Testing the ANC method

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in collaboration with

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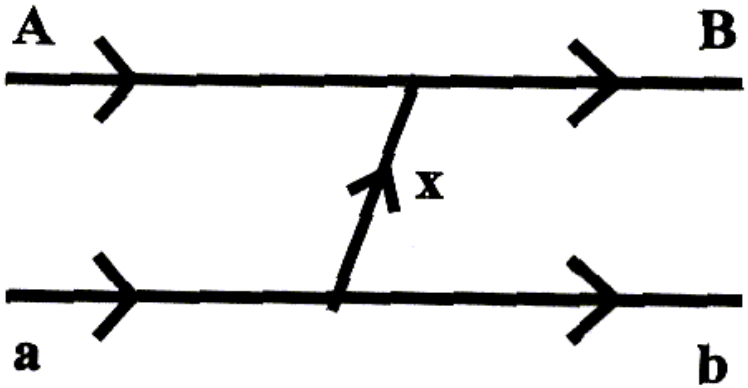
What is an ANC?

Asymptotic Normalisation Constant for $b + x \rightarrow a + \gamma$ vertex is the normalisation of the tail of the overlap $<b|a>$.



It can be determined by measuring the transfer $a + A \rightarrow b + B$, as long as $<A|B>$ is well known and no contribution from the interior.

A little bit of theory

Mukhamedzhanov *et al.*, PRC51(1995)3472

DWBA formalism

Differential cross section ~ square of the transition amplitude

$$T_{fi} = \sum \left\langle \Psi_f^{(-)} I_{AB} \middle| V_{xb} + V_{bA} - U_{bB} \middle| I_{ab} \Psi_i^{(+)} \right\rangle$$

$\psi_f^{(-)}$ and $\psi_i^{(+)}$ are distorted waves [illegible]

I_{AB} and I_{ab} are nuclear overlap integrals $\langle A|B\rangle$ and $\langle a|b\rangle$

Peripheral Assumption

$$I_{ABlj} \approx C_{AB\,\ell j} W_{\eta\,\ell+\frac{1}{2}}(2kr)/r \quad (r >> R_N)$$

C_{ABlj} is the Asymptotic Normalisation Coefficient.

Advantages of the ANC method

- No uncertainties associated with

  single particle parameters: independent on the details of the wavefunction in the interior.

- **ANC** is the **ONLY** quantity needed to calculate S(0) **[PRL73(1994)2027]**

  No further parameters! No extrapolations!

Typical problems that arise when extracting ANC's

- Absolute normalisation of the differential cross sections
  - necessary with good accuracy
- Energy regime and angular range
  - should guarantee peripheral condition
- Dependence on optical potentials
  - should be minimised by fitting the elastic data.

Recent experimental results I

- **^{7}Be(d,n)^{8}B, $E_{c.m.}$= 5.8 MeV** [PRL 77(1996)611] $S_{17}(0) = 27.4 \pm 4.4$eV b.
  More careful analysis of same data $S_{17}(0) = 23.5 \pm 3.7 \pm 4.4$ eV b,
  first error bar is due to the model uncertainties [PRC59(1999)2856]

- **^{9}Be(^{10}B,^{9}Be)^{8}B, $E_{c.m.}$= 47 MeV** [PRC 56(1997)1302]
  C_{19} extracted with great accuracy needed to determine $S_{17}(0)$ from ^{10}B(^{7}Be,^{8}B)^{9}Be

- **^{7}Be(d,n)^{8}B, $E_{c.m.}$= 38.9 MeV** [C. Powell et al., ENAM98]
  Did not guarantee the peripheral condition PRC59(1999)2856.
  $S_{17}(0)$ could not be extracted.

- **^{7}Be(d,n)^{8}B, $E_{c.m.}$= 15.6 MeV** [D. Beaumel et al., MSU, July 1999]
  Data has not yet become available.

- **^{10}B(^{7}Be,^{8}B)^{9}Be $E_{c.m.}$= 49 MeV** [PRL82(1999)3960]
  Together with the previous ANC for <^{9}Be|^{10}B> : S_{17}=17.8 ± 2.8 eV b.
  Accuracy better than Coulomb Dissociation or direct capture measurements.

Recent experimental results II

- **$^{13}C(^{14}N,^{13}C)^{14}N$, E_{lab}= 162 MeV [L.Trache et al., PRC 58(1998)2715]**
  $C_{1\,13}$=19.5 ± 1.2 fm^{-1} extracted with great accuracy to determine
  $S_{17}(0)$ from $^{14}N(^{7}Be,^{8}B)$

- **$^{14}N(^{7}Be,^{8}B)^{13}C$, E_{lab}= 85 MeV [A. Azhari et al., PRC 60, 055803]**
  Using the previous results S_{17}=16.6 MeV ± 1.9 eV b !

