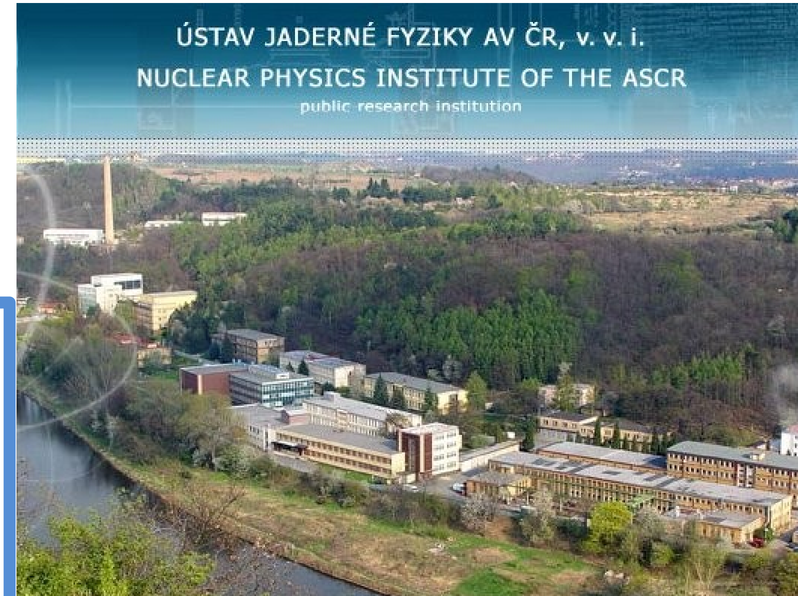
ANC in NPI CAS Rez

Thank you

- for the invitation

- opportunity to join and listen



question from the point of view NPI:

- what is the future directions of ANC ?

- what is the presence of ANC ?

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

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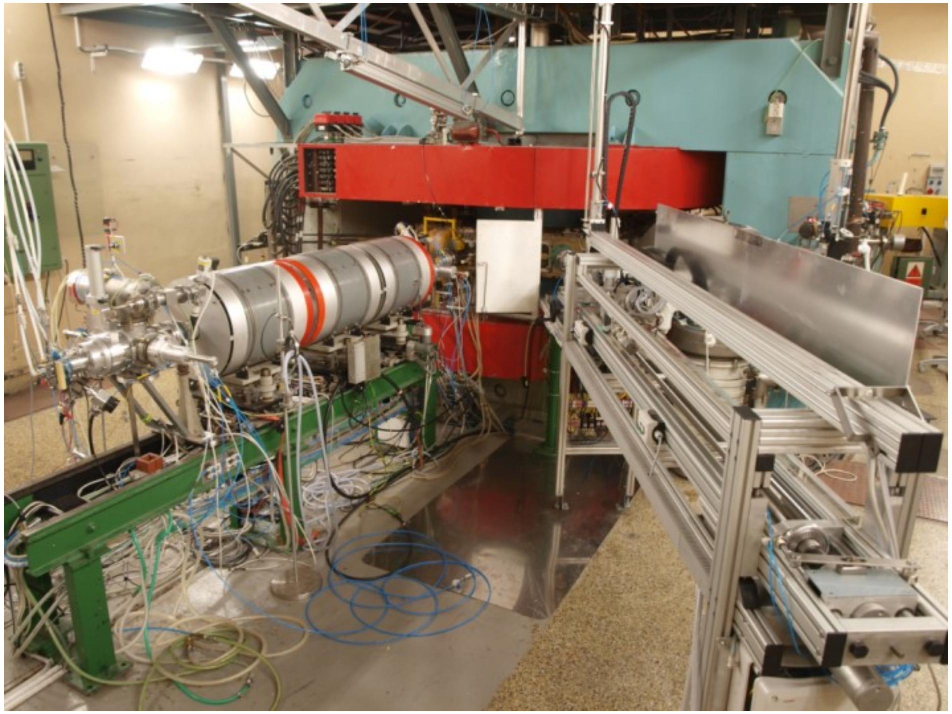
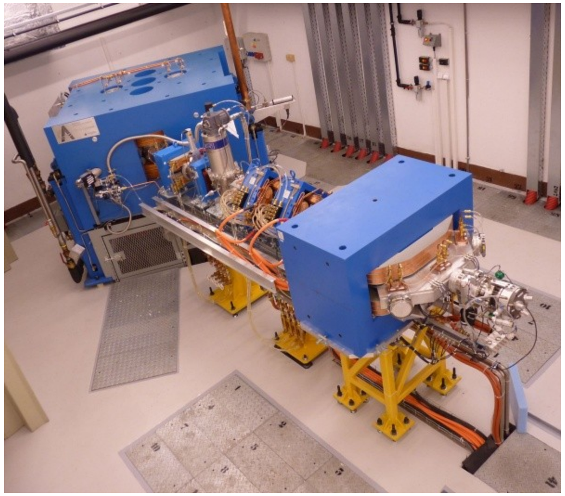
Cyclotrons in NPI CAS





- **Compact cyclotron TR24**
- Beams:
  - **p** 18-24 MeV **300uA**

- **Isochronous cyclotron U120**
- Beams:
  - p 10-25 MeV 5uA
  - **d** 10-20 MeV 5uA
  - **^{3}He** 17-53 MeV 2uA
  - alpha 20-40 MeV 5uA

Typical experimental ANC setup in NPI

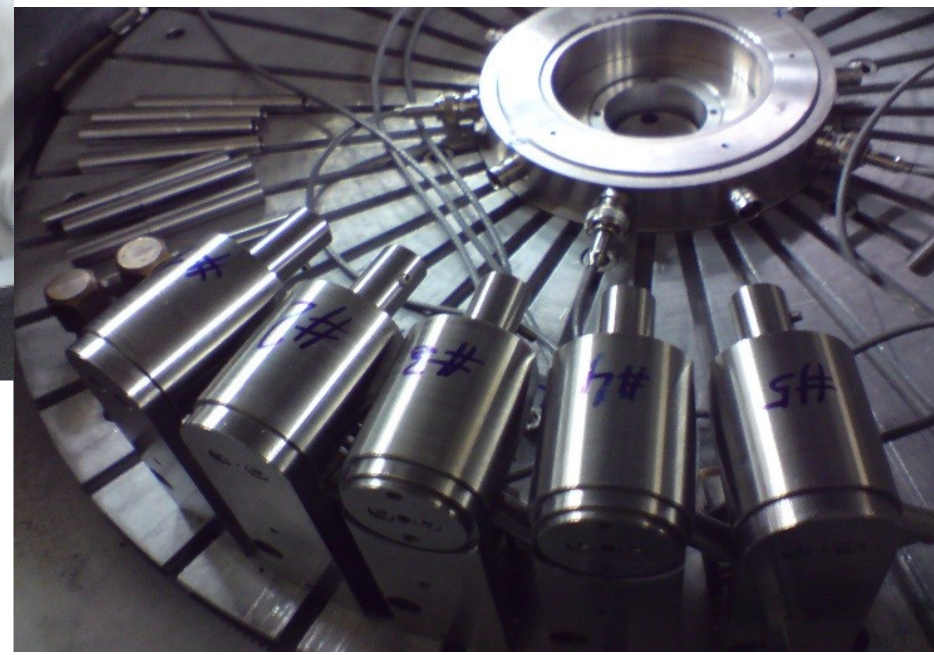
beam

BEAM in experimental hall:

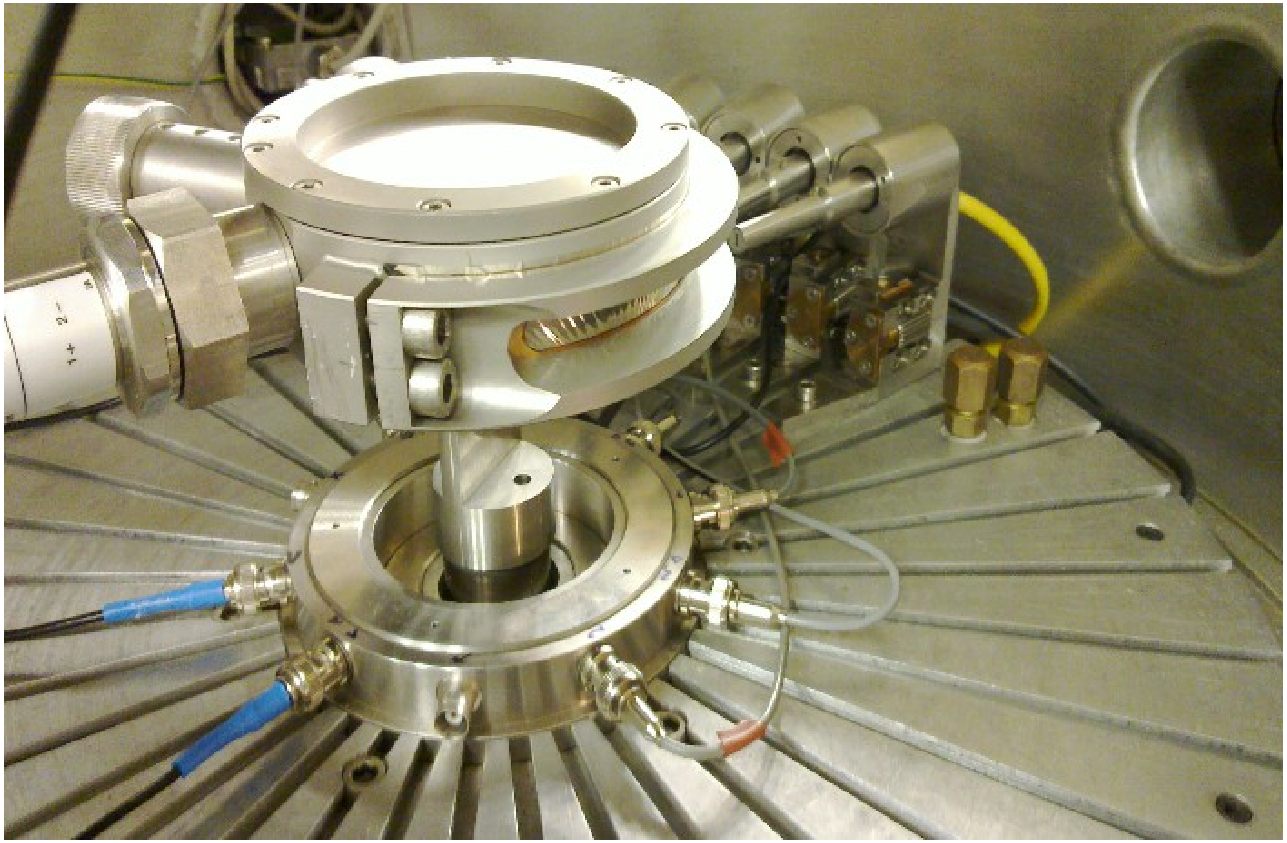
~ 10-20 nA of **3He** for (p,gamma)

