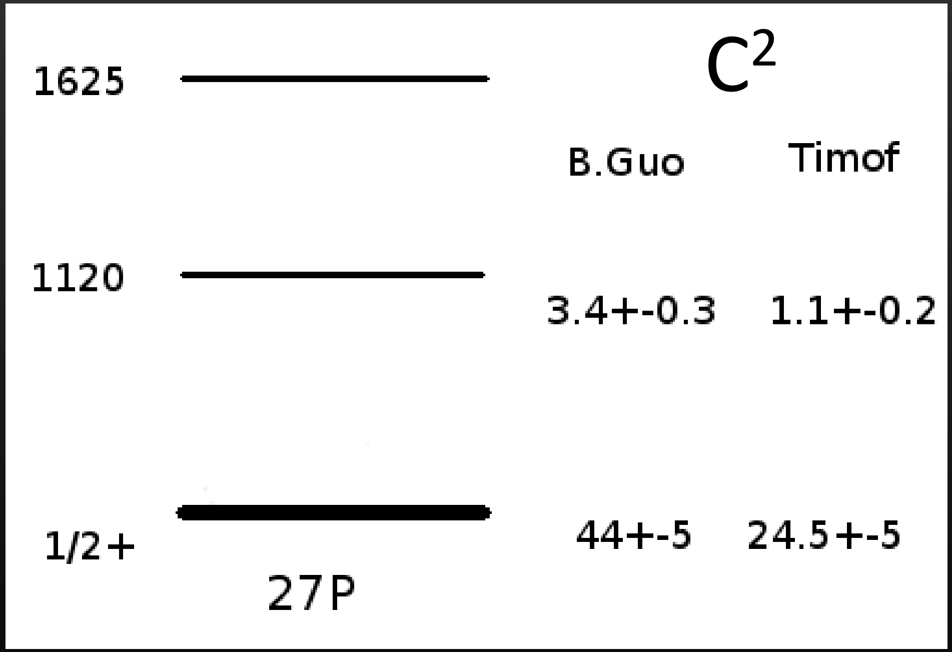
- systematic study of mirror pairs - ANCs

Two re-analysis

Guo et al. PRC73 (2006) (d,p) reaction 12MeV

Timofeyuk, Descouvemont, Thompson PRC78 (2008)

t,d reaction



ANC – new method to determine spectroscopic factors

Matching ANCs at low and high energy - idea of A.Mukhamedzhanov

^{14}C+n pilot experiment ^{13}C(^{14}C,^{15}C)^{12}C and ^{14}C(d,p) in TAMU

McClesky et al., PRC89, 044605 (2014)

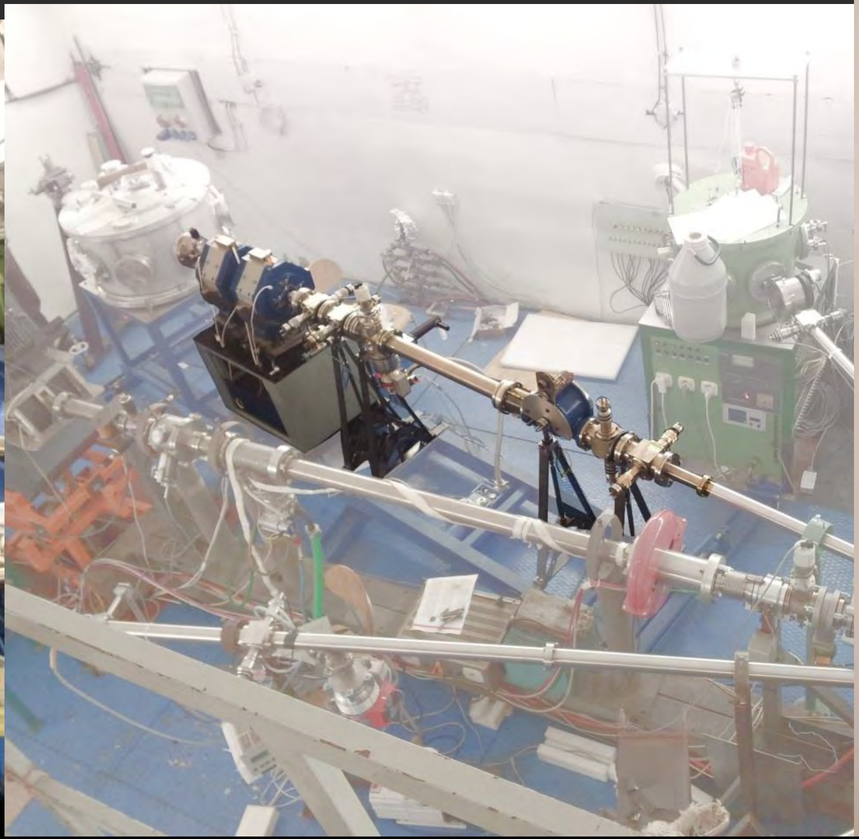
ANCs measured at sub-Coulomb energies can provide good asymptotic tails

