Determination of the S_{17} and S_{18} astrophysical factors from transfer reactions and the breakup of ^{8}B and ^{9}C at intermediate energies[1]

L. Trache
Cyclotron Institute, Texas A&M University
College Station, TX

New indirect method to obtain nuclear astrophysical information from reactions at higher energies

Summary:

1. Introduction of method
2. From proton transfer and breakup cross sections to ANC
3. Breakup of ^{8}B and ^{9}C. Extended Glauber model calc: folding potentials and optical limit approx
4. S_{17}, S_{18} and astrophysical reaction rates for $^{7}Be(p,\gamma)^{8}B$ and $^{8}B(p,\gamma)^{9}C$
5. Conclusions

[1] ***ORNL Transfer Reactions Workshop, June 21-22, 2002***

Different approach to old nuclear astrophysics problems – a new indirect method

- Direct measurements at very low energy (10s-100s keV region) – very difficult experimentally and involve extrapolations
- Indirect methods are few:
  - Inverse reactions
  - Resonance parameters determination
  - Coulomb dissociation
  - Trojan horse method
  - Sub-Coulomb transfer
  - Proton transfer reactions – ANC method (Asymptotic Normalization Coefficient method)

  TAMU
- Use of breakup reactions at intermediate energies

- Proton transfer reactions at about 10 MeV/nucleon (not so low, accessible energies!!!) Problem(s): might involve radioactive beams and/or targets!
- Breakup of loosely bound nuclei at energies above the Fermi energy are peripheral reactions and can also be used to extract ANCs and subsequently astrophysical S-factors! We used ^{8}B breakup results at energies 30-300 MeV/u on various targets to extract the astrophysical factor S_{17} (solar neutrino problem!) and ^{9}C breakup at 285 MeV/u on 4 targets to extract S_{18}.

If successful, such a program offers a promising new method of inferring astrophysical S factors from experiments with beams of loosely bound radioactive nuclei.

Unstable Nuclear Beams were produced at Texas A&M University's K500 superconducting cyclotron (1996-2002) with **MARS** in kinematically inverted reactions induced by heavy projectiles on a cryogenic hydrogen gas target.

The beams used so far and their main characteristics:

Beam	Reaction	E/A	Intensity	Purity	Program
^{7}Be	p(^{7}Li,^{7}Be)n	12 MeV/n	10^5 part/sec	>99.5%	astrophysics
^{11}C	p(^{11}B,^{11}C)n	10 MeV/n	10^6 part/sec	>99%	astrophysics
^{20}F	d(^{19}F,^{20}F)p	32 MeV/n	2.5 10^5 part/sec	>98%	react. mech.
^{20}Na	p(^{20}Ne,^{20}Na)n	32 MeV/n	5. 10^4 part/sec	>98%	react. mech.
^{8}B	p(^{9}Be,^{8}B)2n	20 MeV/n	7. 10^4 part/sec	>98%	astrophysics
^{8}B	p(^{10}B,^{8}B)p2n	12 MeV/n	0.5 10^4 part/sec	>98%	astrophysics
^{13}N	p(^{13}C,^{13}N)n	15 MeV/u	10^6 part/sec	>99%	astrophysics

Other beams were produced and used in decay study programs: ^{57}Cu, ^{62}Ga, ^{22}Mg, ^{30}S, ^{34}Ar, ^{35}Ar, ^{48}Cr, …

Direct Radiative proton capture

$$\sigma \propto |M|^2 \qquad [S(E) = Ee^{2\pi\eta}\sigma]$$

$$M = \left\langle \phi_A(\xi_B, \xi_p, \xi_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \phi_B(\xi_B)\phi_p(\xi_p)\psi_i^{(+)}(r_{Bp}) \right\rangle$$

$$M = \left\langle I_{Bp}^A(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

$$I_{Bp}^A(r_{Bp}) \overset{r_B > R_N}{\approx} C_{Bp}^A \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

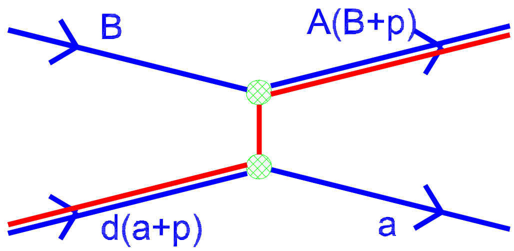
Find:

$$\sigma_{capture} \propto (C_{Bp}^A)^2$$

where $I_{Bp}^A(r_{Bp})$ are the overlap integrals, W is the Whittaker function and C_{Bp}^A the asymptotic normalization coefficients (ANC).

They can be obtained from other peripheral phenomena: proton transfer reactions and breakup!

Transfer Reactions



Transition amplitude: $$M = \sum \left\langle \chi_f^{(-)} I_{Bp}^{A} \middle| \Delta V \middle| I_{ap}^{d} \chi_i^{(+)} \right\rangle$$

Standard approach: $$I_{ap}^{b} = \sum S_{ap}^{\frac{1}{2}} \phi_{n_d l_d j_d}(r_{ap})$$

$$\frac{d\sigma}{d\Omega} = \sum S_{Bpl_A j_A} S_{apl_d j_d} \sigma_{l_A j_A l_d j_d}^{DW}$$

Peripheral transfer: $$I_{Bp}^{A} \overset{r_{Bp} > R_N}{\approx} C_{Bp}^{A} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

$$\frac{d\sigma}{d\Omega} = \sum C_{Bpl_A j_A}^{2} C_{apl_d j_d}^{2} \left(\frac{\sigma_{l_A j_A l_d j_d}^{DW}}{b_{Bp}^{2} b_{ap}^{2}}\right)$$

Spectroscopic factors vs. ANCs

Two issues:

A. Legitimacy of writing for any region, inside and outside the nucleus:

$$\Psi_{J^\pi} = \sum S^{1/2}(c,nlj)\left[\Phi_c^\pi \otimes \varphi_{sp}(nlj)\right]^{J^\pi}$$

(independent particles in a mean field)

or, only for the peripheral region, ***$r>R_N$***

$$I_{bp}^a \to C(c,nlj)\frac{W_{-\eta,l+1/2}(2\kappa r)}{r}$$

B. Practical: choice of the s.p. wave functions $\varphi_{sp}(nlj)$, or equivalent choice of the geometry of the proton binding potential *(r_0,a)*.

