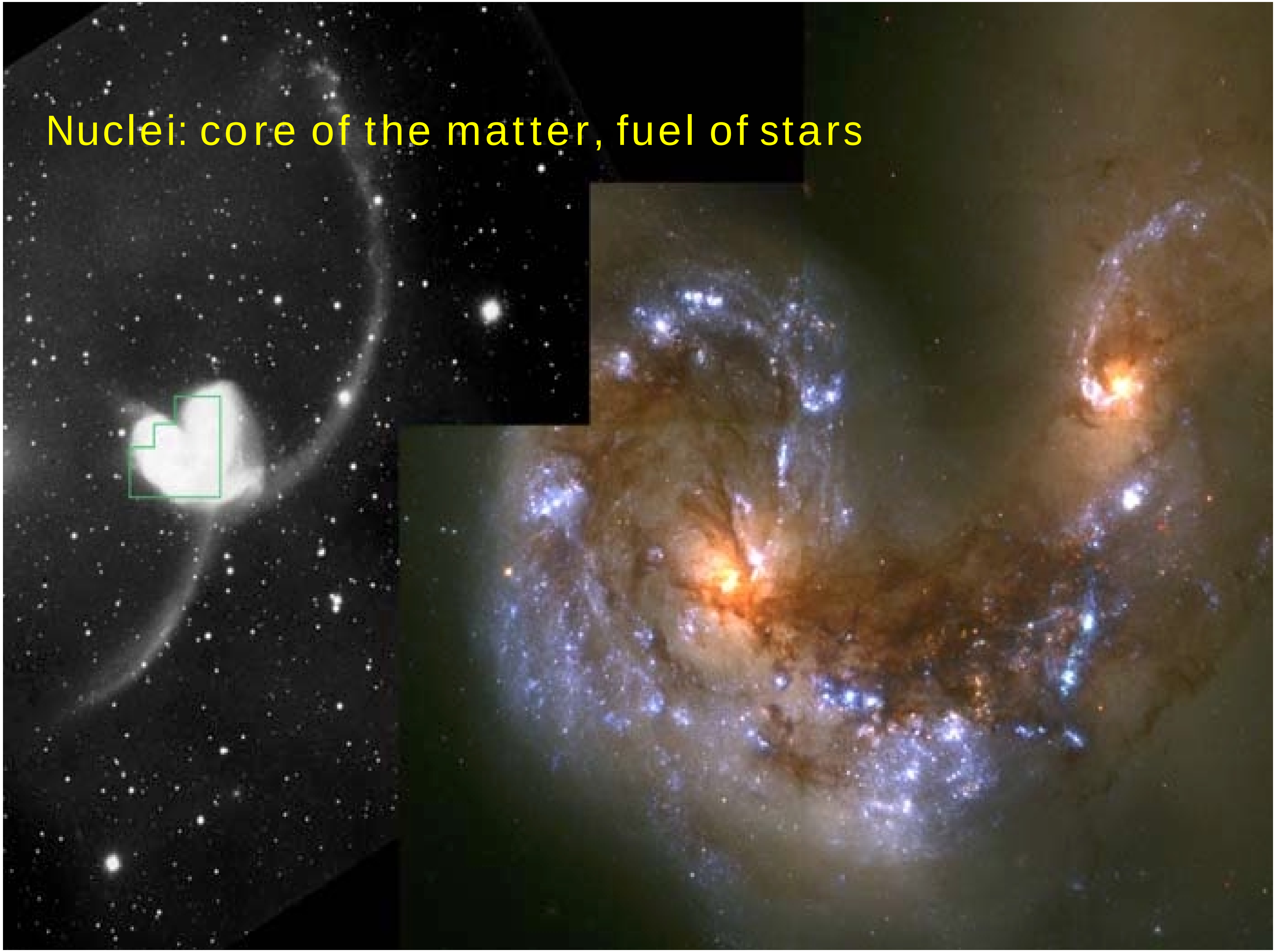
Spectroscopic factors vs Asymptotic Normalization Coefficients from breakup and transfer reactions with loosely bound nuclei

Livius Trache - Cyclotron Institute

Texas A&M University

Trento, March 2004

Nuclei: core of the matter, fuel of stars



Indirect methods to obtain nuclear astrophysical information from reactions at low and intermediate energies

Summary:

1. **Introduction**
2. **Spectr. factors and ANC from transfer reactions for nuclear astrophysics - p and n transfer**
3. **… from breakup at intermediate energies - ^{8}B and ^{9}C**
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**

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A. Azhari, X. D. Tang, G. Tabacaru

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〈 Direct measurements at very low energy (10s-100s keV region) – very difficult experimentally and involve extrapolations (especially for charged particles)

Indirect methods are few:

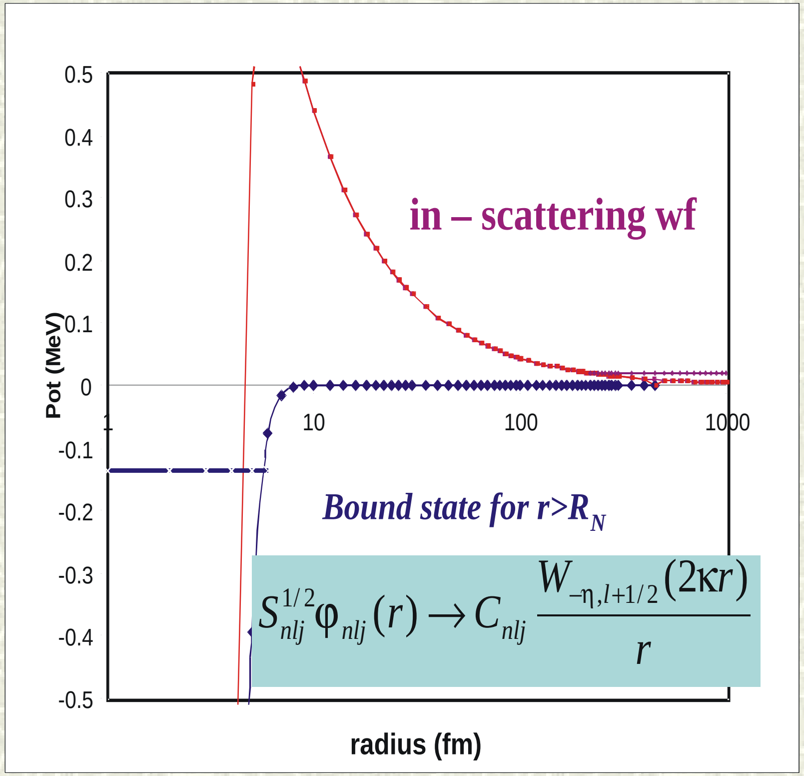
- Inverse reactions
- Resonance parameters determination
- Coulomb dissociation
- Trojan horse method
- Sub-Coulomb transfer
- Transfer reactions – **ANC method** (Asymptotic Normalization Coefficient method)
- **Breakup reactions** at intermediate energies

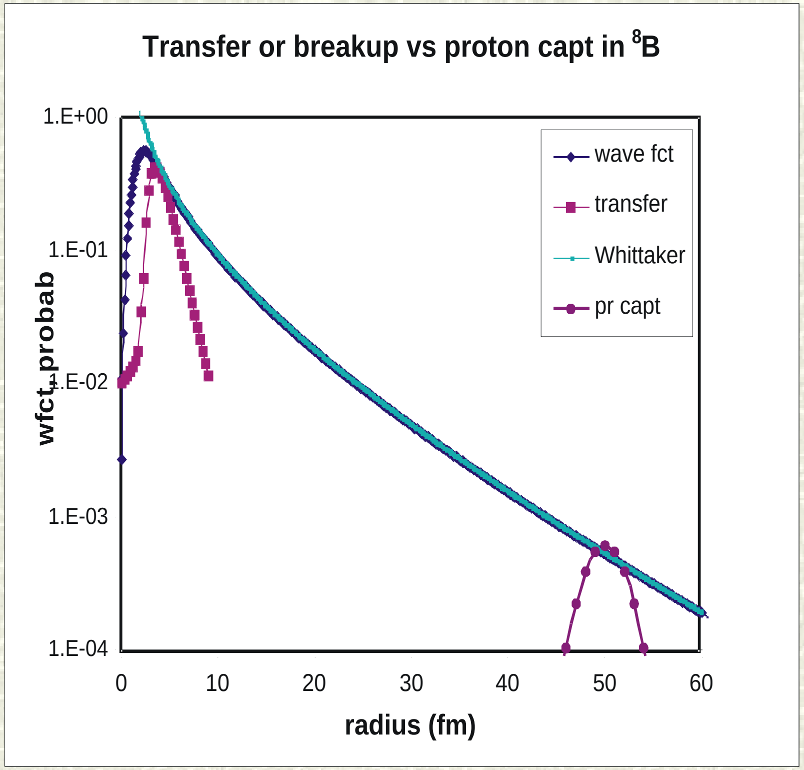
TAMU

Transfer reactions at about 10 MeV/u and breakup of loosely bound nuclei at energies above the Fermi energy are peripheral reactions and can be used to extract ANCs and subsequently astrophysical S-factors!

Use ***p*** or ***n*** transfer and **^{8}B breakup (one-proton removal)** results at energies 30-1000 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} (hot pp chain). Extend to neutron breakup?! ^{14}C(n,γ)**^{15}C** (Inhomogeneous Big Bang Model).