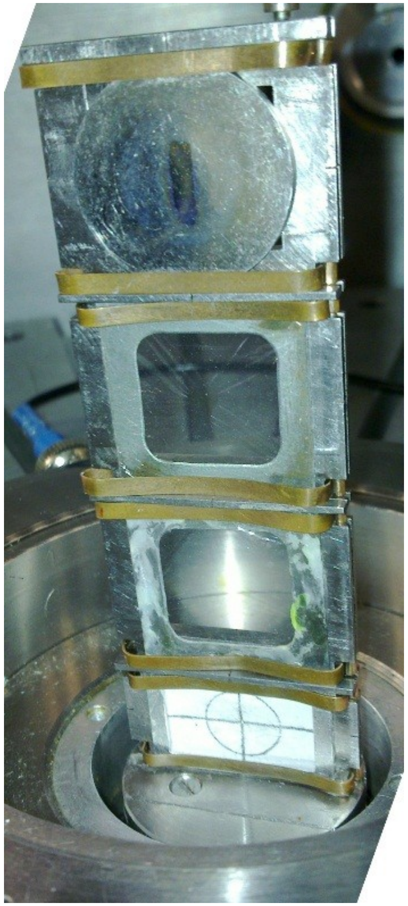
~ 10-20nA **deuteron** beam for (n,gamma) and mirror studies

Detectors setup

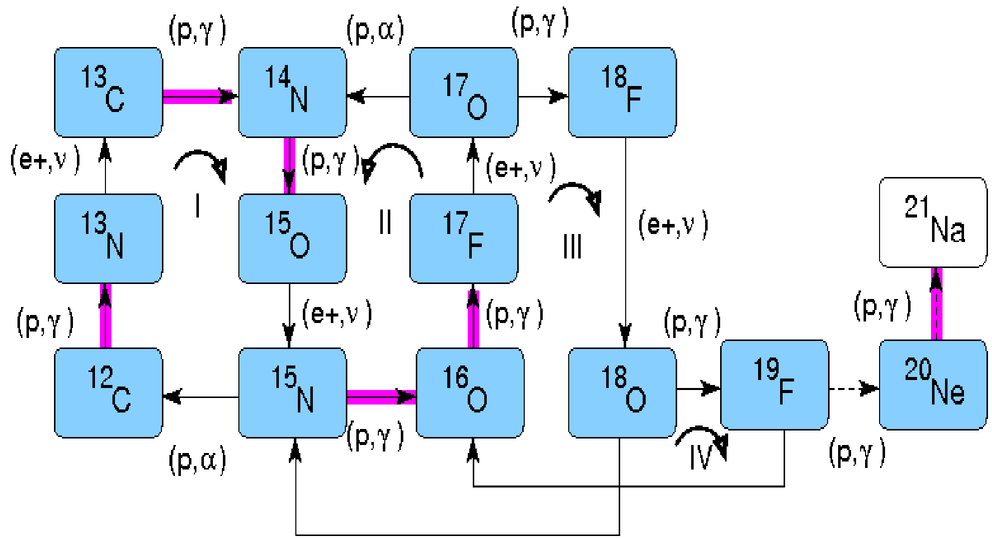


Gas and solid target setup





- $^{9}Be + p \leftrightarrow {}^{10}B$



- $^{13}C + p \leftrightarrow {}^{14}N$
- $^{14}N + p \leftrightarrow {}^{15}O$
- $^{16}O + p \leftrightarrow {}^{17}F$
- $^{15}N + p \leftrightarrow {}^{16}O$
- $^{20}Ne + p \leftrightarrow {}^{21}Na$

- $^{14}C + n \leftrightarrow {}^{15}C$
- $^{13}C + n \leftrightarrow {}^{14}C$

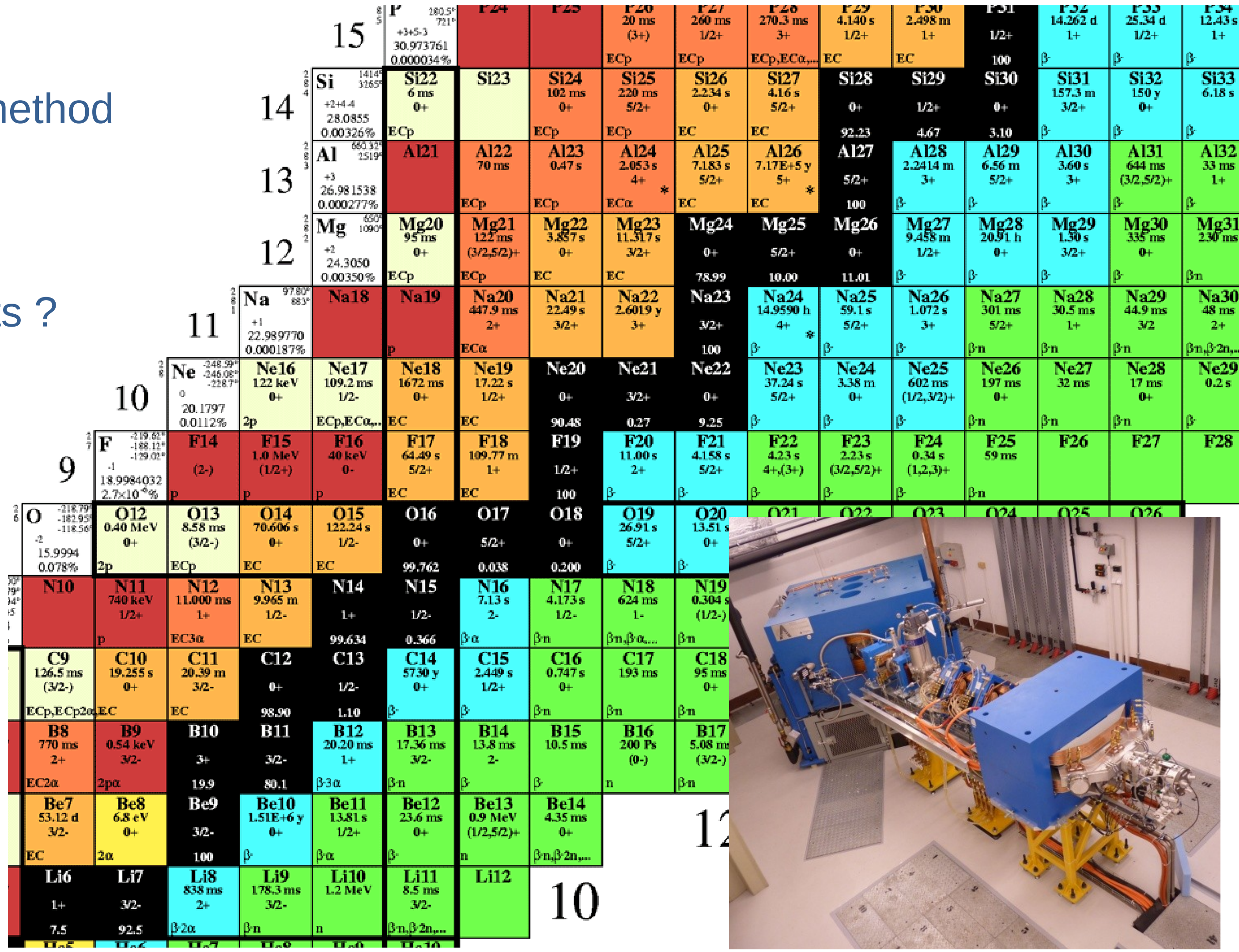
V.Kroha, S.Piskor, Z.Hons, V.Burjan, JM, + T A&MU (A.Mukhamedzhanov)...

retired

appearing postdocs, students
connection to GANIL/SPIRAL2 with SPIRAL2-CZ project

NPI - limited to stable targets

Limits due to the method
- **stable** targets
- nuclear scheme complexity
- (dp) reaction limits ?