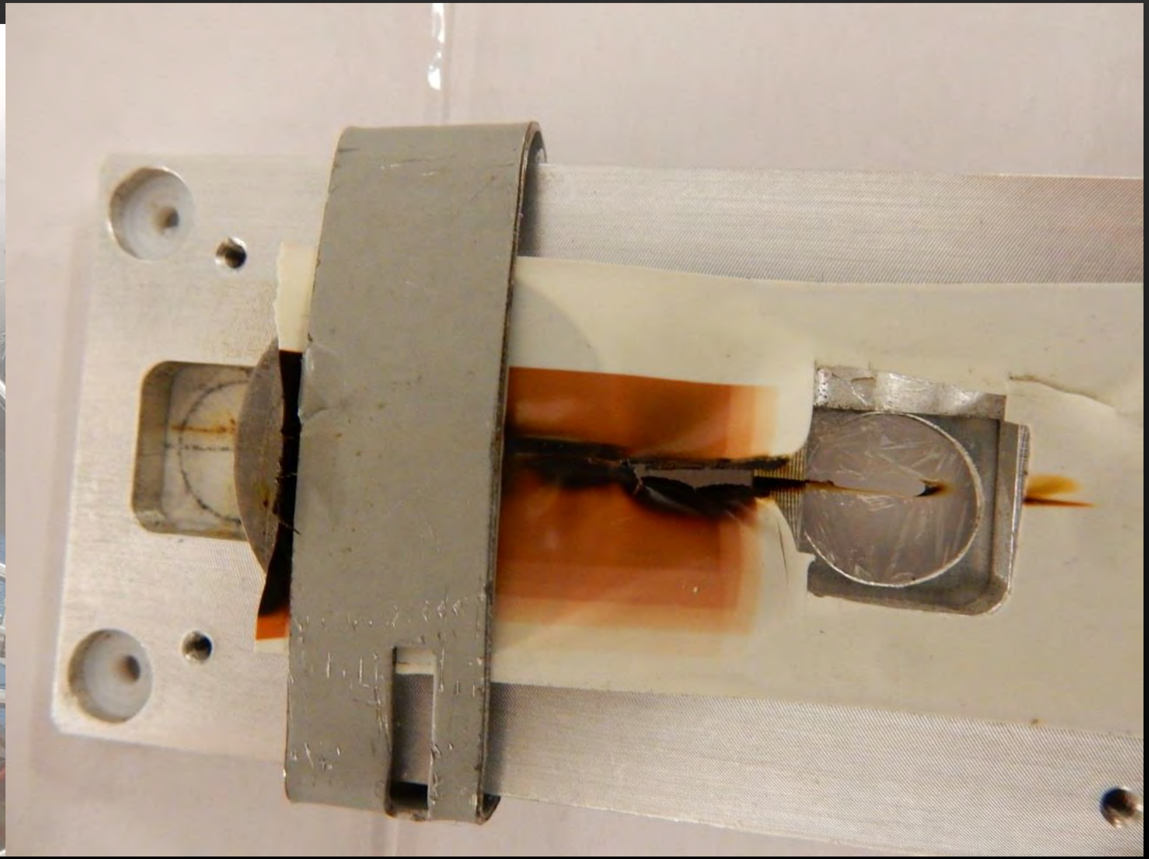
At high energies –knowing the tails (SPANC) – ANC can be produced