Radiative proton capture is peripheral e.g. $^{7}Be(p,\gamma)^{8}B$





$$(T+V_{coul})Y(\hat{r})\varphi(r)=-\varepsilon Y(\hat{r})\varphi(r)$$

Direct **Radiative** **proton** capture

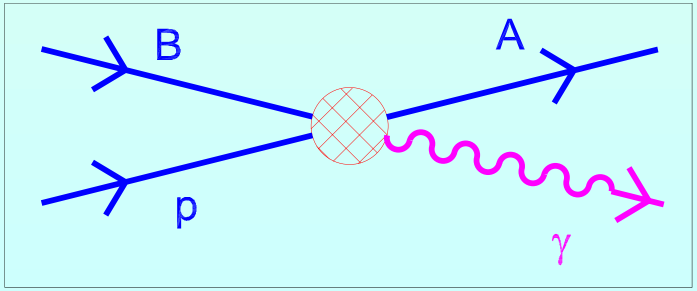
$$\sigma \propto |M|^2 \qquad [S(E) = E e^{2\pi\eta}\sigma]$$

M is:

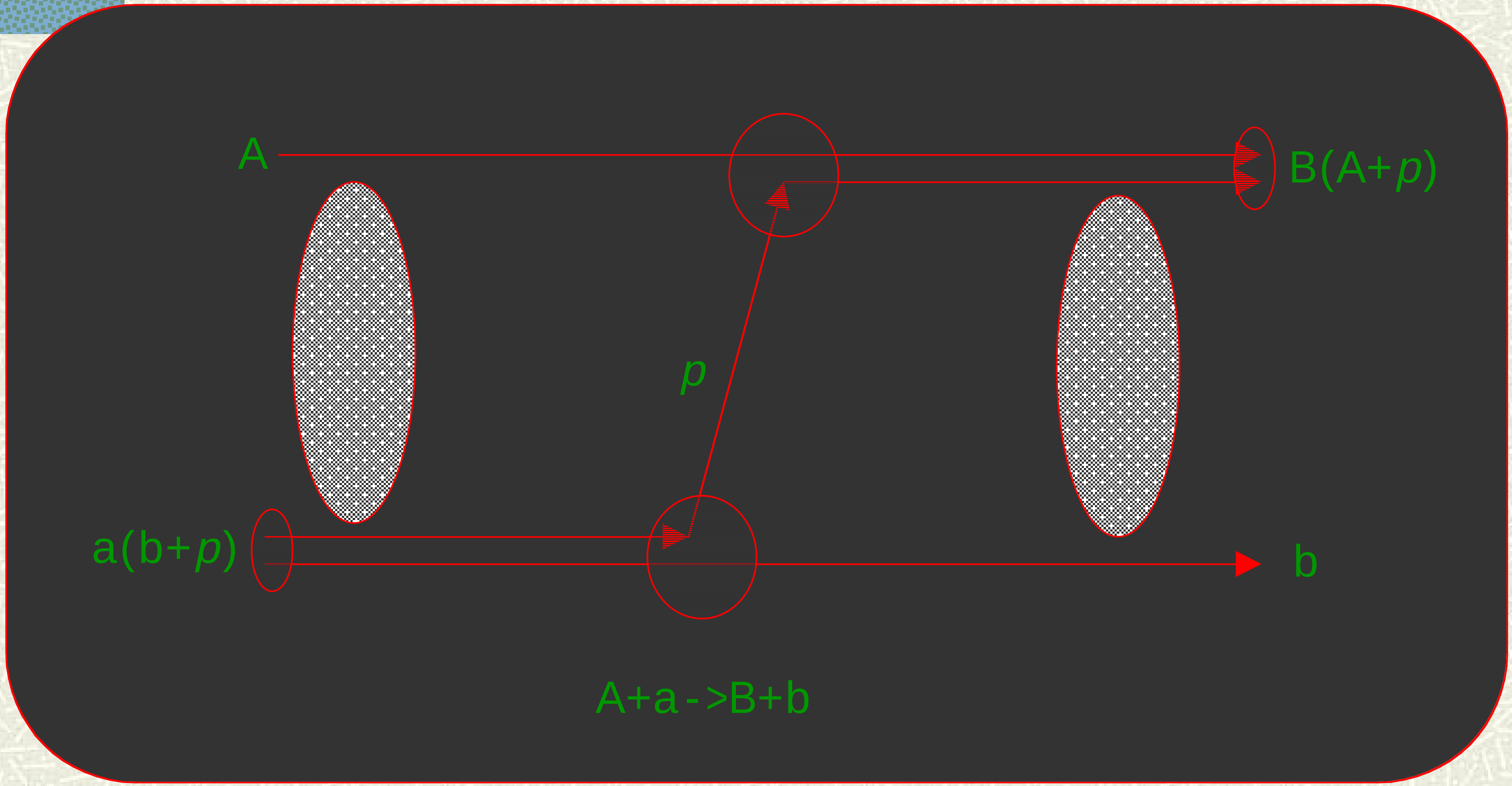
Integrate over _:

Low B.E.:

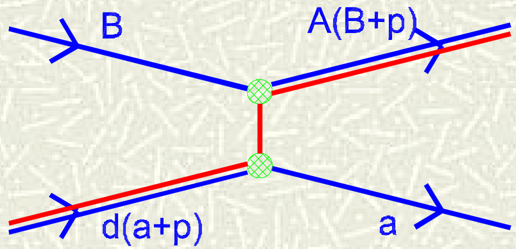
Find:



Transfer Reactions



Transfer Reaction

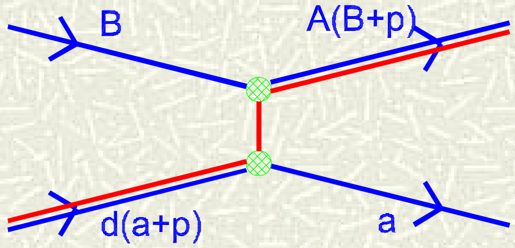


Transition amplitude:

Standard approach:

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

Transfer Reaction



Transition amplitude:

Peripheral transfer:

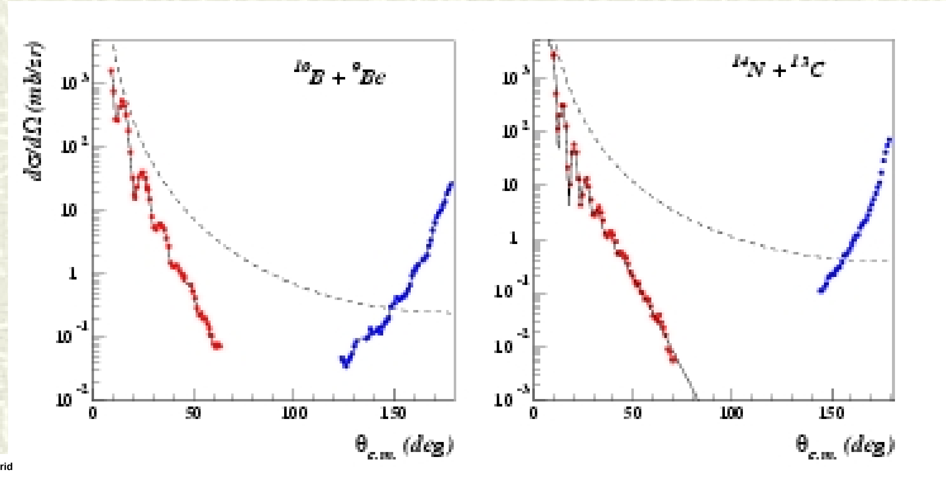
ANC vs sp. factors – transfer reaction examples