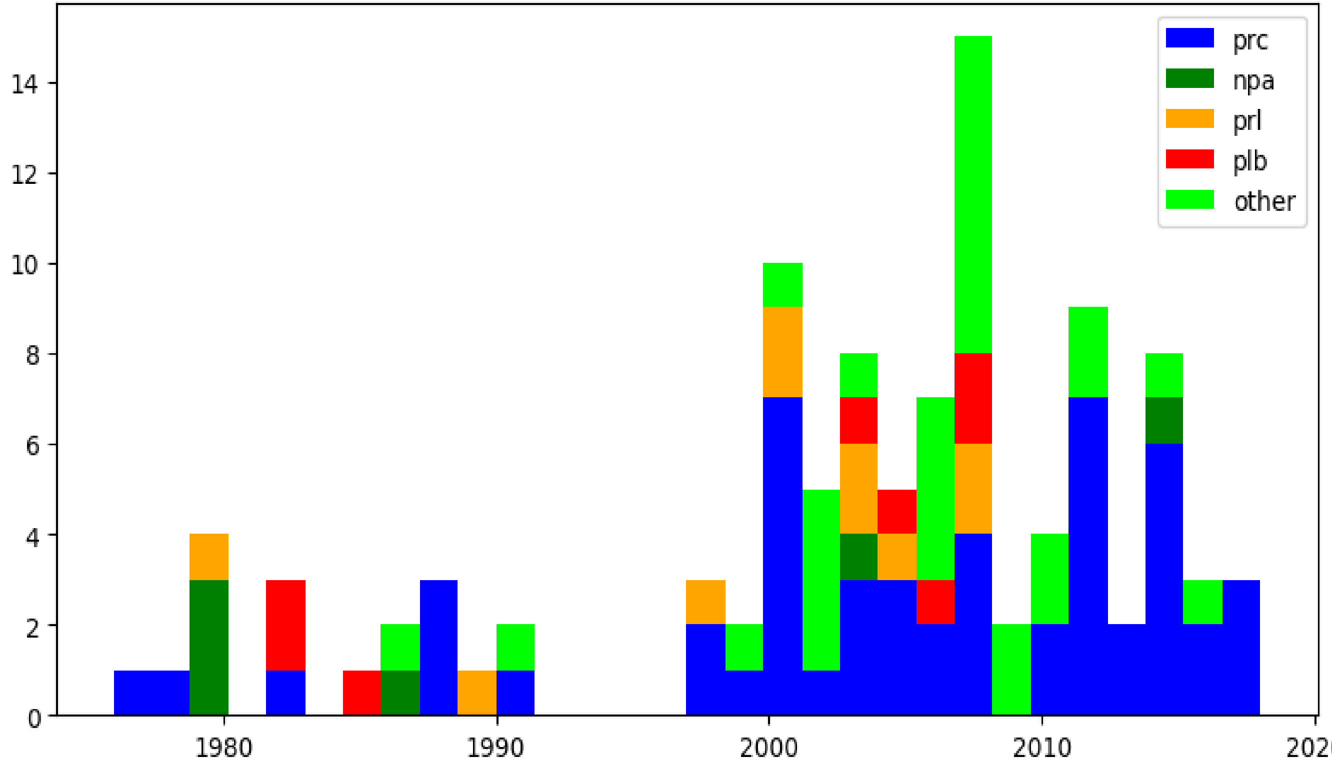
radioactive beams/targets

ANC situation

PLB 6
NPA 10
PRC 52
PRL 8

total 104

Articles with “Asymptotic Normalization” in a title



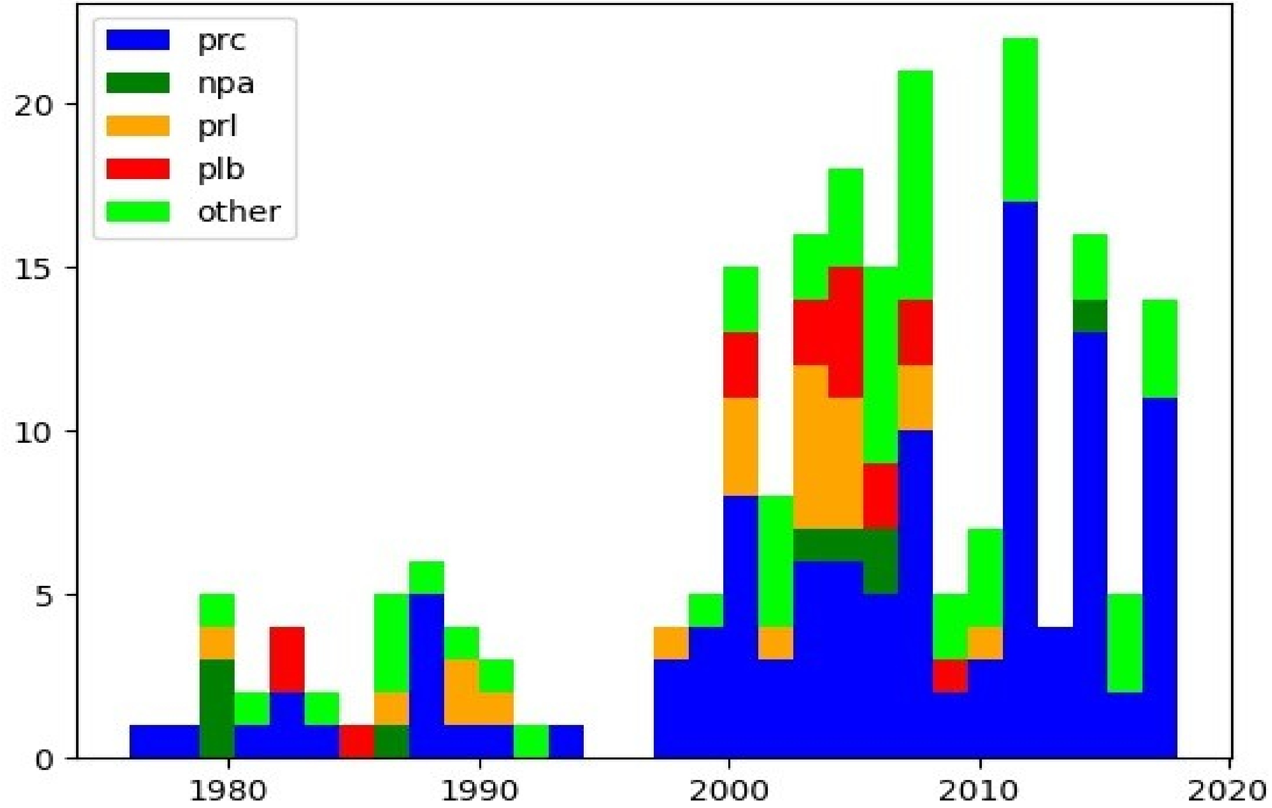
ANC situation

PLB 16
NPA 22
PRC 111
PRL 9
other 53

total 234

not complete...

+ Articles with “Asymptotic Normalization” keyword



ANC

1976 D.R.Lehman, B.F.Gibson
Integral relation for the A.N. of the Triton
Phys.Rev.C13, 35 (1976)

3 body problem

1994 H.M.Xu, C.A.Gagliardi, R.E.Tribble, A.M.Mukhamedzhanov, N.K.Timofeyuk
Overall Normalization of the Astrophysical S Factor an the Nuclear Vertex Constant for 7Be(p,gamma)8B Reactions
Phys.Rev.Lett 73 (1994) 2027

theory

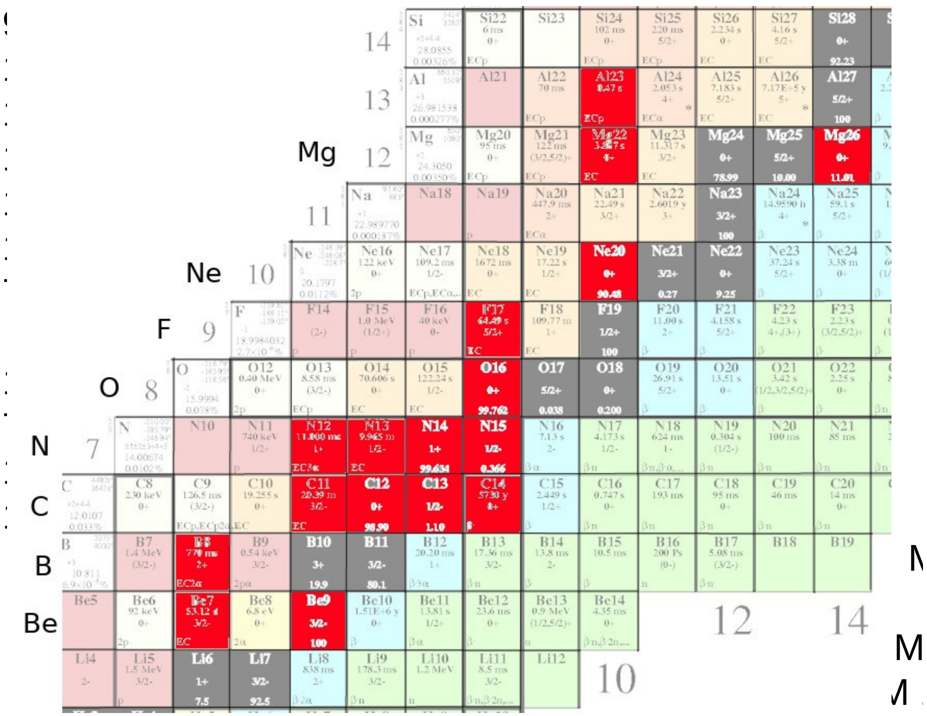
S17(0) : 22.5eVb -> 17.6 eVb

1990 A.M.Mukhamedzhanov, N.K.Timofeyuk
Astrophysical S-factor for the reaction7Be+p->8B+gamma
Pisma Zh.Eksp.Teor.Fiz. 51, No.5, 247-249 (1990) ... Uzbekistan