In either formulation:

$$S_{nlj} = \frac{\sigma_{\exp}}{\sigma_{calc}}$$

or

$$C_{nlj}^2 = \frac{\sigma_{\exp}}{\sigma_{calc} / b_{nlj}^2}$$

Need good experimental data!

Need good, reliable, calculations!!!

Treat here: ^{7}Be(p,γ)^{8}B - solar neutrino problem!!

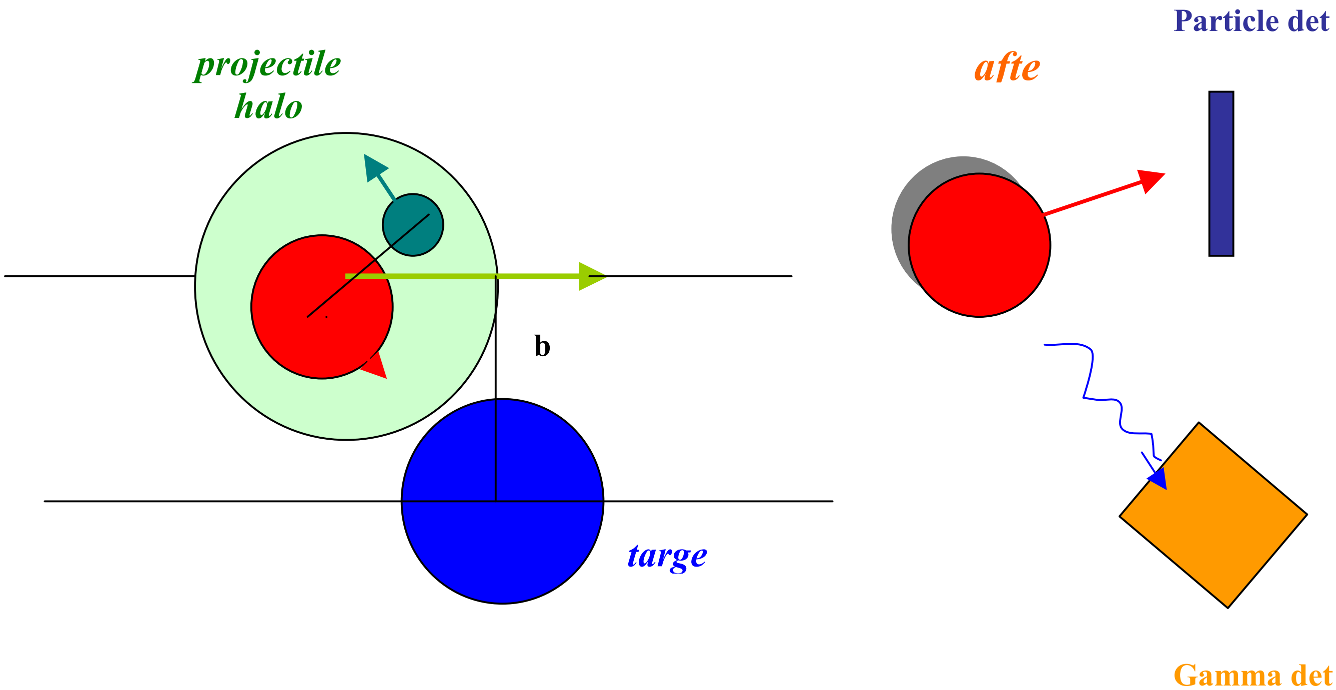
using proton transfer ^{10}B(^{7}Be,^{8}B)^{9}Be and ^{14}N(^{7}Be,^{8}B)^{13}C
At E(^{7}Be) = 12 MeV/u at TAMU Cyclotron, using MARS
(see A. Azhari, PRL 82, 3960 (1999), PRC 63, 055803 (2001))

and ^{8}B breakup at E/A= 30 –300 MeV/u.

and ^{8}B(p,γ)^{9}C - explosive hydrogen burning!

from ^{9}C breakup at 285 MeV/u.

Breakup reactions



2. Extended Glauber model

- eikonal method: straight line trajectory and sudden approximation
- independent proton-target and core-target interactions

Typically we assume a structure for the projectile (^{8}B, ^{9}C, ^{11}Be, ^{14}B, ^{15}C, etc…)

$$\Psi_{J^\pi} = \sum S^{1/2}(c,nlj)\left[\Phi_c^\pi \otimes \varphi_{sp}(nlj)\right]^{J^\pi}$$

and calculate:

$$\sigma_{-1p} = \sum S(c,nlj)\sigma_{sp}(nlj) = \sum C_j^2 \frac{\sigma_{sp}(nlj)}{b_j^2}$$

Same for the momentum distributions!

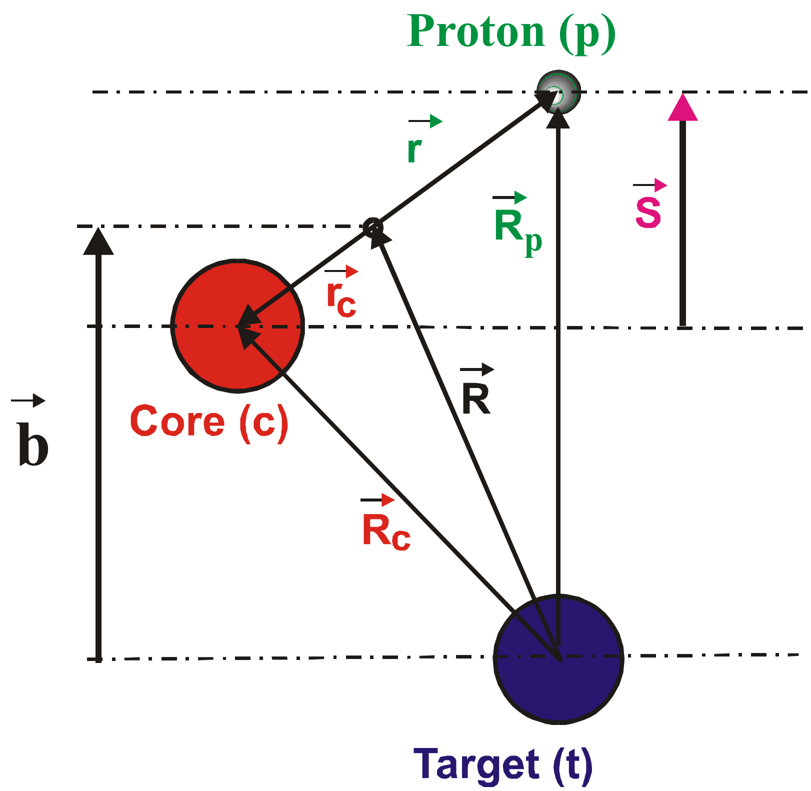
Cross section contributions:

- stripping (the loosely bound proton is absorbed by the target and the core is scattered and detected)
- diffraction dissociation (the nucleon is scattered away by the target, the core is scattered by the target and is detected)
- Coulomb dissociation term

$$\sigma_{sp} = \int_0^\infty 2\pi b db\,(P_{str}(b) + P_{diff}(b)) + \sigma_{Coul}$$

If the process is peripheral we can reverse the process: use experimental data to extract ANC! For ^{8}B and ^{9}C:

$$\sigma_{-1p} = (S_{p_{3/2}} + S_{p_{1/2}})\sigma_{sp}(p_j) = (C_{p_{3/2}}^2 + C_{p_{1/2}}^2)\frac{\sigma_{sp}}{b_p^2}$$



The coordinate system used in the Glauber model calculations.

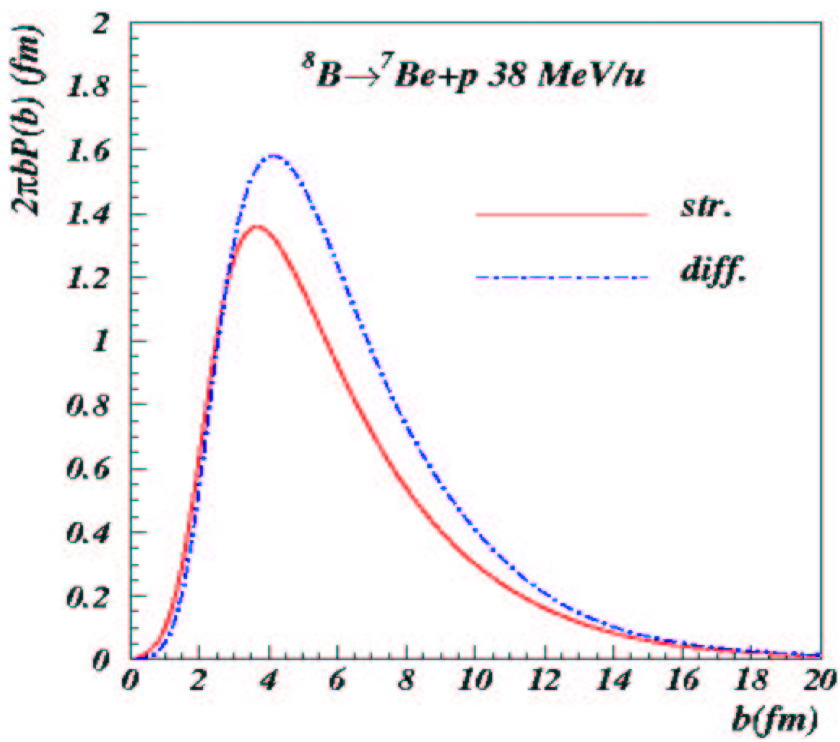
^{8}B S_p=0.137 MeV
^{9}C S_p=1.296 MeV

In Glauber model calculations we used potentials from double folding with JLM effective interactions, as tested before (LT – PRC 61, 024612 (2000)).

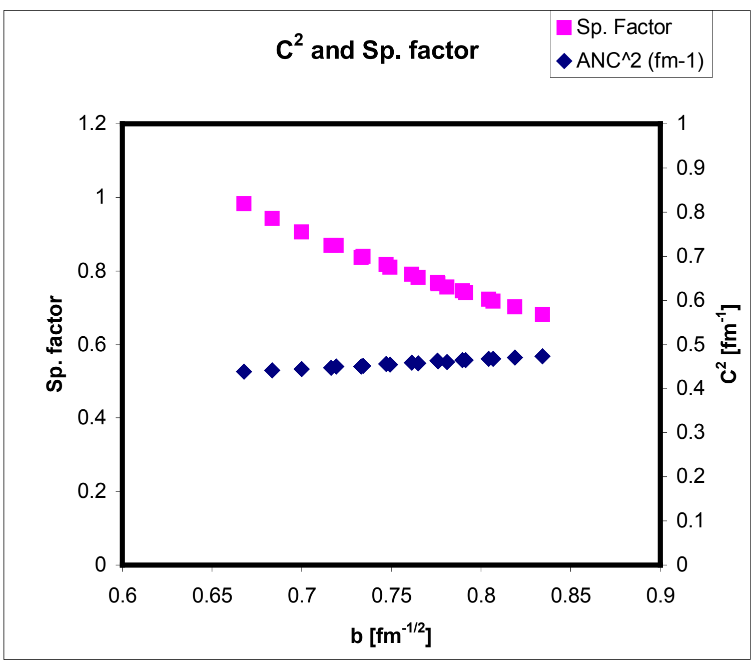
The breakup of ^{8}B and S_{17}

Q: Is ^{8}B breakup peripheral?!

^{8}B on Si target at 38 MeV/u (Negoita et al, PRC **54**, 1187 (1996))



From comparison with data, extract spectroscopic factor and ANC with various binding potential wells: R=2.2-2.6 fm, a=0.5-0.7 fm.