- **$^{13}C(^{3}He,d)^{14}N$, E_{lab}= 26.3 MeV [P. Bem et al., PRC 62, 024320]**
  $C_{1\,13}$=18.7 ± 1.3 fm^{-1} in agreement with the previous results.

- **$^{12}C(^{6}Li,d)^{16}O$, E_{lab}= 1.5 to 2.5 MeV [C. Brune et al., PRL 83(1999)4025]**
  extracting the information for $^{12}C(\alpha,\gamma)^{16}O$:
  S_{E1}(0.3 MeV) = 101 ± 17 keV b and S_{E2}(0.3 MeV) = 42_{-23}^{+16} keV b

First test on ANCs

Gagliardi *et al.*, PRC(1999)1149

S(0) for $^{16}O(p, \gamma)^{17}F(5/2-,1/2+)$

were extracted from $^{16}O(^{3}He,d)^{17}F$

Agreement with direct measurements was better than 9%!

Set of transfer reactions used in our test

Best Candidate: C_{19} (^{10}B,^{9}Be)
very accurate published value for this ANC

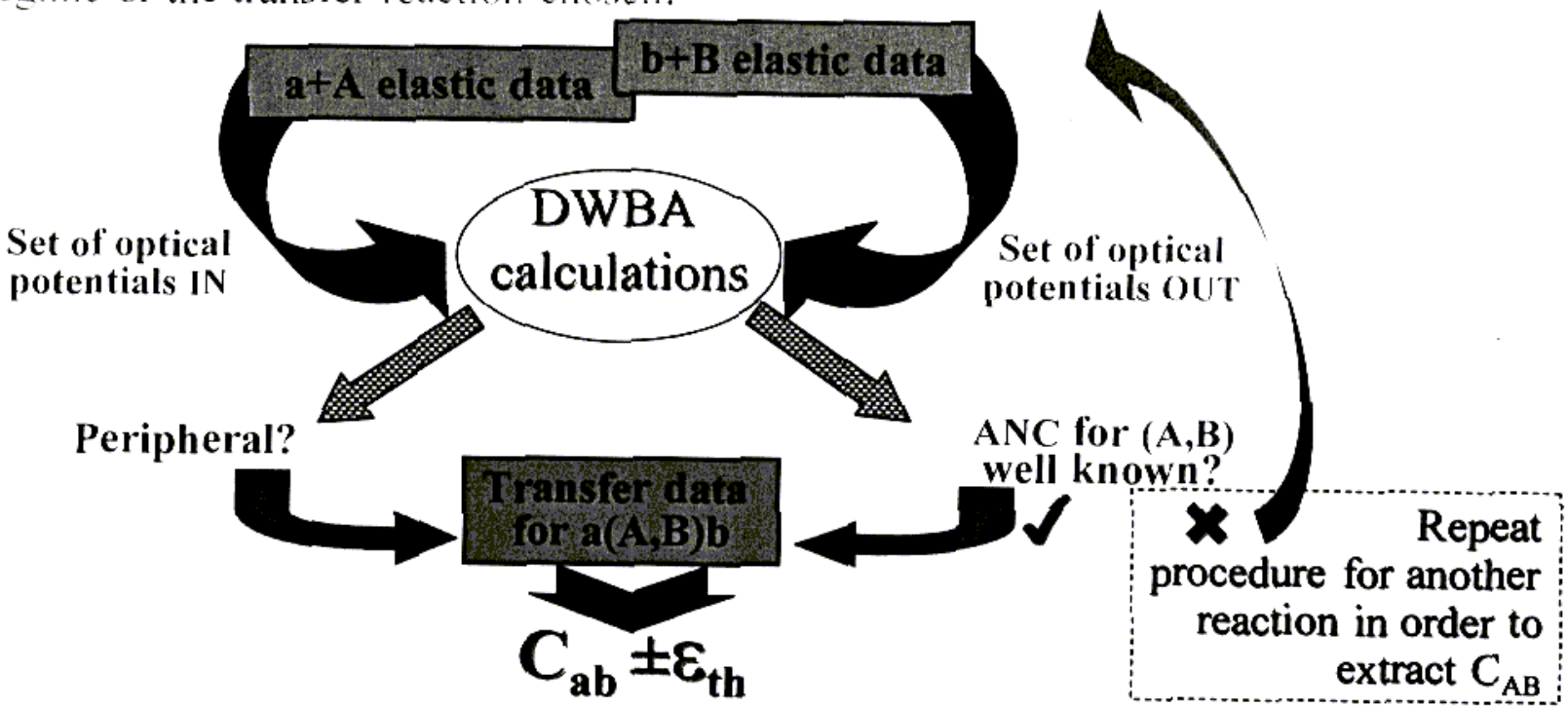
Reaction	E_{lab} (MeV)	Sys. Error	N_{exp}	θ_{min}	θ_{max}	Ref.
$^{9}Be(^{10}B,^{9}Be)^{10}B$	100	7%	7	0.5°	6.5°	PRC56(97)1302
$^{9}Be(d,n)^{10}B$	7	20%	7	5.7°	40.0°	NPA134(69)277
	15	20%	7	10.9°	44.3°	NPA134(69)277
$^{10}B(d,^{3}He)^{9}Be$	11.8	25%	3	19.2°	31.5°	NPA101(67)449
$^{12}C(^{10}B,^{9}B)^{13}N$	100	–	7	14.2°	27.0°	PRL33(74)1599
$^{12}C(d,n)^{13}N$	9	12%	6	10.8°	36.9°	NPA414(84)67
	9	16%	7	0.7°	27.1°	NPA179(72)101
	12.4	20%	4	18.0°	33.2°	NPA414(84)67