----> spectroscopic factors can be better constrained

ANC – new method to determine spectroscopic factors

Low energy beamline - Van de Graaff - UTEF, Prague, ~ 2MV,   2uA





SPIRAL2 – CZ project/ MEYS support 2016-2022

NPI CAS has long term collaboration with GANIL – SPIRAL2

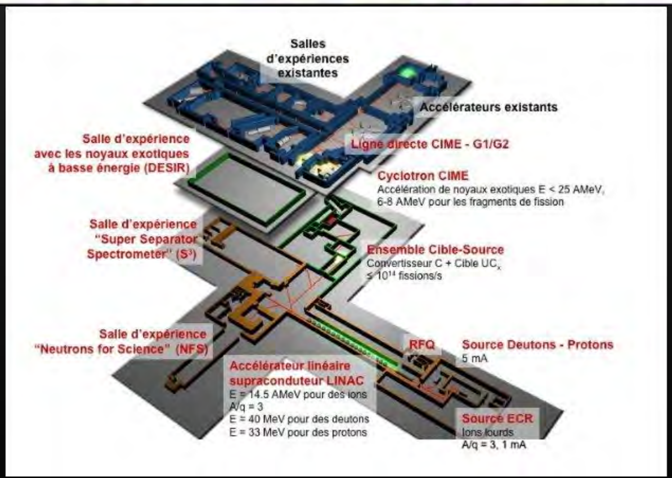
this collaboration was/is also supported by

LEA NuAG (2011-2014) **prolonged** for years **2015-2018**

Associated EU Laboratory – Nuclear Astrophysics and Grids –

support for experiments in GANIL, Orsay, NPI Rez

– helped to promote SPIRAL2-CZ project



SPIRAL2 – CZ project/ MEYS support 2016-2022

Project SPIRAL2-CZ has passed into the

Czech Roadmap of large research infrastructures 2016 - 2022

Nuclear Astrophysics,

Nuclear data: activation by charged particles and neutrons,

radioisotopes for medicine

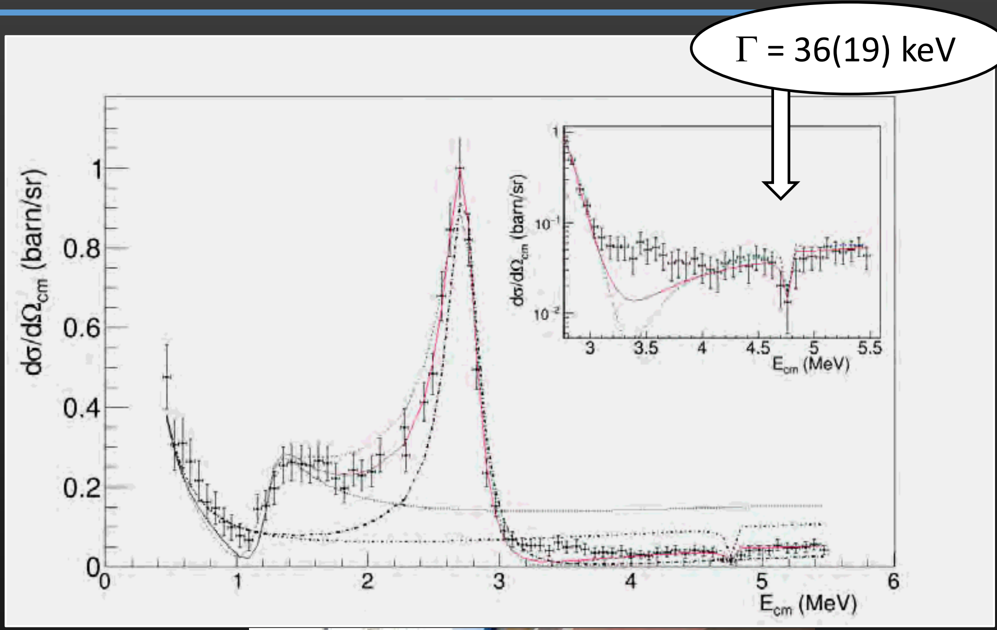
The **research infrastructure** project **SPIRAL2-CZ** was positively evaluated in 2015