Core excitation contribution

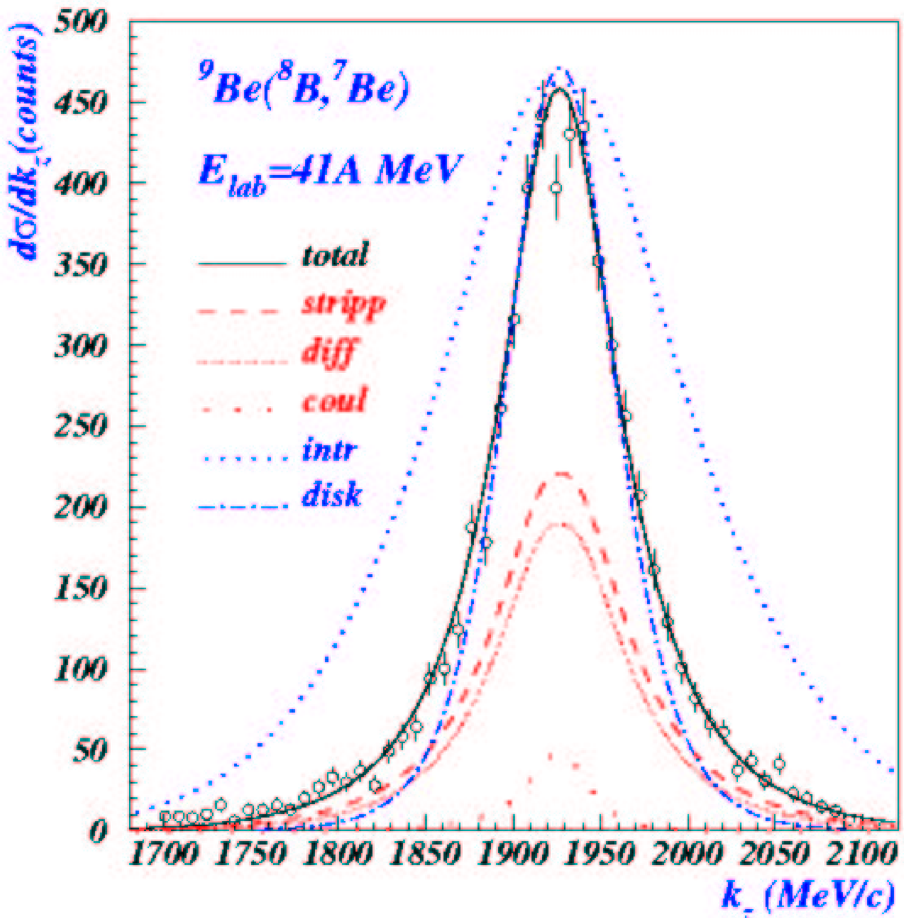
Experiments considered did not measure the contribution of the $^7Be^*$ in the g.s. wave function of ^8B

$$\Phi(^8B g.s.) = S_g^{1/2} \left| ^7Be \otimes p_j \right\rangle + S_e^{1/2} \left| ^7Be^* \otimes p_{3/2} \right\rangle$$

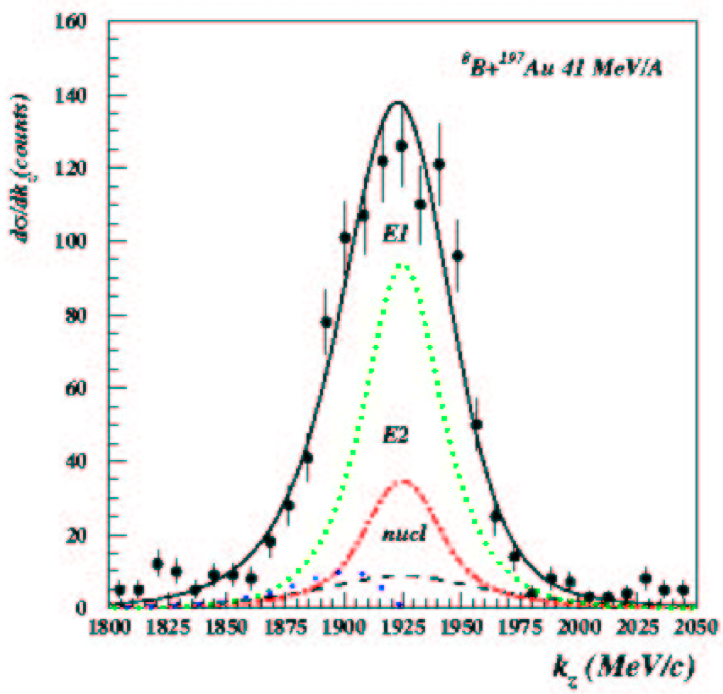
A Coulomb dissociation measurement ^8B @50 MeV/u on Pb found 5% (T. Motobayashi et al, NPA 682, 345c (2001))

From this 5% we calculate a $S_e/(S_g+S_e)=0.10$ and could estimate and subtract the core excitation contribution to the cross section for each target and energy.
[From more recent data: ^8B at 936 MeV/u (D. Cortina-Gil et al., Phys. Lett. B529, 36 (2002) - GSI data), we find a similar result: $S_e/(S_g+S_e)=0.13(4)$]

No such problem for ^9C**!!!**



9Be(8B,7Be)
Elab=41A MeV
total
stripp
diff
coul
intr
disk
dσ/dkz(counts)
kz (MeV/c)
0
50
100
150
200
250
300
350
400
450
500
1700
1750
1800
1850
1900
1950
2000
2050
2100