The uniqueness of the ANC method

J. Fernandes,R. Crespo, F.M. Nunes, PRC61, 064616

According to the assumptions of the ANC method, the extracted ANC should be independent of the energy regime or the transfer reaction chosen.

Aim of our work: check this property!



Numerical Results for the ANC test

- ^{7}Be(d,n) reaction at 15 MeV was not peripheral
- Inconsistencies for ^{12}C(d,n) data made it impossible to extract a reliable $C_{1\ 12}$ thus ^{12}C(^{10}B,^{9}B)^{13}N had to be eliminated

Reaction	E (MeV)	$\overline{S_{exp}}$	$\overline{\chi^2}$	$\overline{C_{19}^2}(fm^{-1})$
^{9}Be(^{10}B,^{9}Be)^{10}B	100	0.52	.80	4.90 ± 0.25
^{9}Be(d,n)^{10}B	7	0.42	4.29	4.80 ± 0.35
^{9}Be(d,^{3}He)^{9}Be	11.8	0.48	4.07	4.92 ± 0.54

Quoted uncertainties arise only from **optical model** analysis of the elastic channels

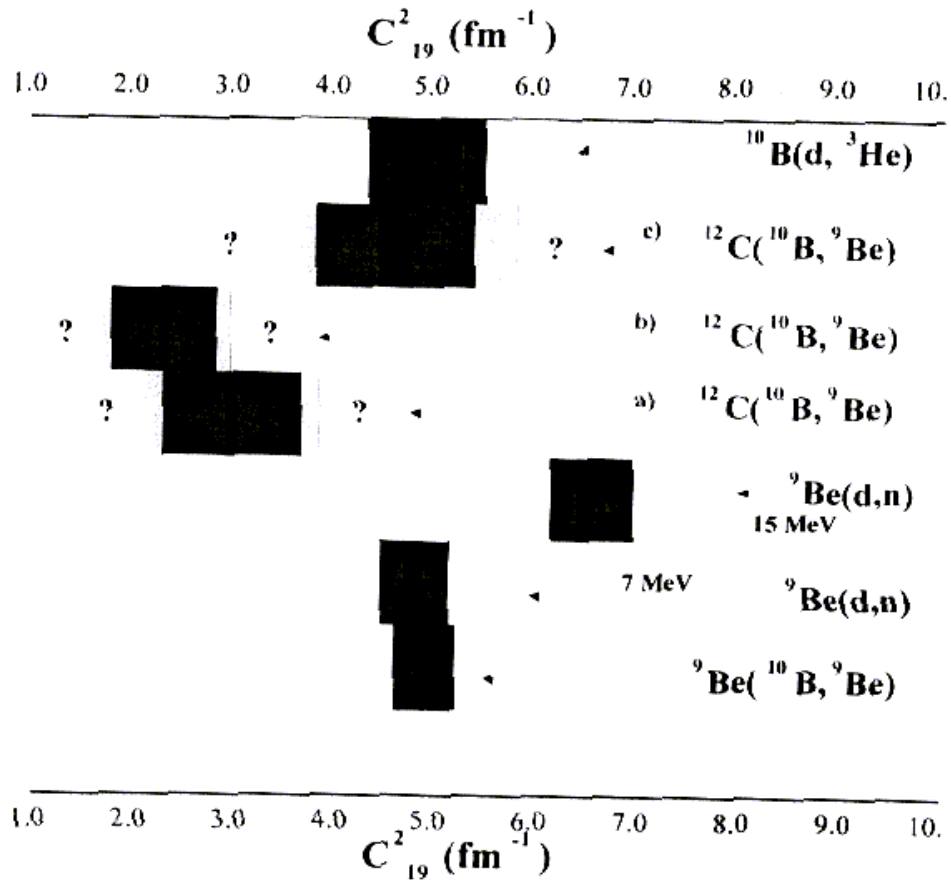
Does the ANC method pass the test?