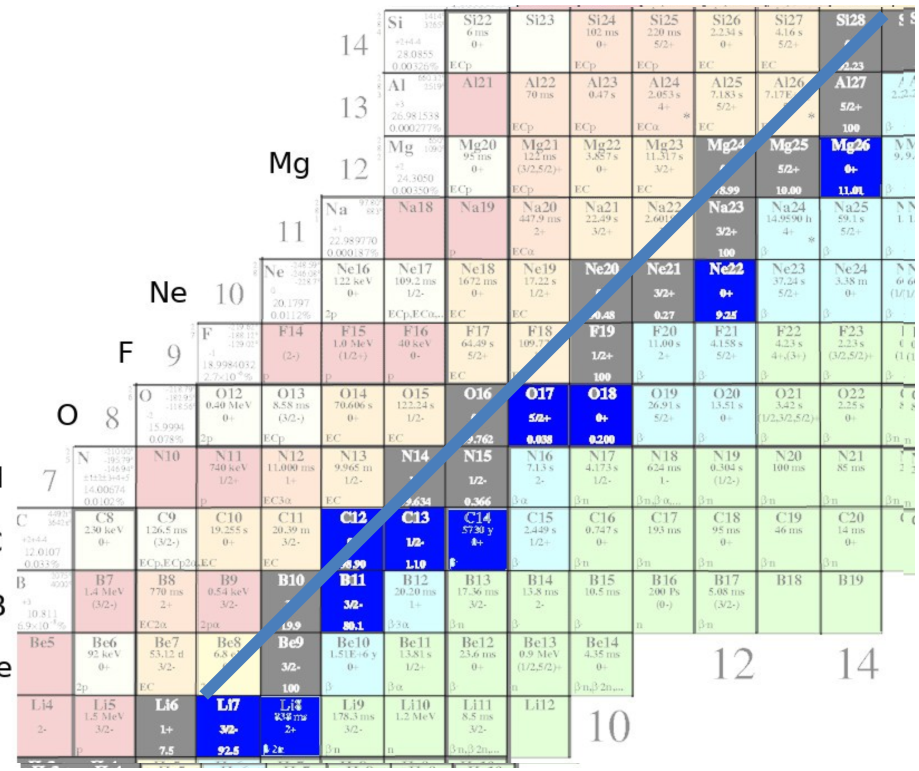
S17(0) : 15.5 eVb

3 body problem

2018 M.L.Avila et al. Phys.Rev.C97, 014313 (2018)
Sub-Coulomb 3He transfer and its use to extract three-particle ANC
6Li(13C,t)16O



15N (p,gamma) 2008
12C (p,gamma) 2008
16O (p,gamma) 2009
13C (p,gamma) 2008
15N (p,gamma) 2010
22Ne (n,gamma) 2010
14C (n,gamma) 2011
22Mg (p,gamma) 2011
23Al (p,gamma) 2012



7Li (n,gamma) 2013 - (8Li,7Li)
14C (n,gamma) 2014 SF
17O (n,gamma) 2014 AlAbdulah
8B (p,gamma) 2015 Fukui, Ender (2013)
17F (p,gamma) 2017 Kuvin
20Ne (p,gamma) 2017 (low)
12N (p,gamma) 2013 Guo

ANC method – Asymptotic Normalization Coefficients

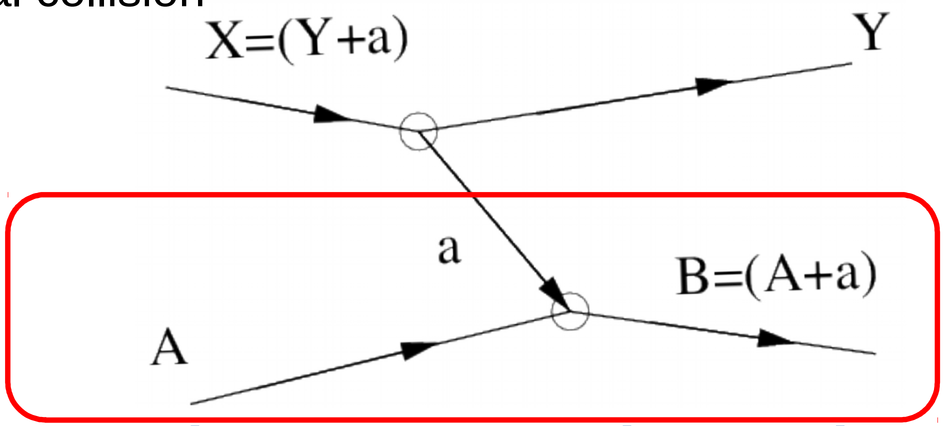
Tool to deduce a **direct** radiative capture $a + A \rightarrow B + \text{gamma}$

$$\sigma \sim G^2_{ABa}$$

The trick:

- determine the vertex constant(s)/ANCs $X+A \rightarrow Y+B$
  from binary reaction in peripheral collision

$$\sigma \sim G^2_{XYa} G^2_{ABa}$$

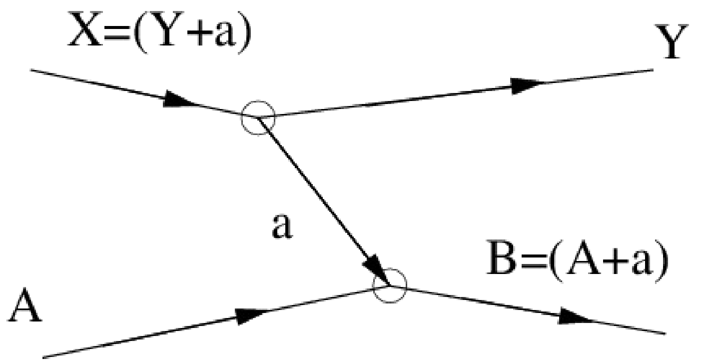


In low energy nuclear reactions

G is nuclear vertex constant NVC

but more than that

DWBA - distorted wave Born approximation



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

$I^c_{a,b\ l_c j_c}(r)$ being the **radial overlap function**

Approximated by (**model**) **bound state wave** function $\phi_{n_c l_c j_c}(r_{ab})$

Shell model,
Woods-Saxon well

$$I^c_{abl_c j_c}(r_{ab}) = S^{1/2}_{abl_c j_c} \phi_{n_c l_c j_c}(r_{ab})$$

Spectroscopic Factor

extension to Monday's discussion

What are the conditions for the transfer reaction to study ANC?

Experimental

peripherality 7-10 MeV/A for fenom.OP
for (n,gamma): what with L=0?
beam / target (light beams+ stable targets limited)
level complexity (stable sd-shell nuclei)
state of the art detection systems for inverse kinematics ?

Theoretical

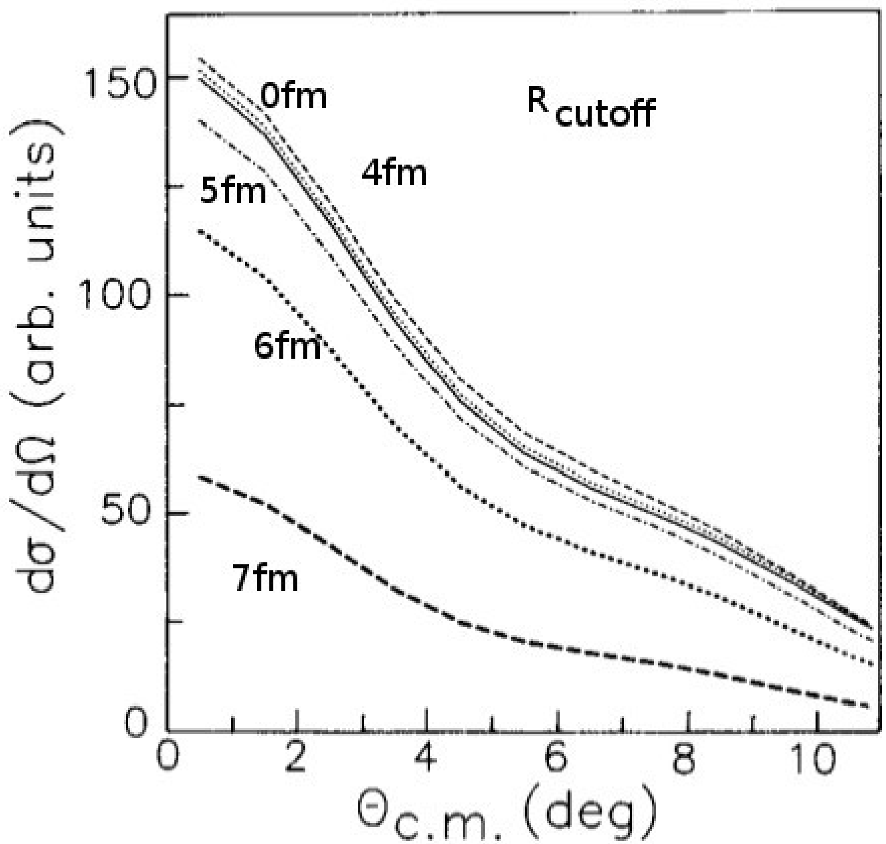
potential selection - (discussion on Monday)
reaction selection (natural question)
- uncertainty of the 2nd $|C|^2$?
- (3He,d) nice - but as a target?
- (d,p) not so much - (t,d)?
- (d,n) used nowadays in inv.kin. - comments?
n-detection, 3-body problem

Practical

Sources for ANC
impact of ANC on astrophysical S factor
Using mirror reactions
Spectroscopic Factor improvements using ANC
Nuclear radius measurement - (method of 2nd choice?)

ANC - Reaction peripherality from 9Be(p,gamma)

To verify a peripherality of the reaction in experimental conditions, several checks are done.
- optical potentials were deduced first from the angular distributions