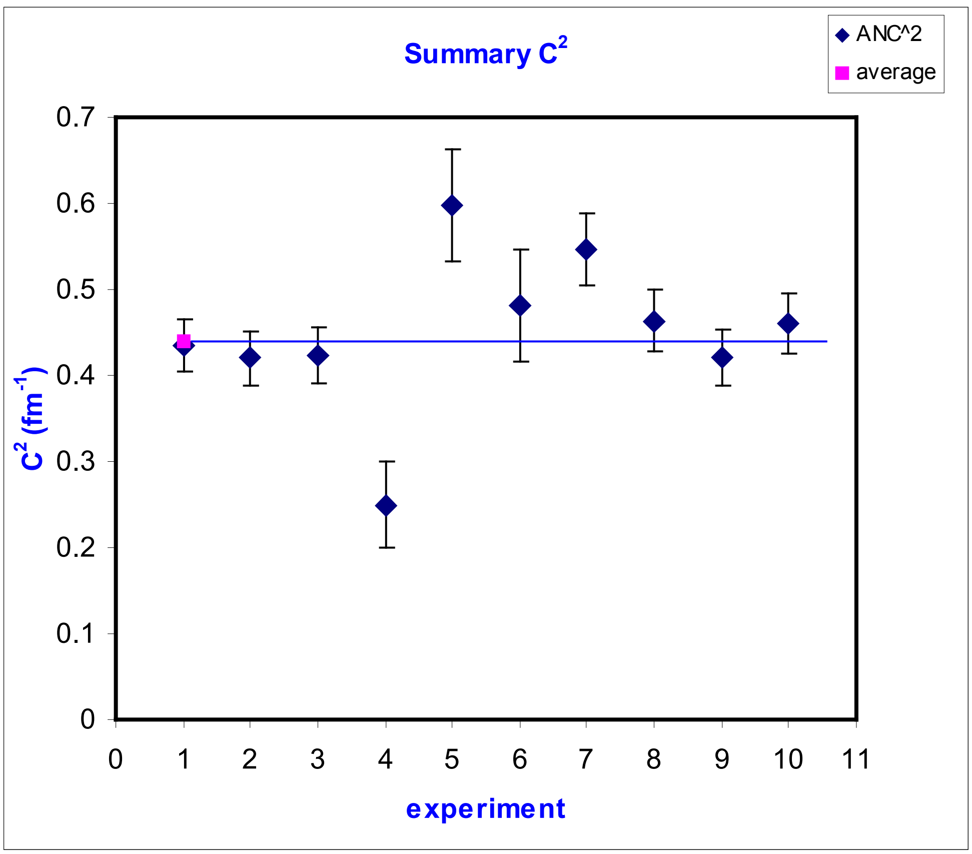


$^8B+^{197}Au$ 41 MeV/A
$d\sigma/dk_z$ (counts)
E1
E2
nucl
k_z (MeV/c)

Summary of the ANC extracted from different ^{8}B breakup reactions

Target	E/A (MeV/u)	exp c.s. (mb)	Reference	C^2_{tot} (fm^{-1})
^{28}Si	28	244(15)	Negoita ea, **PRC 54** (1996)	0.435(31)
	35	225(15)		0.420(32)
	38	222(15)		0.423(32)
^{12}C	40	80(15)	Pecina ea, **PRC 52** (1995)	0.250(50)*
	142	109(1)	Blank ea, **NP A624** (1997)	0.597(65)*
	285	89(2)		0.482(65)
Sn	142	502(6)		0.547(42)
	285	332(6)		0.464(37)
^{208}Pb	142	744(9)		0.421(32)
	285	542(9)		0.460(35)
aver all				0.450(39)
aver sel				0.456(28)

* - discarded in the selected average



Averages

a) – all points, no weight (adopted)

C^2=0.450±0.039 fm^{-1} S_{17}=17.4±1.5 eV·b

b) - selected 8 points – same weight

C^2=0.456±0.028 fm^{-1} S_{17}=17.6±1.1 eV·b

c) – selected 8 points - weighted average

C^2=0.447±0.024 fm^{-1} S_{17}=17.2±0.9 eV·b

Contributions to error:

- **std dev around average: 6.8%**
- **ANC method: 3%**
- **Renorm of optical model Nw, Nv: 4%**
- **Core excitation: 2%**

Total: 8.7%

Data from:

F. Negoita et al, Phys Rev C 54, 1787 (1996)

B. Blank et al, Nucl Phys A624, 242 (1997)

I. Pecina et al, Phys Rev C 52, 191 (1995)

J. H. Kelley et al, Phys Rev Lett 77, 5020 (1996)

T. Motobayashi et al, Nucl Phys A682, 345c (2001)

Result

- from ^{8}B breakup data at 30-300 MeV/u:

$$C^2_{tot} = 0.450 \pm 0.039 \text{ fm}^{-1}$$

and using:

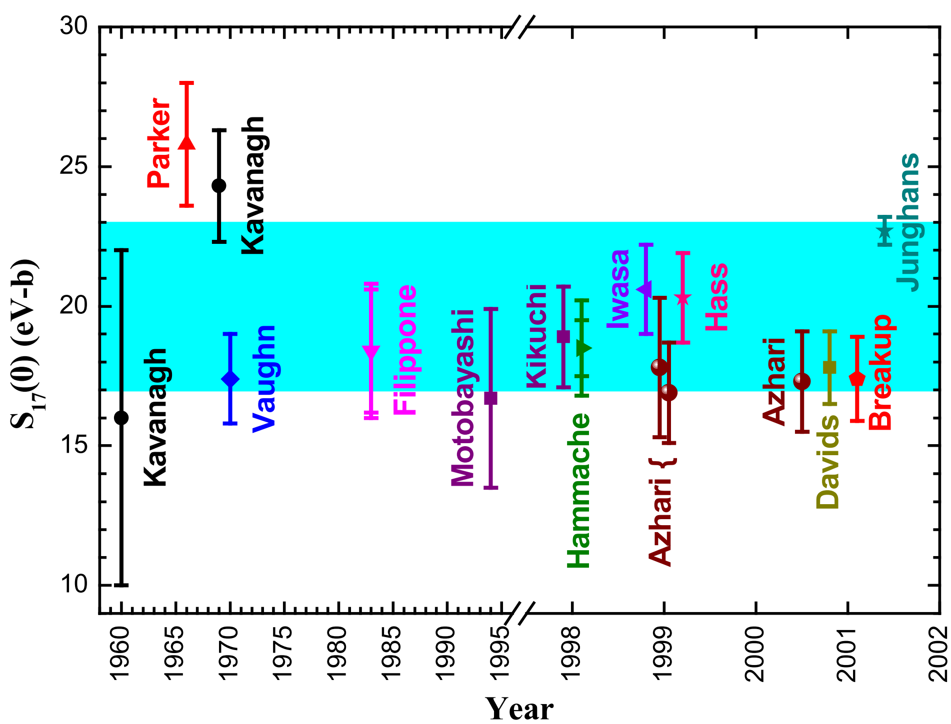
$$S_{17}(0) = \frac{38.6 \text{ eV b}}{\text{fm}^{-1}} \left(C^2_{p_{3/2}} + C^2_{p_{1/2}} \right)$$

$$S_{17}(0) = 17.4 \pm 1.5 \text{ eV}\bullet\text{b}$$

- compared with (^{7}Be,^{8}B) proton transfer at 12 MeV/u on two targets:

$$C^2_{tot} = 0.449 \pm 0.046 \text{ fm}^{-1}$$

$$S_{17}(0) = 17.2 \pm 1.8 \text{ eV}\bullet\text{b}$$



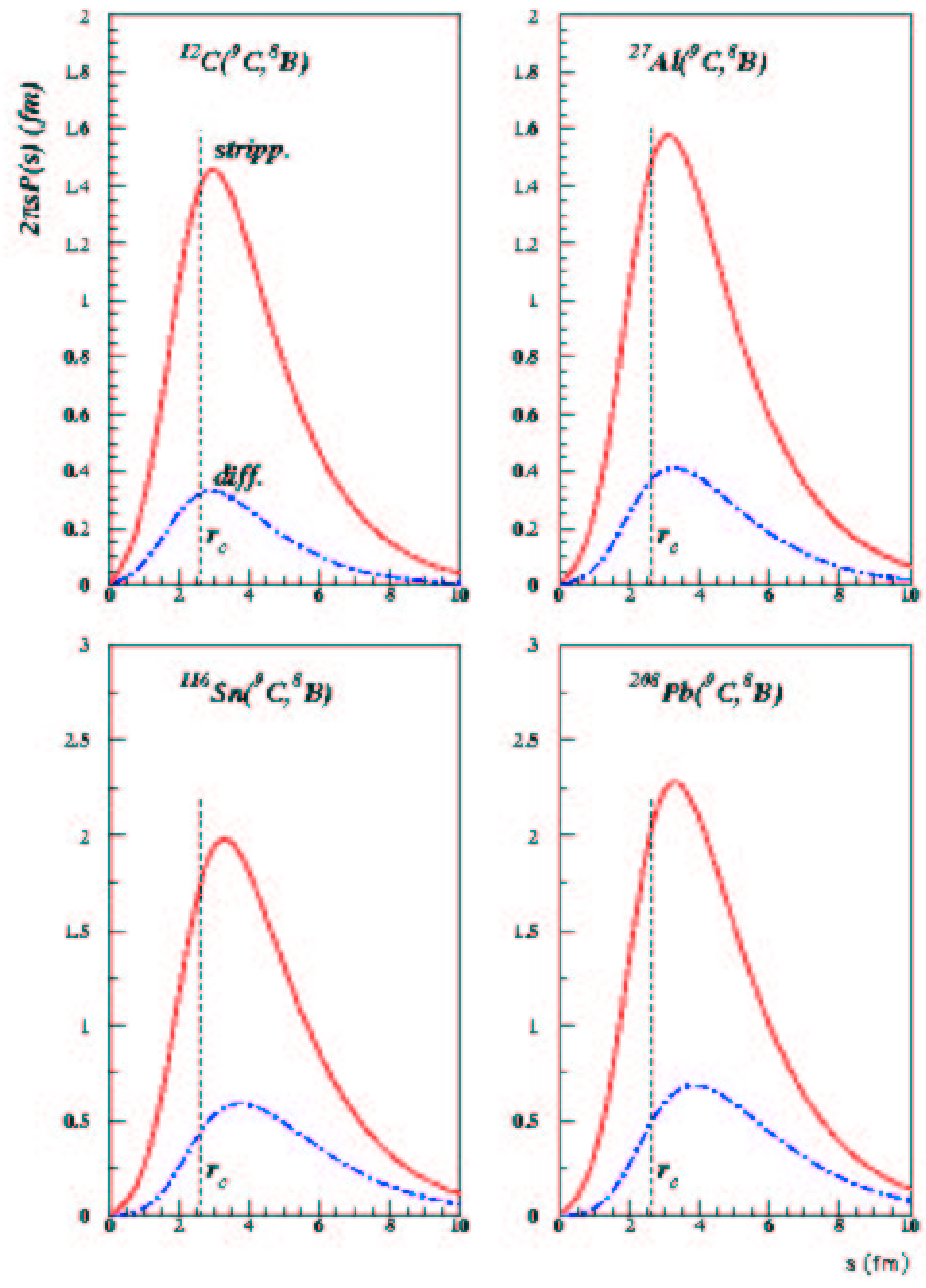


Figure 1 The stripping and diffraction dissociation components of the breakup probability of 285 MeV/u ^{9}C on C, Al, Sn and Pb targets as a function of the proton impact parameter.

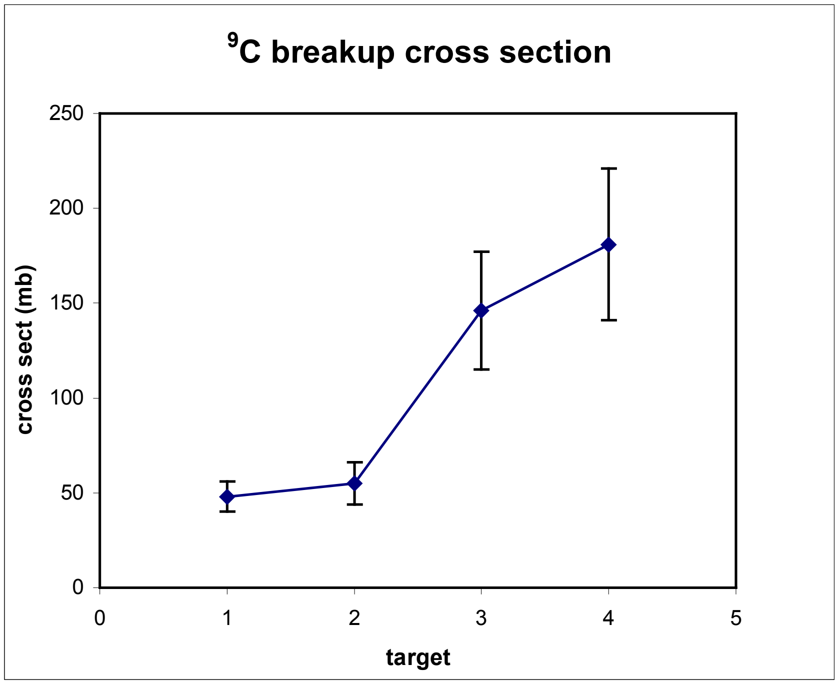


Figure 2 Breakup cross sections ^{9}C at 285 MeV/u on C, Al, Sn and Pb (Blank ea)