- supporting EU program appeared – evaluated in 2016/2017
- Total planned budget ~300 kE / year
  supporting people, administration, investments + travels
- ongoing new evaluation in 2017

SPIRAL2 – CZ / LEA NuAG

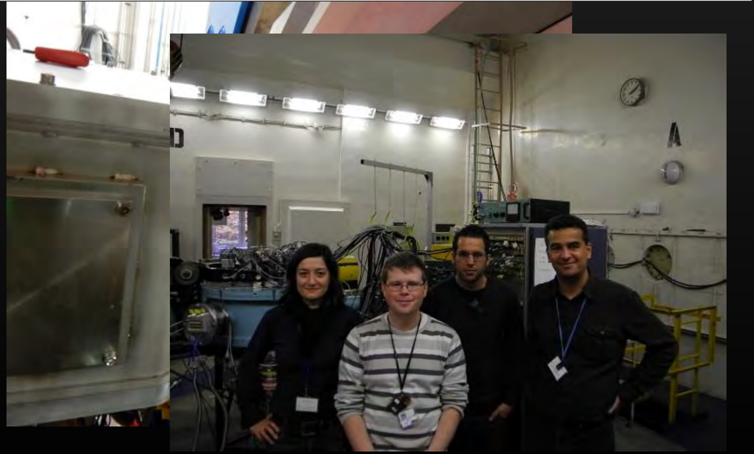
- **Astrophysical program with GANIL and IPN Orsay**

- $^{14}O(p,p')^{14}O$ in GANIL Phys.Lett.B, 758, 26-31. (2016)
  predictions of 2nd ½- narrow state - Canton et al Phys. Rev. Lett, vol.96,072502,
  observed in experiment in GANIL,
  ^{2}He decay, cluster near threshold – coupling to nearby cluster decay channel
  follow up proposal in GANIL , accepted by PAC (I.Stefan)



- Lifetime measurement of 7.786 MeV state in ^{23}Mg (C.Michelagnoli)
  - destruction of 22Na produced in noavae dominating 22Na(p,gamma)23Mg – AGATA+VAMOS

- new experimental efforts at low energies – GANIL - SPIRAL2/NFS (B.Bastin)
  $^{28}Si(p,gamma)^{29}P$ $^{29}Si(p,gamma)^{30}P$ have uncertainties 21% and 30% accepted by PAC