As far as the present data set is concerned, the uniqueness property cannot be questioned.

Some of the data sets should not be used (a+b+c).

Tighter tests needed to assess validity of this method.

blue - statistical error
red - optical model error
white - systematic error



Requirements for future experiments

- Careful theoretical study to choose energy regime and angular range for measurement that ensures peripheral condition
- Measurements of the elastic scattering for entrance and exit channels
- High statistics in the region where the peripheral condition is satisfied
- Good angular resolution - typically in the forward angle region

ANC method relies on accuracy of ABSOLUTE cross section

- Low systematic errors: the target thickness should be determined with great accuracy as well as neutron detector efficiency for (d,n) reactions.

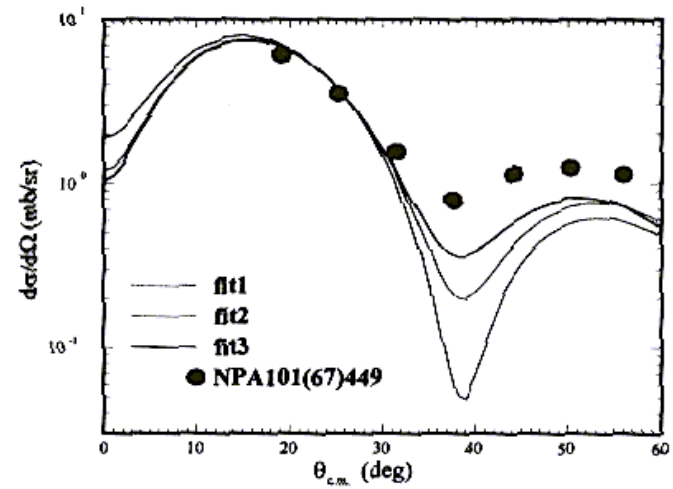
Procedure for $^{10}B(d,^3He)^9Be$ (E_{lab}=11.8 MeV)

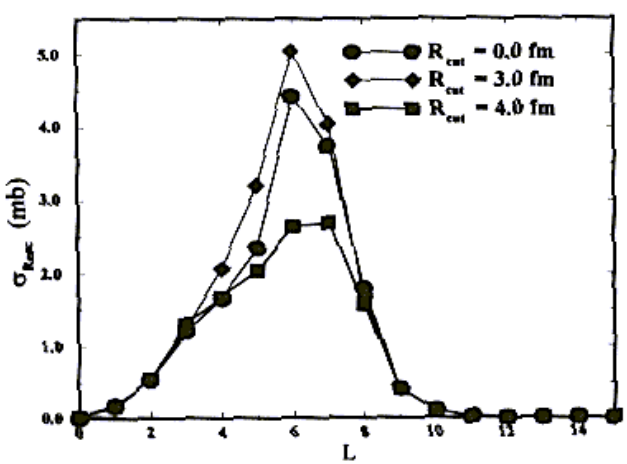
$$C_{19}^2 C_{12}^2 \propto S_{exp} \qquad S_{exp} = \frac{\sigma_{exp}}{\sigma_{dwba}}$$

Figure: predicted transfer cross section

Optical potential for entrance channel: pinned down with d + ^{10}B elastic measured with the transfer

Optical Potential for exit channel: 3 sets of data were used {NPA101(67)449; NPA95(67)639;NPA134(69)277}





Peripheral condition

Figure: L-distribution of transfer cross section.

Finally, using the established value for C_{12}^2 [PRC51(95)3472] we extract:

$C_{19}^2 = 4.92 \pm 0.54$ fm^{-2}

Motivation for Indirect Methods

Many reactions [(p,γ);(α,γ);(α,d)...] are needed at very low relative energies for primordial and stellar Nucleosynthesis

Coulomb Repulsion ⇒ cross sections for direct capture measurements are generally **very low**

Coulomb Dissociation Method
&
Asymptotic Normalisation Method
have been suggested for indirect measurements

The need for TESTS on these methods has been stressed, given the lingering scepticism among the scientific community [Rev. Mod. Phys. 70 (1998)1265].

Suggestions for future experiments to validate the method

- The (^{12}C,^{13}N) vertex should be measured with precision
  - repeating the (d,n) measurements
  - using the reaction ^{12}C(^{3}He,d)^{13}N
  - using the symmetric reaction ^{13}N(^{12}C,^{13}N)^{12}C
- The data for the **^{10}B(d,^{3}He)^{9}Be** reaction should be improved
- The **^{10}B(^{13}C,^{14}N)^{9}Be** reaction could be measured
- The transfer **^{16}O(^{10}B,^{9}Be)^{17}F** could be measured with identification of final states