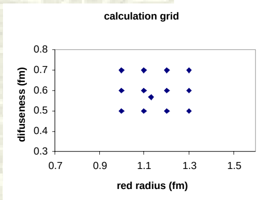
$^{9}Be(^{10}B,^{9}Be)^{10}B$ 10A MeV

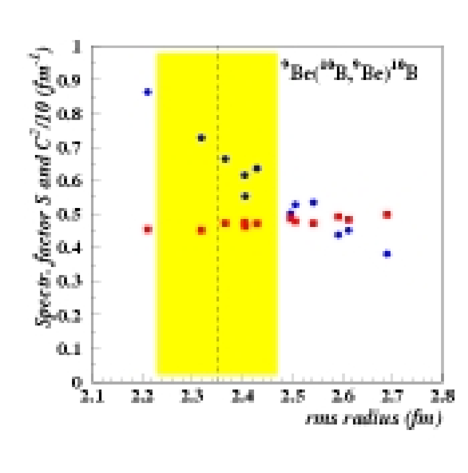
$^{13}C(^{14}N,^{13}C)^{14}N$ 10A MeV

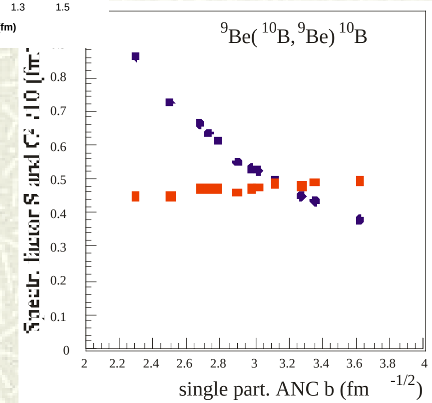
Elastic and proton transfer

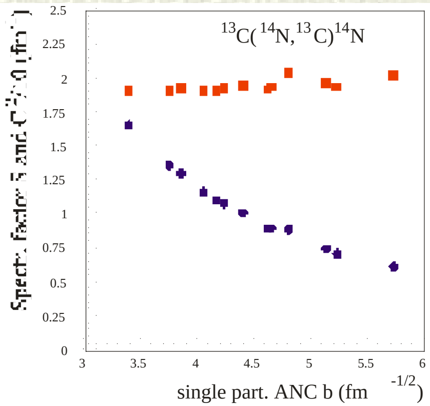
MDM spectrometer



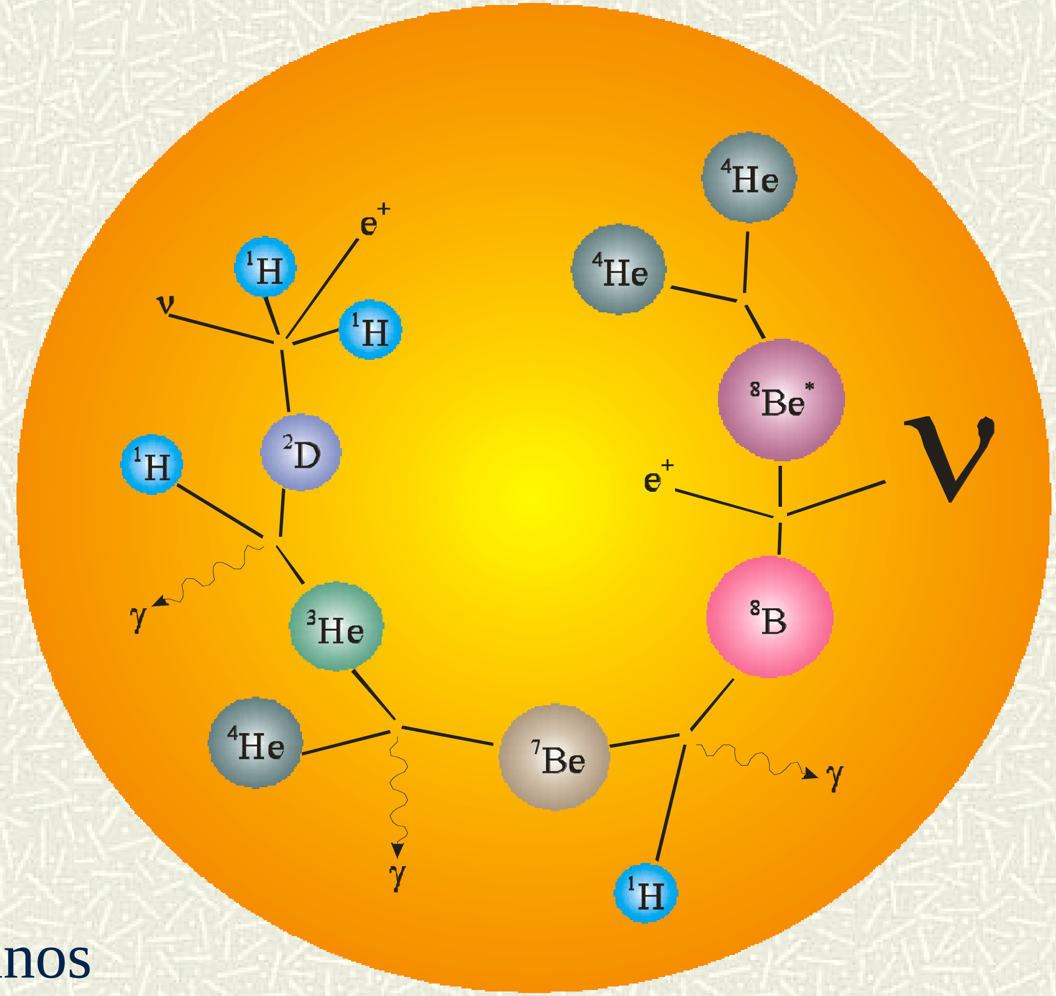








Solar neutrinos



^8B neutrinos

pp III chain (0.01%)