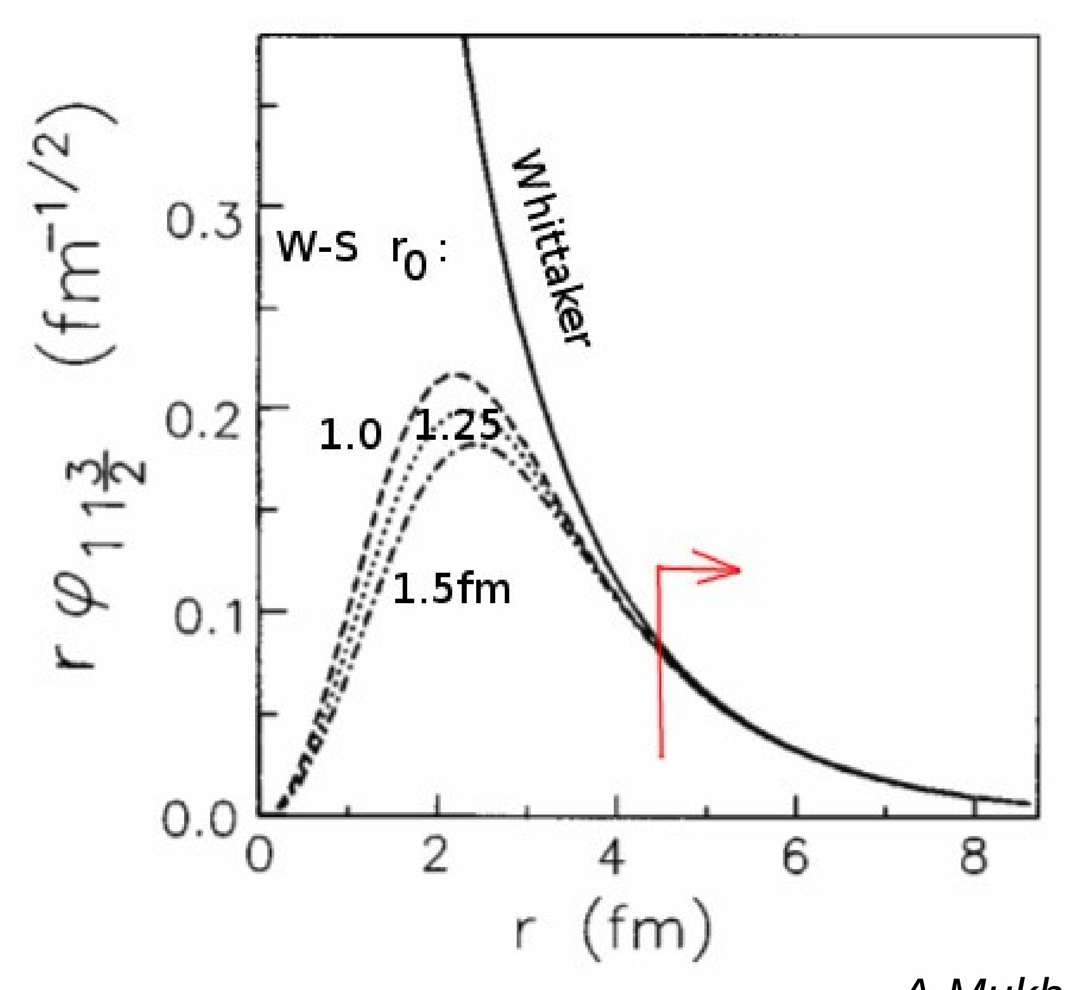


cross section.behavior
without interior(R_{cutoff})

different integration cutoff used to prove the small dependence on the interior

A.Mukhamedzhanov et al.,PhysRev56,1302

from 9Be(p,gamma)



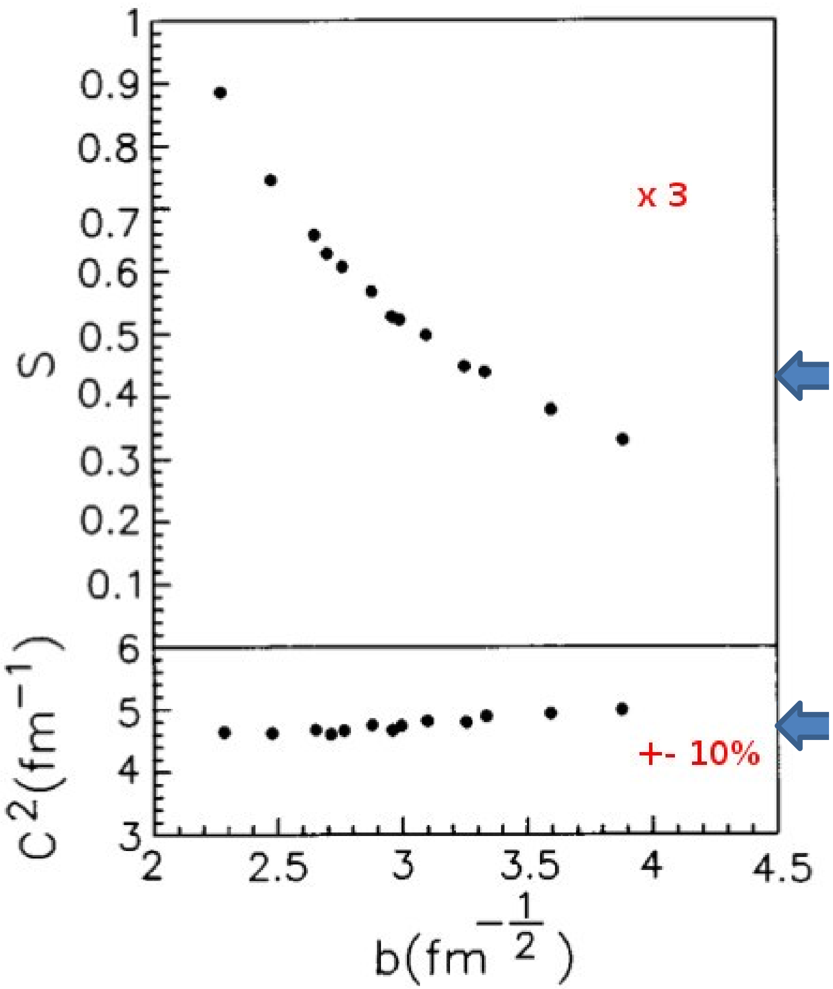
Radial asymptotic (<u>normalized</u>)

Asymptotics of s.p. bound state w.f. for different W-S parameters r0

correspond to Whittaker f.

A.Mukhamedzhanov et al.,PhysRev56,1302

from 9Be(p,gamma)



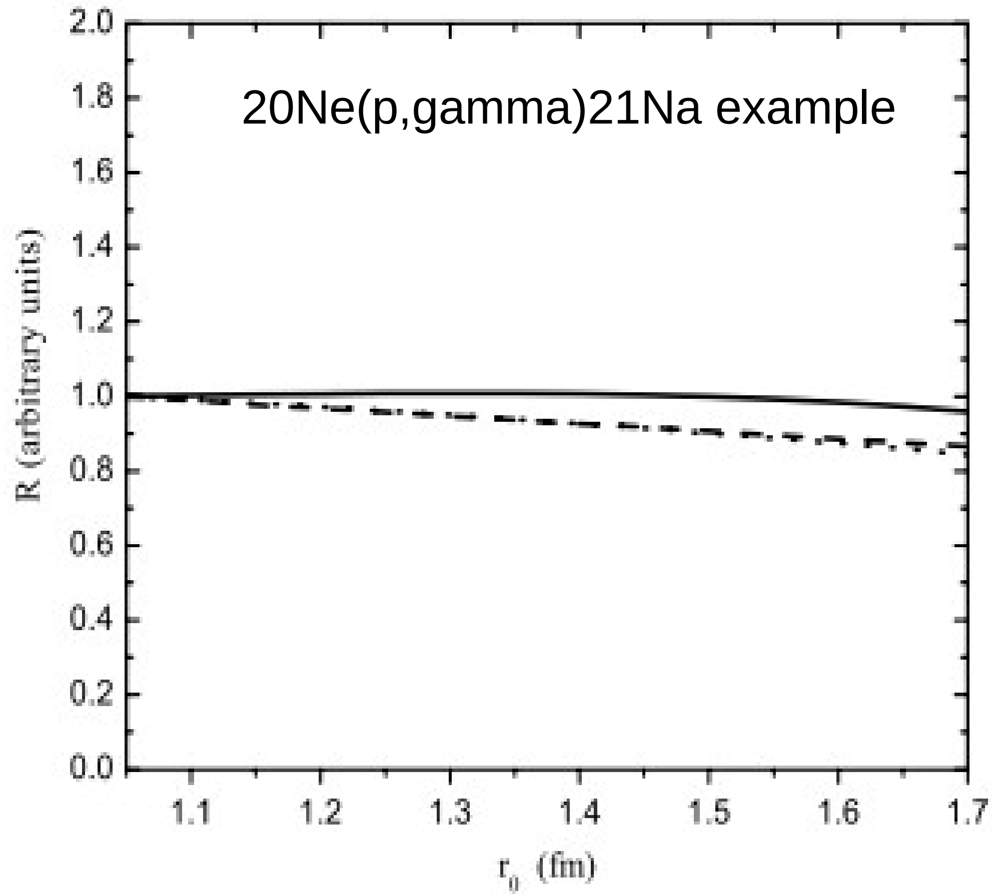


FIG. 5. The ratio R for three transitions from the $^{20}Ne(^3He,d)^{21}Na$ reaction. The solid line and dashed and dotted curves are for the transitions to the subthreshold state, the ground state, and the first excited state, respectively.

Optical Potential questions

(d,p) reaction usage problem

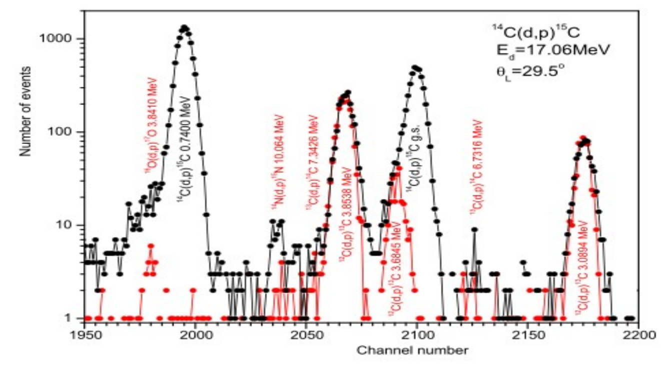
- 14C(d,p)
- nice illustration on 26Mg(n,gamma)
- what to use - CDCC ? FR-ADWA ? different reaction ?

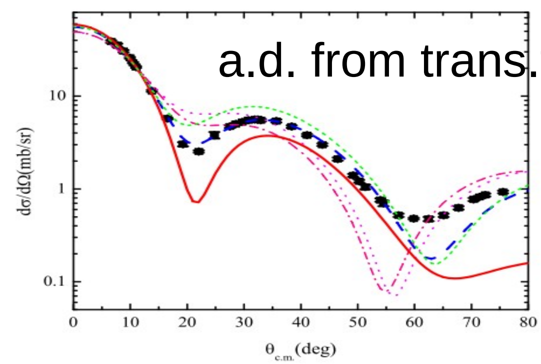
^{14}C(n,gamma)

A.M.Mukhamedzhanov et al., Phys.Rev.C84, 024616 (2011)

ANC for the ^{14}C(n,gamma)^{15}C from (d,p) reaction

- 'depletes' ^{14}C in inhomogenous big bang models (production A>20)





a.d. 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%)
- 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
1.64+-0.26	**NPI CAS**

JLM	**C²(14C,15C)**	**2.09 +- 0.29 fm-1**
ADWA	**C²(d,p)**	**1.77 +- 0.21 fm-1**

McCleskey, A.M.Mukhamedzhanov et al., Phys.Rev.C89, 044605 (2014)

PHYSICAL REVIEW C, VOLUME 61, 064616

How unique is the asymptotic normalization coefficient method?