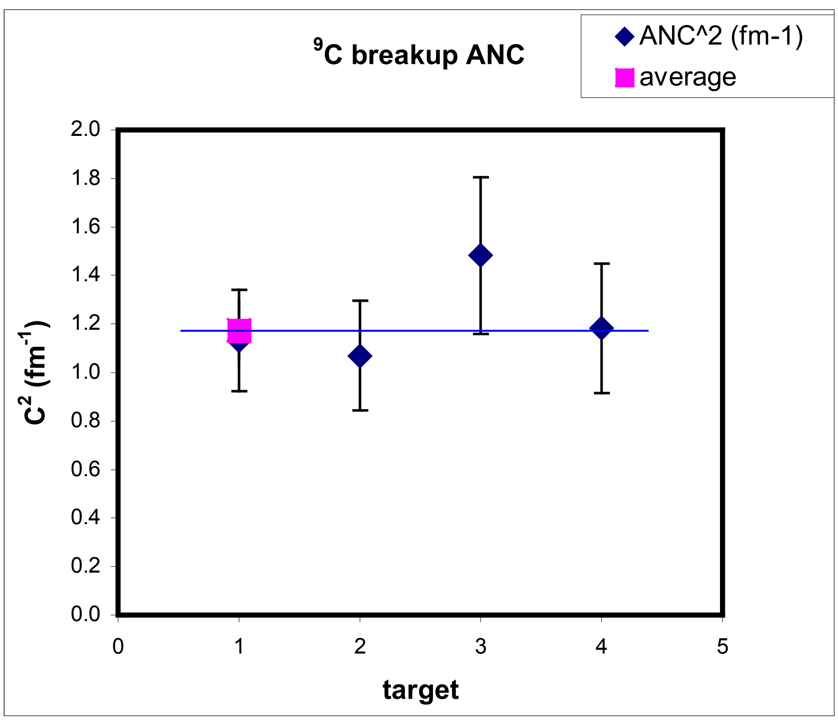


Figure 3 The Asymptotic Normalization Coefficients for ^{9}C extracted from the beakup of ^{9}C at 285 MeV/u on C, Al, Sn and Pb targets, respectively. Data from B. Blank et al., Nucl Phys A624 (1997) 242.

New for ^{9}C: DIFFERENT Calculations

A. Glauber model with folded potentials

1) JLM -uses the G-matrix effective interaction of Jeukenne, Lejeune and Mahaux (PRC 16, 1977 tested before because:

- independent geometry for imaginary part
- normalization independent of partners and energy
- reproduces ELASTIC and TRANSFER data

for loosely bound p-shell nuclei with experimentally determined renormalizations (^{7}Be and ^{11}C on ^{12}C, ^{14}N)

2) the free t-matrix NN interactions of Franey and Love (PRC 31, 1985)

B. Glauber model calc in the optical limit

$$\chi(b)=\frac{1}{2}\sigma_{NN}(i+\alpha_{NN})\int d\vec{b}_1 d\vec{b}_2\,\rho(b_1)\rho(b_2)\tilde{v}(\vec{b}+\vec{b}_1-\vec{b}_2)$$

$$\tilde{v}(r)=\frac{1}{\pi^{3/2}\mu^{3}}e^{-\frac{r^2}{\mu^2}}$$

Use three ranges for interactions, to check the sensitivity:

3) zero-range $\mu\to 0$

4) "standard" μ=1.5 fm for all terms

5) "Ray", ranges for each term, as determined by Ray (PRC 20, 1979)

Test how the calculations reproduce other observables: reaction cross-sections (p, ^{8}B and ^{9}C on a ^{12}C target) and total cross sections (p on ^{12}C) in zero-range approximation (figure).

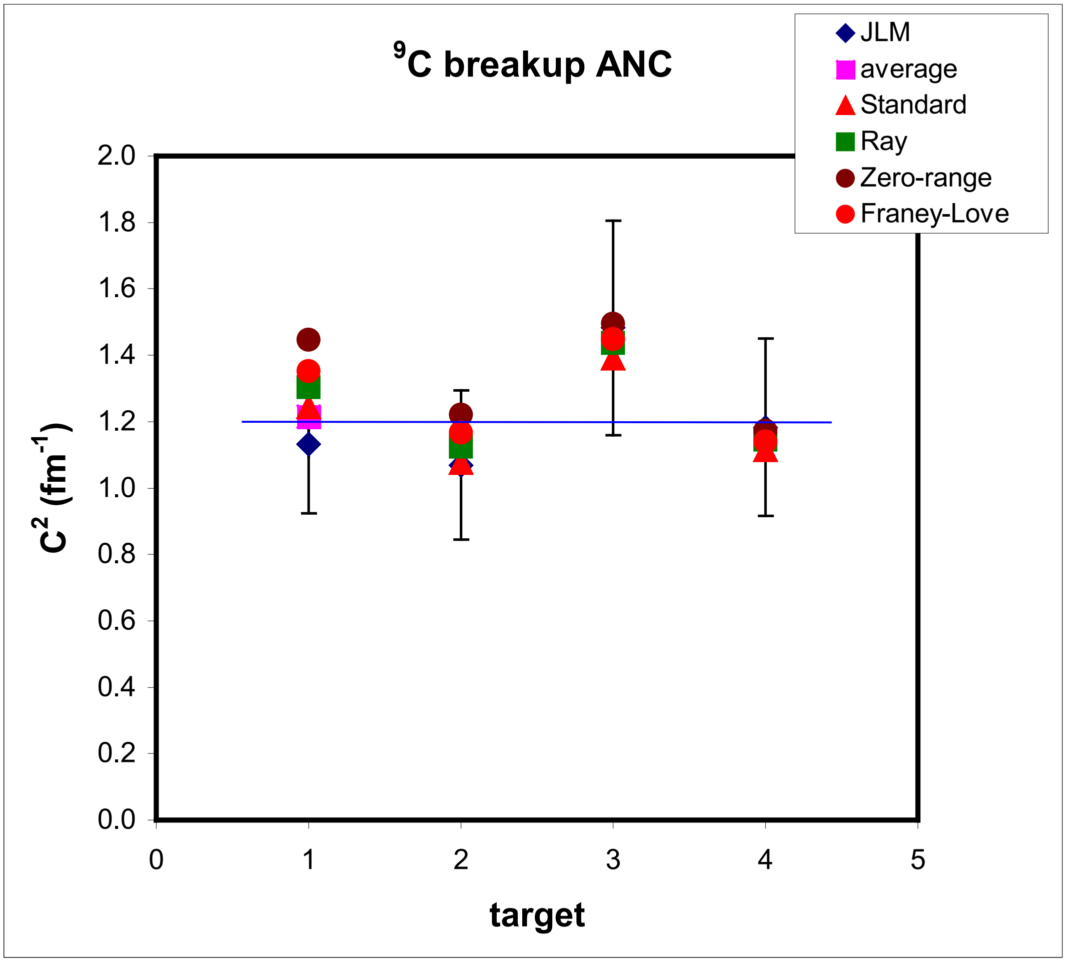


Figure 5. The results of all calculations with Glauber model (potential and the optical limit) are included. Two potential types (JLM and Franey-Love) and three n-n interactions are considered (standard, Ray and zero-range).