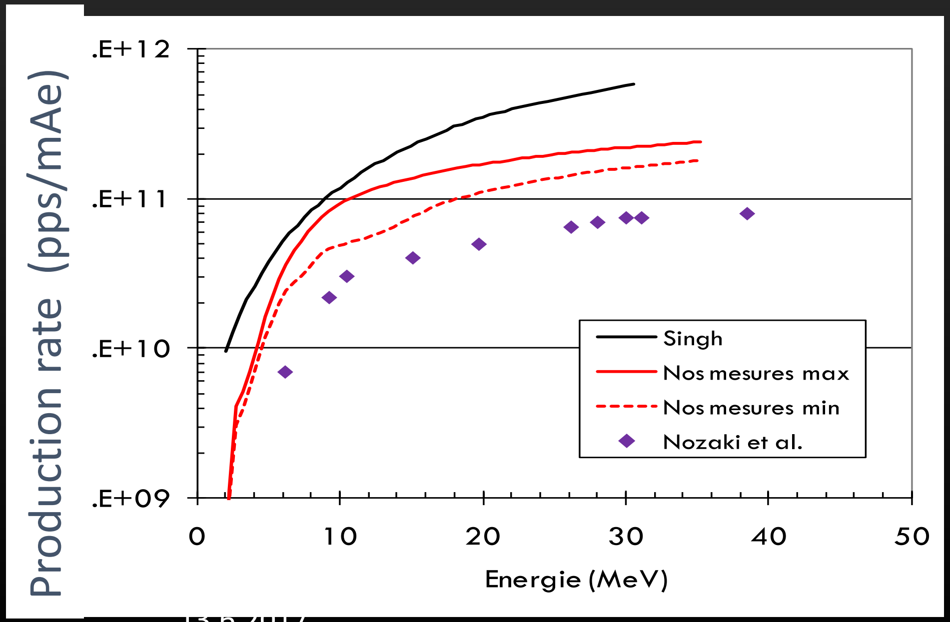


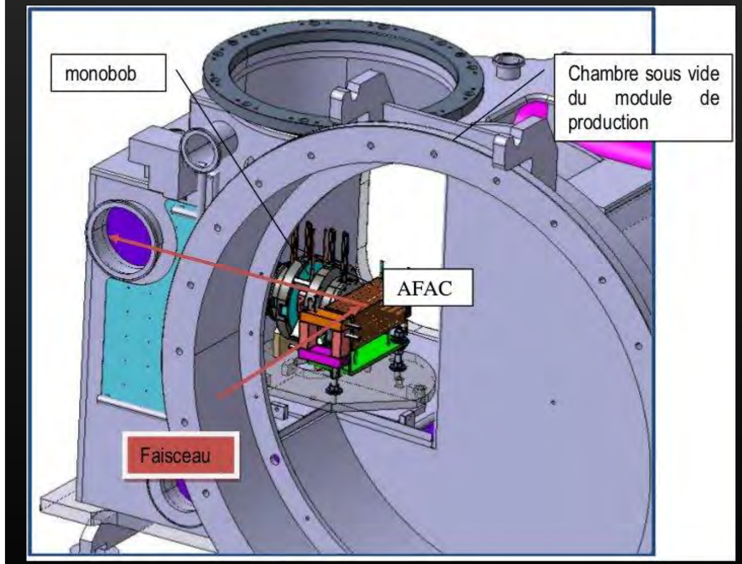
SPIRAL2-CZ - ROBOT target

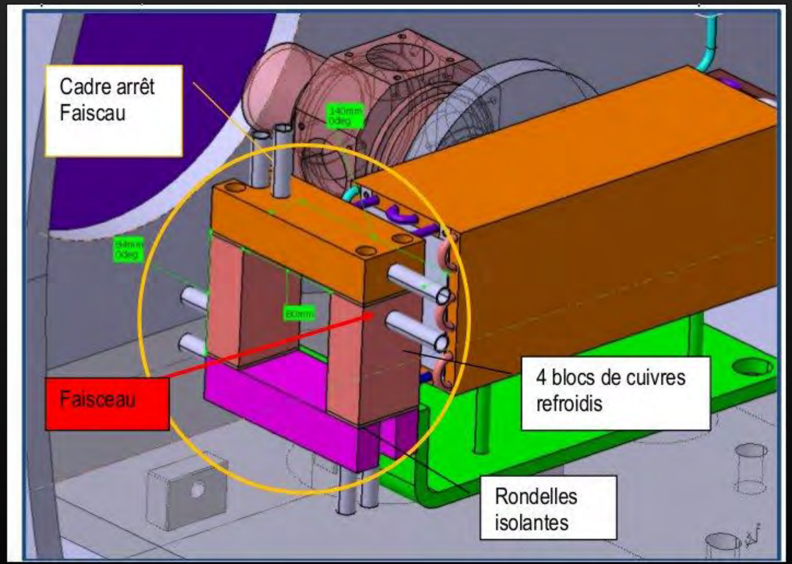
Production target – Rez-Other Targets Other Beams - investment in SPIRAL2-CZ

- ^{14}O production measurements $^{3}He+^{12}C$ to in NPI CAS in 2011 – **~2 x 10^11 pps in SPIRAL2 at 35kW**
- *demonstrator* development of the $^{14,15}O$ beam for SPIRAL/SPIRAL2 – (2019)

A. Pichard et al EPJ A 47 (2011) 1







Collaboration

NPI CAS : V.Burjan, V.Kroha, J.Mrázek, I.Sivacek, Yi Xu, Š.Piskoř, Z.Hons

TAMU : A.M.Mukhamedzhanov, R.E.Tribble, McCleskey ...

INFN-LNS : C.Spitaleri, S.Romano, M.LaCognata, G.Pizzone, L.Lamia, G.Rappissarda .....

GANIL: F.de Oliveira, B.Bastin, C.Michalognoli, M.Lewitowicz, ...

IPN Orsay: F.Hammache, N.de Serreville, I. Stefan .....