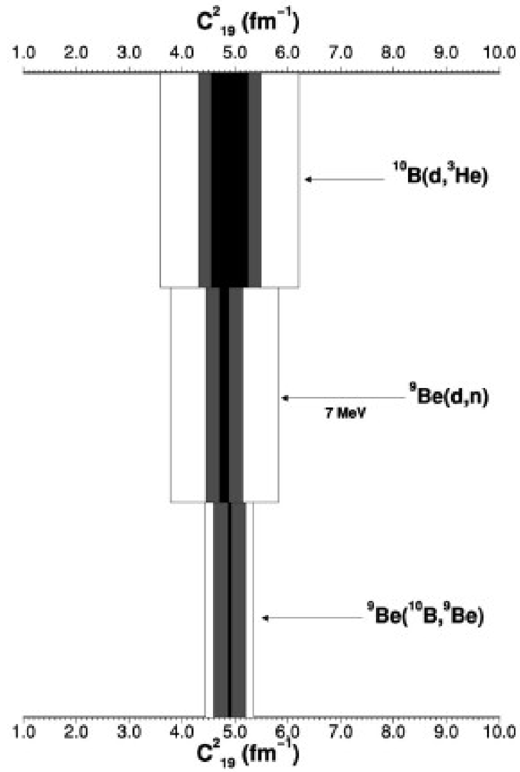
J. C. Fernandes* and R. Crespo†
Departamento de Física, Instituto Superior Técnico, and Centro Multidisciplinar de Astrofísica (CENTRA), Av. Rovisco Pais 1096 Lisboa Codex, Portugal

F. M. Nunes‡

How unique is ANC deduced from different transfer reactions or at different energies ?

What is the actual answer?

Because we (NPI CAS) have data on 26Mg(d,p) @19MeV



ANC for mirror nuclei

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

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

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

there exists a link between C_n and Γ_p

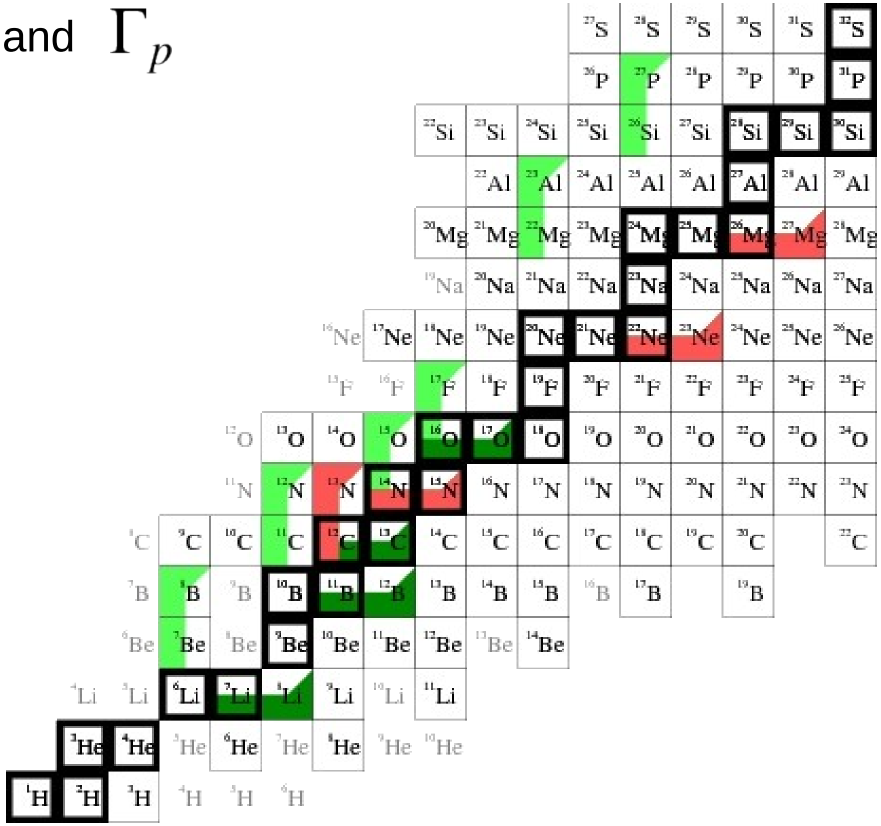
$$\Gamma_p / |C_n|^2 = \mathcal{R}_\Gamma \approx \mathcal{R}_0^{res} = \frac{\kappa_p}{\mu} \left| \frac{F_l(\kappa_p R_N)}{\kappa_p R_N j_l(i\kappa_n R_N)} \right|^2$$

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

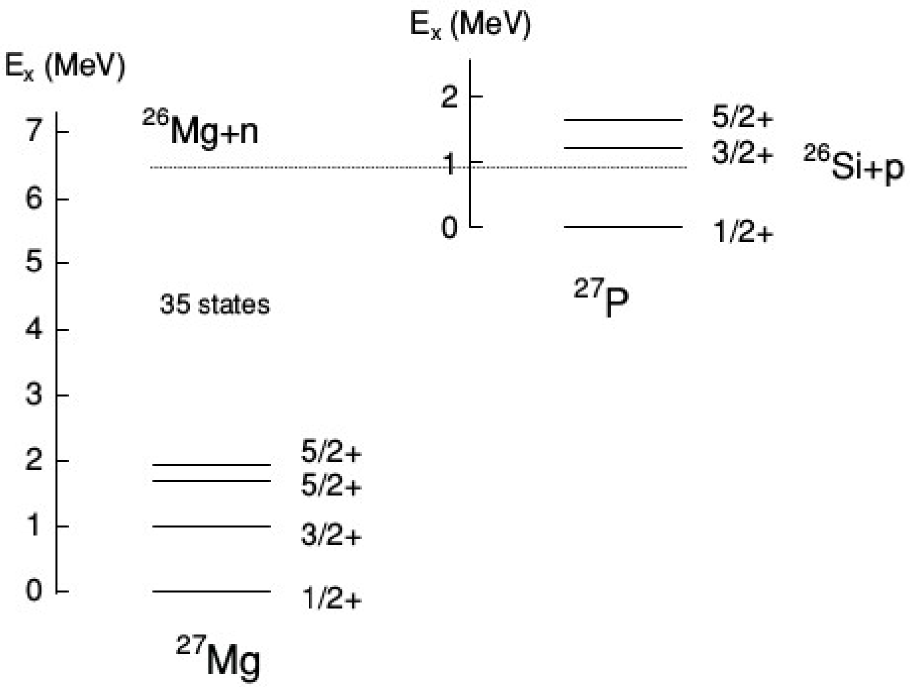
- microscopic cluster model calculations should be used to deduce mirror ANC,

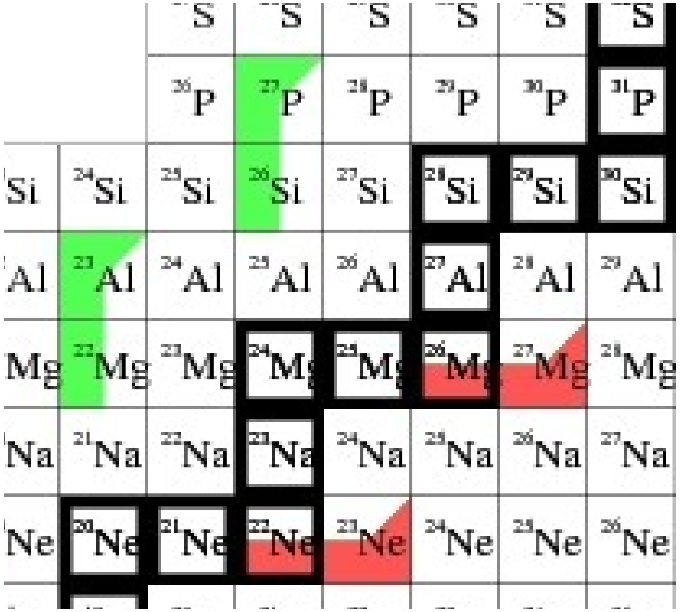
- or simultaneous use of the above analytical formulae and single-particle estimate.

Core polarization effects created 12%.