K500 SUPERCONDUCTING CYCLOTRON FACILITY
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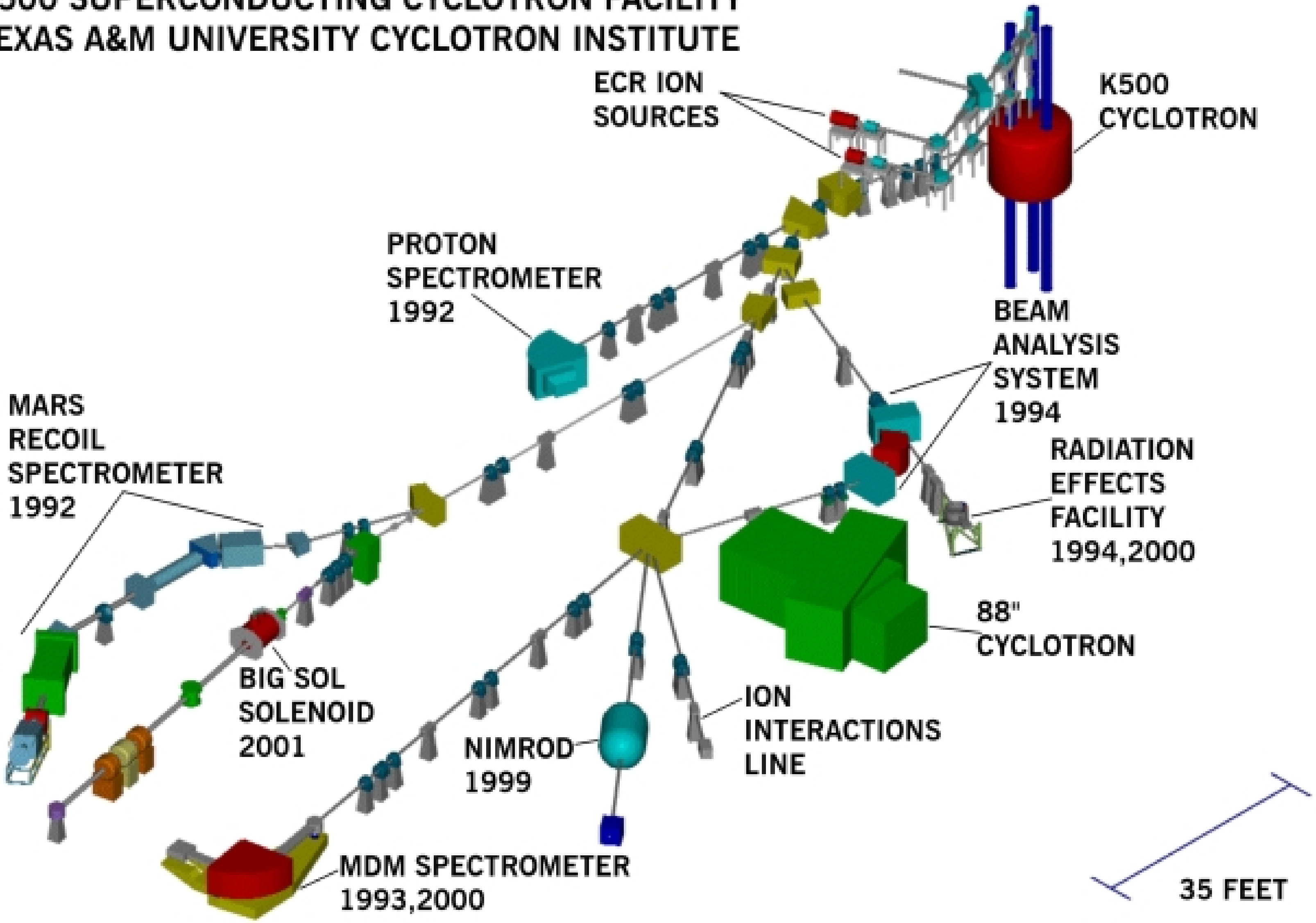
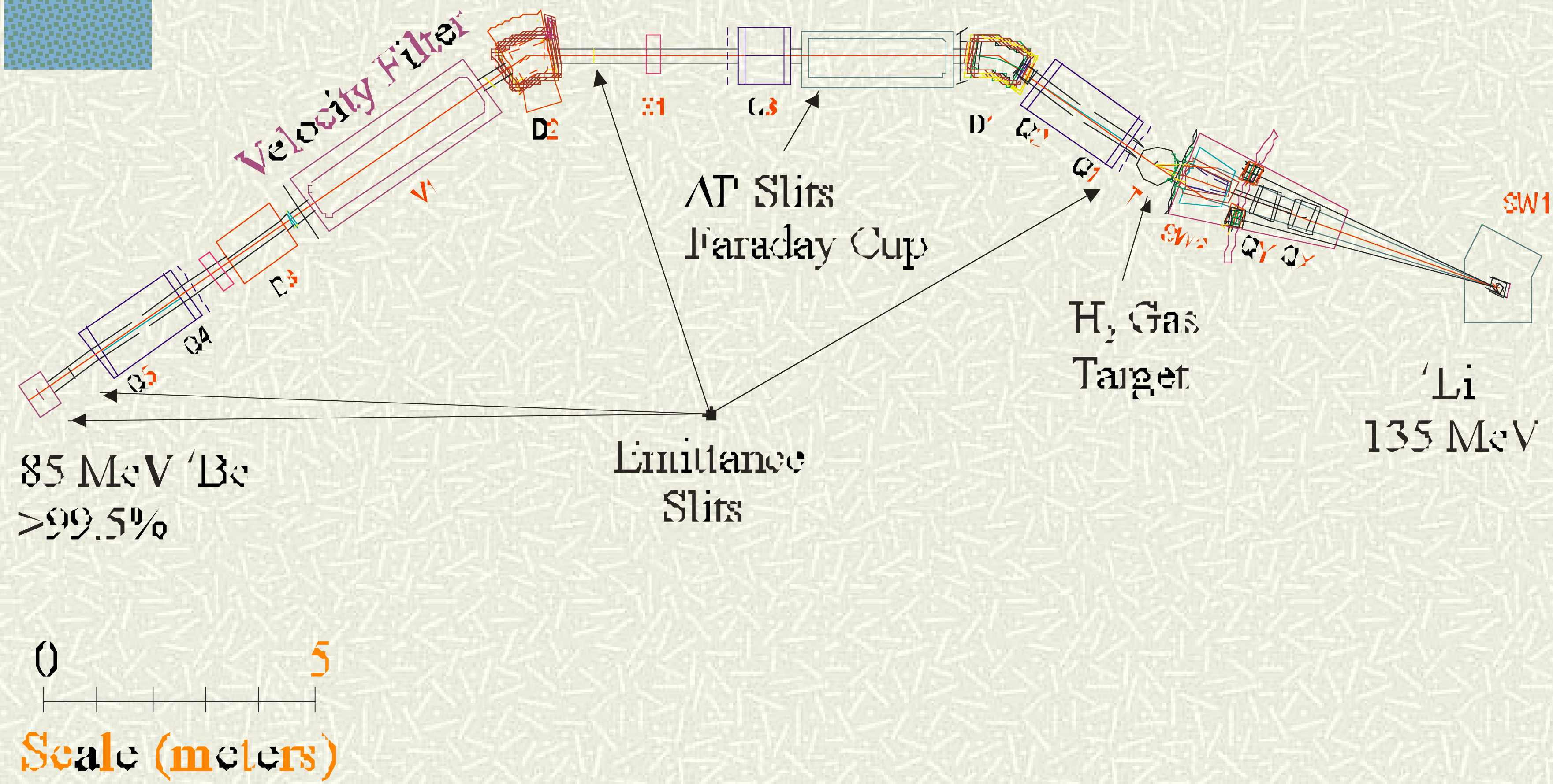