Average JLM: $C^2_{tot} = \left(C^2_{p_{3/2}} + C^2_{p_{1/2}}\right)$**=1.18±0.12 fm^{-1}**

Average all: $C^2_{tot} = \left(C^2_{p_{3/2}} + C^2_{p_{1/2}}\right)$**=1.22±0.13 fm^{-1}**

Which leads to **$S_{18}(0)$=46±6 eV·b** for the reaction $^{8}B(p,\gamma)^{9}C$

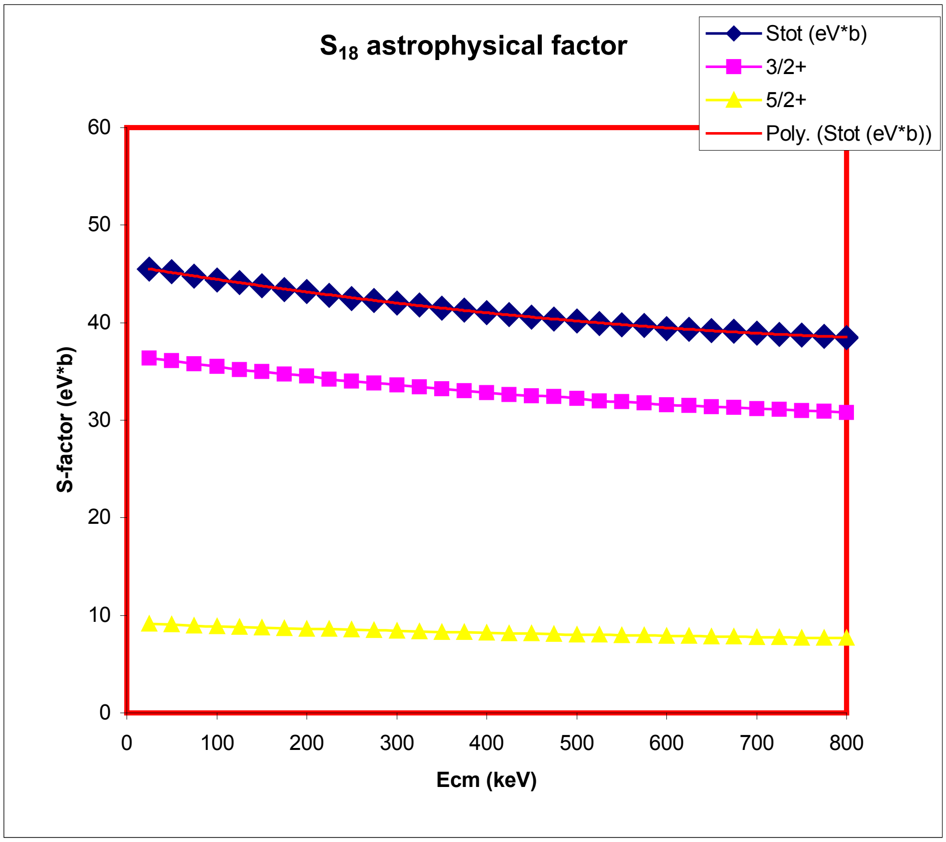


Figure 6 The astrophysical factor S_{18} for the $^{8}B(p,\gamma)^{9}C$ reaction for E=0-800 keV.

$S_{18}(E)=45.8-15.1E+7.34E^2$ eVb (E in MeV)

For comparison:
M. Wiescher (above) estimates S_{18}=210 eVb from a two-body model;
P. Descouvemont, Nucl. Phys. A646 (1999)261 calculates with GCM model S_{18}=80 eVb (using Minnesota and Volkov n-n interactions).
N. Tymofeyuk: S_{18}=53 eVb (using M3Y interaction…)

Sole exp data: D. Beaumel et al, Phys Lett **B514** (2001) 226
Use $d(^{8}B,^{9}C)n$ reaction at 14.4 MeV/u MeV/u to extract ANC and find:
C^2=0.97 to 1.42 fm^{-1} and **$S_{18}(0)$=45±13 eV·b**, in agreement with the present result.

The reaction is important in the hot pp chains, in explosive H burning, at large temperatures, for creating alternative paths across the A=8 mass gap
(see e.g. M. Wiescher et al., Ap. J. 343 (1989)352.)

pp IV $^{8}B(p,\gamma)^{9}C(\beta^{+}\nu)^{9}B(p)^{8}Be(\alpha)^{4}He$ and
rap I $^{8}B(p,\gamma)^{9}C(\alpha,p)^{12}N(p,\gamma)^{13}O(\beta^{+}\nu)^{13}N(p,\gamma)^{14}O$.

new reaction rate:

$$R = N_A < \sigma v > = T_9^{-2/3} \exp(-\frac{B}{T_9^{1/3}})(A_0 + A_1 T_9^{1/3} + A_2 T_9^{2/3}) \quad \text{cm}^3\text{/s/mol}$$

with $B=11.94$, $A_0=6.64e5$, $A_1=8.50e4$, $A_2=-2.41e5$.

In conclusion:

- reliable spectroscopic information can be extracted from one-nucleon breakup reactions of loosely bound nuclei at energies around and above the Fermi energy (as per GANIL, GSI, MSU, RIKEN results).
- a good, unambiguous quantitative description is achieved in terms of the asymptotic normalization coefficients. In turn, these can be used to calculate observables that are dominated by the periphery of the nucleus, notably astrophysical S-factors (another example: halo rms radii).
- determined $S_{17}(0)$ and $S_{18}(0)$.

The validity of the method is wider than for the ^{8}B, ^{9}C cases discussed above. Conditions:

- peripherality (loosely bound, halo nuclei)
- good absolute values for the cross sections,
- identification of the final state of the core
- reliable cross section calculations.

Very difficult or even impossible direct measurements for nuclear astrophysics that would involve bombarding short-lived targets with very low energy protons can be replaced or supplemented by indirect measurements with radioactive beams at larger energies, seeking the relevant ANCs, rather than an elusive complete knowledge of the ground state wave function of these exotic nuclei.

Collaborators:

A. Azhari
C. A. Gagliardi
A. M. Mukhamedzhanov
R. E. Tribble
X. D. Tang
Texas A&M University, College Station, TX

F. Carstoiu
IPNE Bucharest, Romania and LPC/GANIL Caen, France