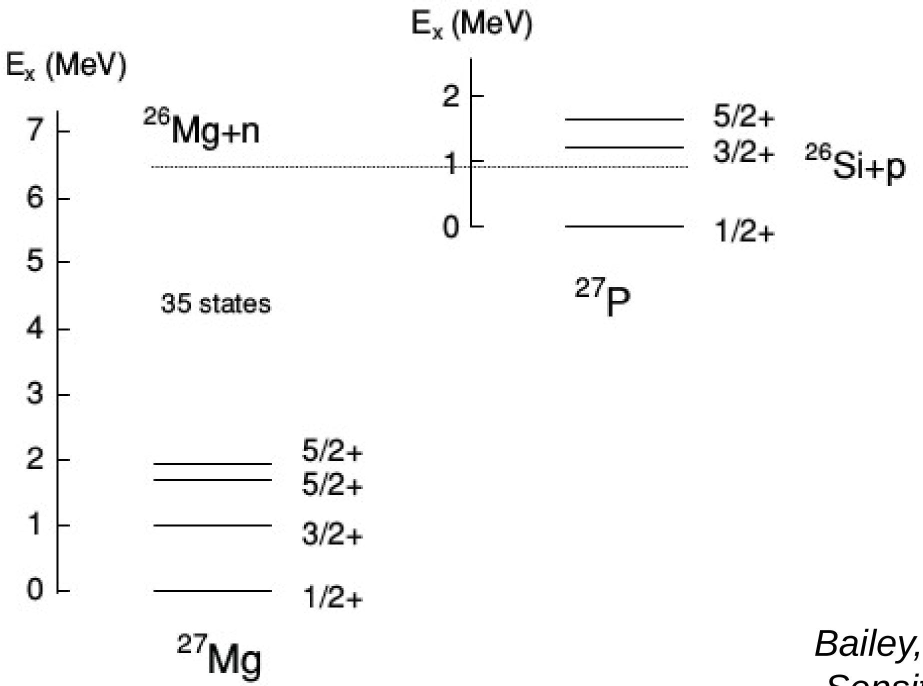


Case of $^{26}Mg(d,p)$ for ^{27}P





Case of ^{26}Mg(d,p) for ^{26}Si(p,g)



	Guo	Timofeyuk
½+	44+-5	24.5 +- 5
3/2+	3.4+-0.3	1.1+- 0.15

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

Timofeyuk, Descouvemont, Thompson
PRC78 (2008)
reanalysis of (t,d) data
theoretical arguments against (d,p)

Bailey, Timofeyuk, Tostevin, PRL117 162502 (2016)
Sensitivity (d,p) to high n-p momenta, consequences

- x.s. can be very sensitive to n-p interatcions in Ad.Approx

Gomez-Ramos, Timofeyuk, PRC98 011601R (2018)
Reduced sensitivity of (dp) x.s to the deuteron model
beyond adiabatic approximation

CDCC - recom. to extend (d,p) analysis beyond Ad.approx.

Sources for ANC

analysis of elastic scattering

Irvinski et al. PRC29, 349 (1984)
Blokhintsev et al. PRC 48 2390 (1993)
...
Ramirez Suarez PRC96, 034601 (2017)

peripheral transfer reactions

9Be (p,gamma) (1997) Mukhamedzhanov et al.
...
...
17F(p,gamma) (2017) Kuvin et al. PRC96 via (d,n)

theoretical calculations

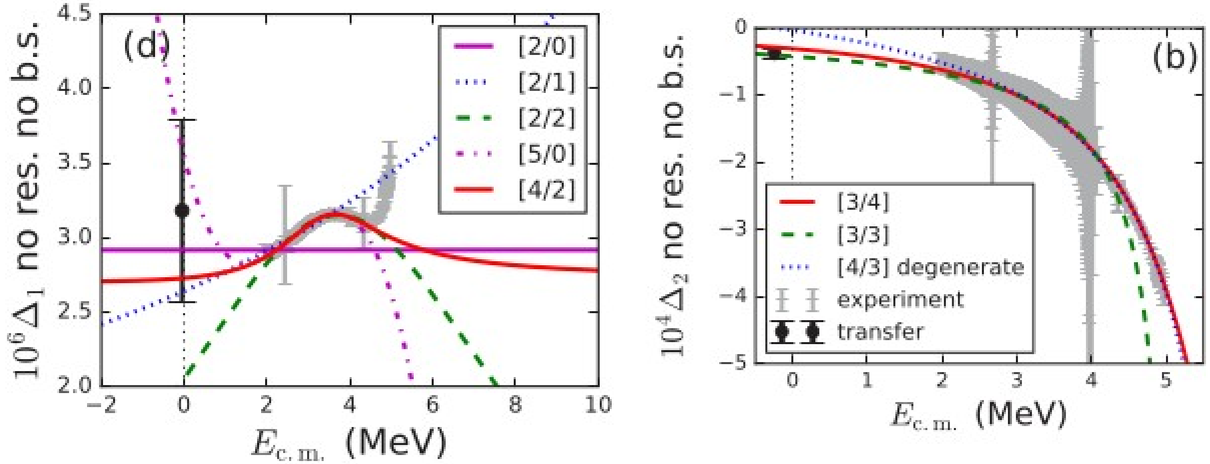
Mukhamedzhanov Timofeuyk, Sov.J.Nucl.Phys.51, 431 (1990)
...
Mukhamedzhanov PRC86, 044615 (2012)
Coulomb renormalization ANC for mirror
Timofeyuk, Phys.Rev. C 88, 044315 (2013)
SF and ANC for 0p shell nuclei

analysis of elastic scattering

Suarez-Ramirez, Sparenberg PRC 96 034601 (2017)

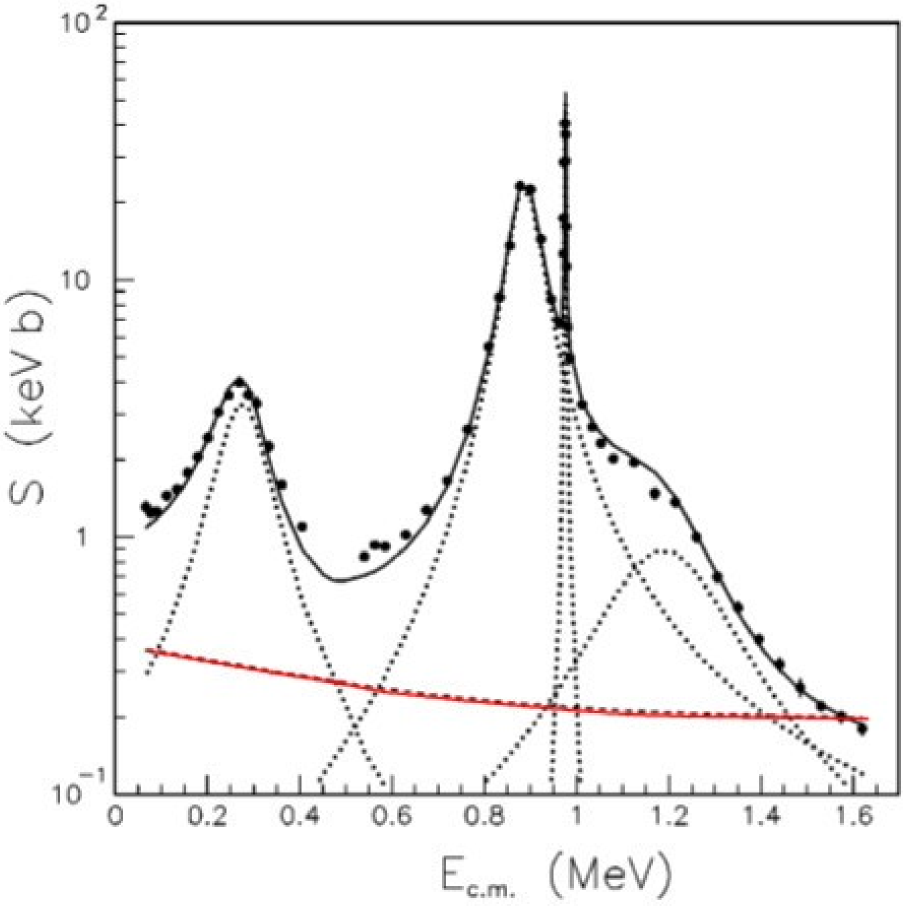
Instead of effective range function

$$\Delta_l = \frac{2\pi}{a_N}\frac{\cot \delta_l}{e^{2\pi\eta} - 1}$$



extrapolation to subthreshold state of alpha+12C

Impact of ANC



ANC values for 4 states from $^9Be(^{10}B,^9Be)$ **agree** to those from $^9Be(^3He,d)$ reaction

Later - **R-matrix** fit –

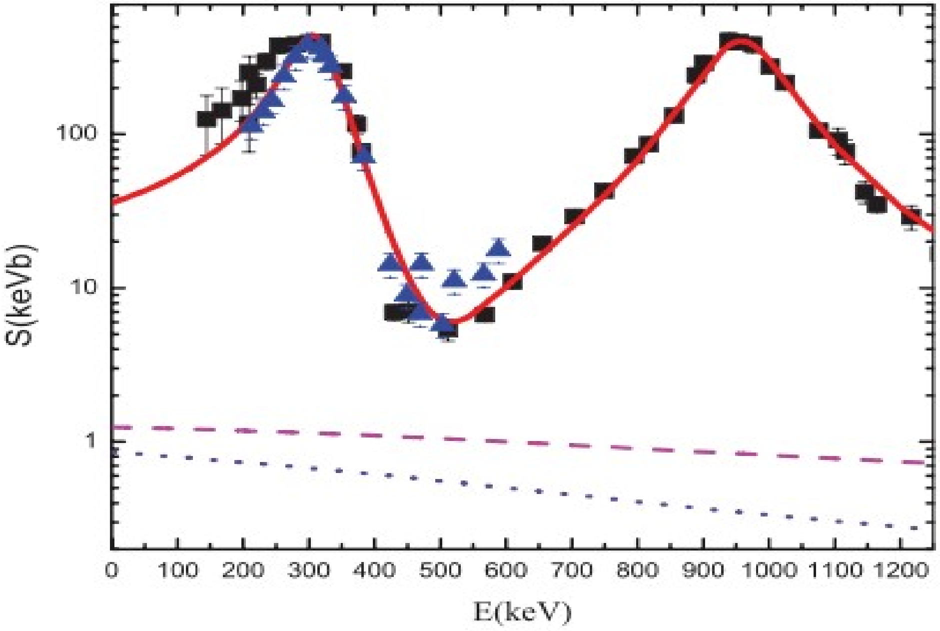
Sattarov et al. Phys.Rev C60, 035801 (TAMU)

S=3.98+-0.12 keV b @ 269 keV

~30% of S

deduced **ANC C^2=192 +- 26 fm-1** for the g.s.