Momentum Achromat Recoil Separator



RI beams with MARS

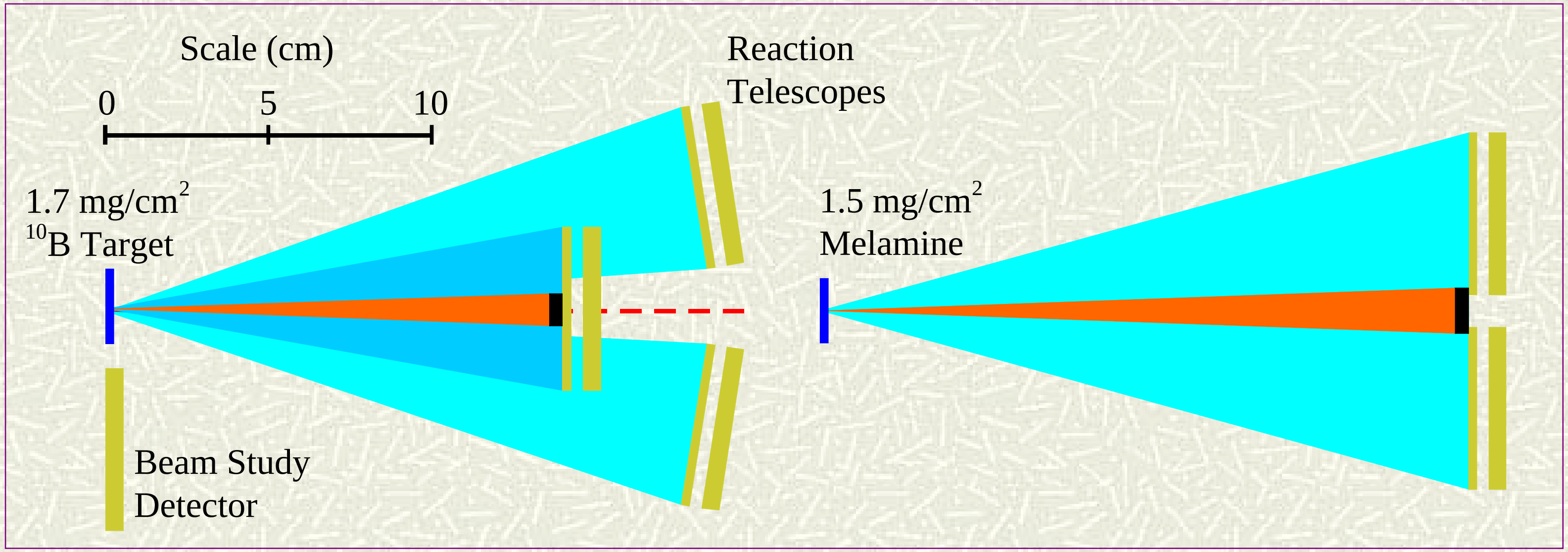
Beam	Reaction	E/A	Intensity	Purity	Program
^{7}Be	p(^{7}Li,^{7}Be)n	12 MeV/n	10^{5} part/sec	>99.5%	astrophysics
^{8}B	p(^{9}Be,^{8}B)2n	20 MeV/n	7. 10^{4} part/sec	>98%	astrophysics
^{8}B	p(^{10}B,^{8}B)t	12 MeV/n	0.5 10^{4} part/sec	>98%	astrophysics
^{11}C	p(^{11}B,^{11}C)n	10 MeV/n	5. 10^{5} part/sec	>99%	astrophysics
^{13}N	p(^{13}C,^{13}N)n	11 MeV/u	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.
^{22}Mg	p(^{23}Na,^{22}Mg)2n	28 MeV/n	6. 10^{4} p/sec	>99.6%	β-decay
^{14}O	p(^{14}N, ^{14}O)n	6 MeV/u	8. 10^{4} p/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, …