- the dominated by resonant capture to g.s. through two J=1- resonances



S(0)=36.0 (6.0) keV b
… below the previous value NPA235 (1974)

rate of leak from CN cycle -
- **one in every 2200 (300) (previously 1200)**

~3% of S

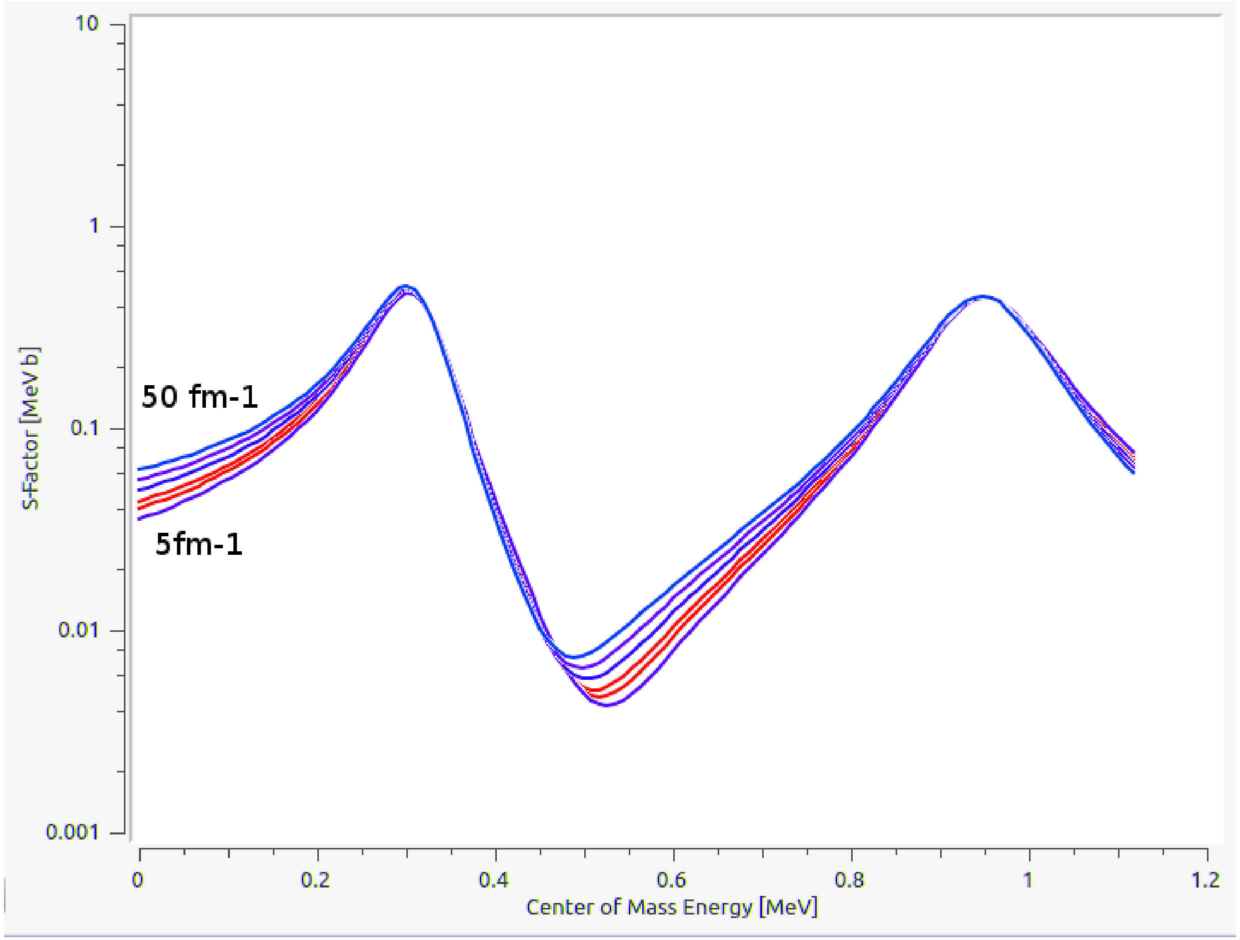
A.M.Mukhamedzhanov et al., PRC78, 015804 (2008)

Influence of ANC in R-matrix fit

Values of |C| for g.s. ^{15}N
(used for the ground state)

5 $fm^{-1/2}$ $|C|^2$ 25
13.8 $fm^{-1/2}$ $|C|^2$ 198
20 $fm^{-1/2}$
30 $fm^{-1/2}$
40 $fm^{-1/2}$
50 $fm^{-1/2}$ $|C|^2$ 2500

15% unc. in ANC
induces 2% inc. in S(0)
(if all parameters fixed)



SF – rely on internal wave functions

SF are not observables, they are not invariant under finite range unitary transformations of the phase equivalent N-N potentials

Mukhamedzhanov et al PRC82 051601 (2010)

Are occupation numbers observable?, *Furnstahl,-W. Hammer, PLB531 (2002)*

Unitary correlation in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors,
A.M. Mukhamedzhanov and A.S. Kadyrov, (2010)

SF are meaningful within the context of the model used.

Non-observability of spectroscopic factors, B.K. Jennings, (2011)

Complementing SF with ANC

Akram Mukhamedzhanov came with idea -

DWBA transition amplitude

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

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

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

A.Mukhamedzhanov, F.Nunez, PRC72, 017602 (2005)

Complementing SF with ANC

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

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

to split inner part and outer part of the DWBA amplitude

depends on b **fixed by ANC in a peripheral reaction**

$$M = K_{n,lj}\; M_{int}[b] + K_{n,lj}\; b_{n,lj}\; M_{ext}$$

K has a sense of S

$$\sum_{M_a} \langle \chi_f^{(-)} I_{Aa}^B | \Delta V | I_{Ya}^X \chi_i^{(+)} \rangle_{r<R} \qquad \sum_{M_a} \langle \chi_f^{(-)} I_{Aa}^B | \Delta V | I_{Ya}^X \chi_i^{(+)} \rangle_{r>R}$$

M is divided by ANC and ...

A.Mukhamedzhanov, F.Nunez, PRC72, 017602 (2005)

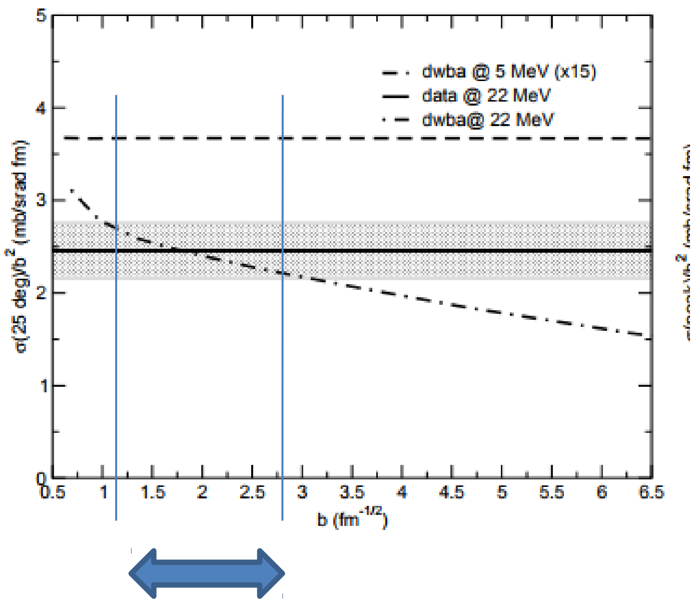
Complementing SF with ANC

The idea can be written as two new functions – theoretical and experimental

$$R^{DW}(b_{n,lj}) = \left| \frac{\tilde{M}_{int}[b]}{b_{n,lj}} + \tilde{M}_{ext} \right|^2 \quad = \quad R^{exp} = \frac{d\sigma^{exp}}{d\Omega} / C_{lj}^2$$

imposing **equality** between the two will provide a correct **b**nlj and thus a correct **S=C/b**

the procedure to find **SF** looses an artificial degree of freedom - *calculation on ^{208}Pb*



DWBA prediction adiabatic

DWBA prediction

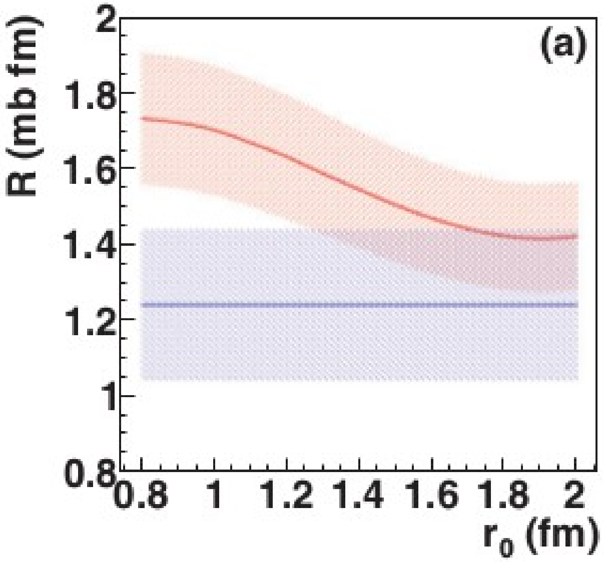
^{14}C(n,gamma) @ TAMU

14C(n,gamma) – neutron capture 13C(14C,15C)12C and on deuterium target

C^2(g.s.) 1.88 +- 0.18 fm-1

1st experiment trying to complement SF with ANC deuterons 60MeV

reaction with 60MeV d
was expected
to be nonperipheral



analysis gives a range for SF 1.62 - 1.18
BUT other methods (mirror) <= 0.95 !
... bad momentum matching

McCleskey, A.M.Mukhamedzhanov et al., Phys.Rev.C89, 044605 (2014)

ANC is observable - are there other applications of ANC?

nuclear radii measurements:

16N Li, Guo
13C, 11Be Belyaeva 2014
8Li Howel
9C Guo 2005
8B 2001
12B,13C 2001

`

ANC under breakup energy - can they help enlighten the situation with (d,p) ?

Thank you

Can new theories improve the situation or CDCC is the final step?

Not only Yarmukhamedzhanov but also Mukhamedzhanov creates a **new reaction theory:**

A.M.Mukhamedzhanov, PRC 84, 044616 (2011)
Theory of deuteron stripping: From surface integras to a generalized R-matrix approach