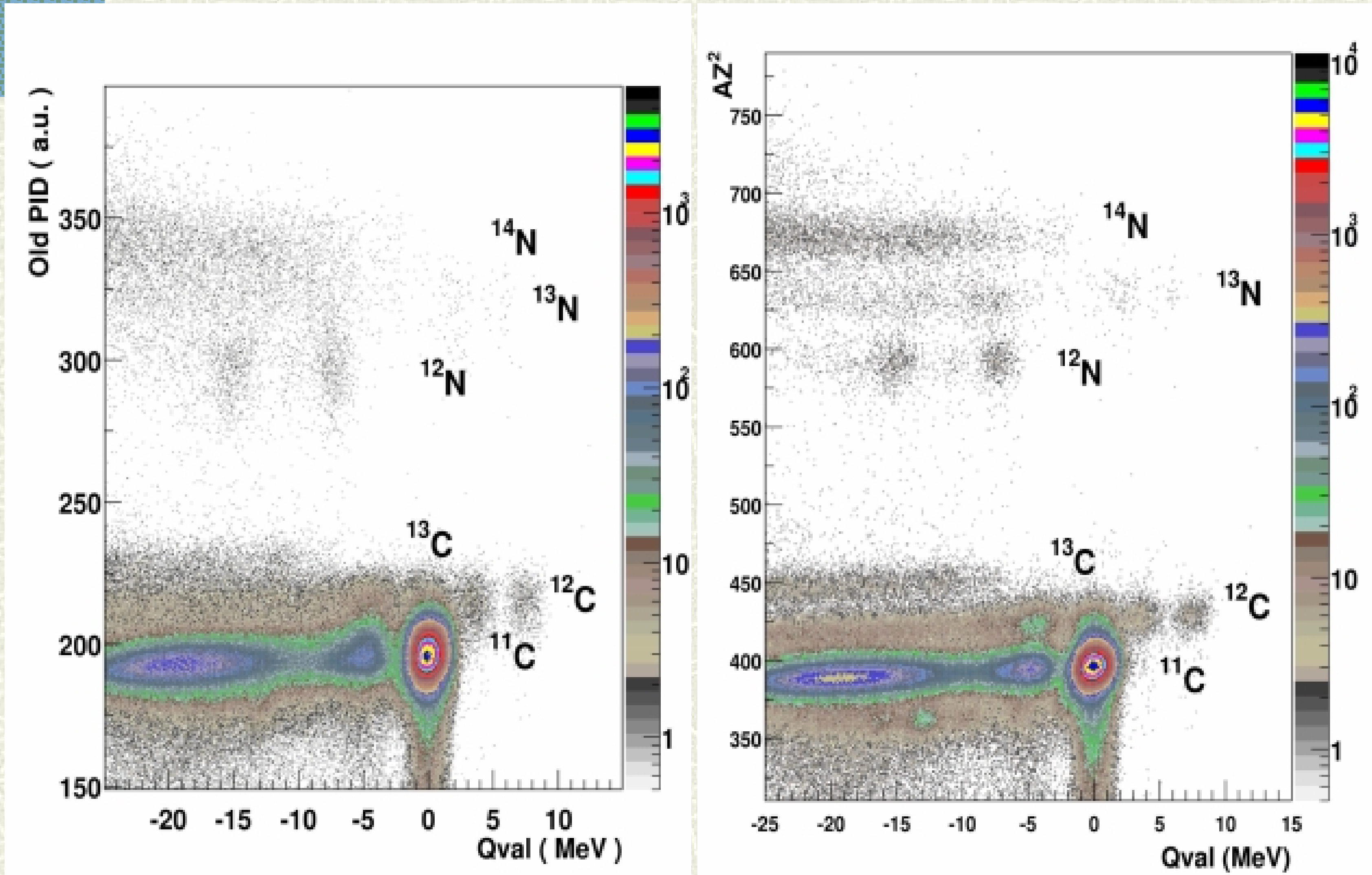
Transfer reactions for ANCs

$^{10}B(^{7}Be,^{8}B)^{9}Be$ $^{14}N(^{7}Be,^{8}B)^{13}C$



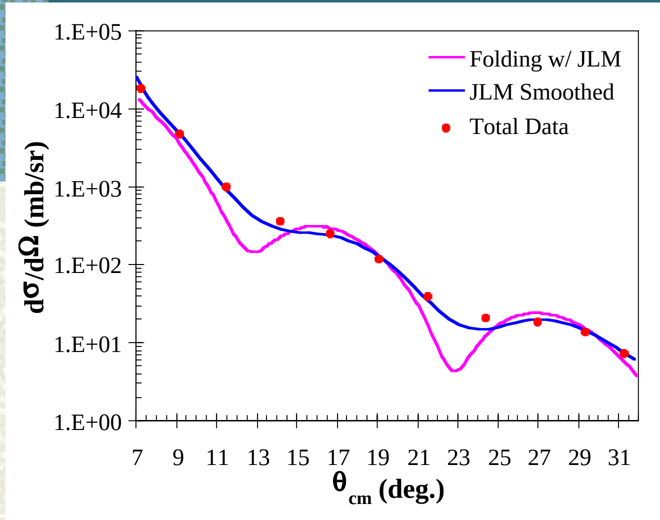
- Beam Study Detector: **1 mm** Si strip detector
- Reaction Telescopes:
  - **105 µm** Si strip detector
  - **1 mm** Si detector

PID vs. Qval ex: $^{14}N(^{11}C,^{12}N)$

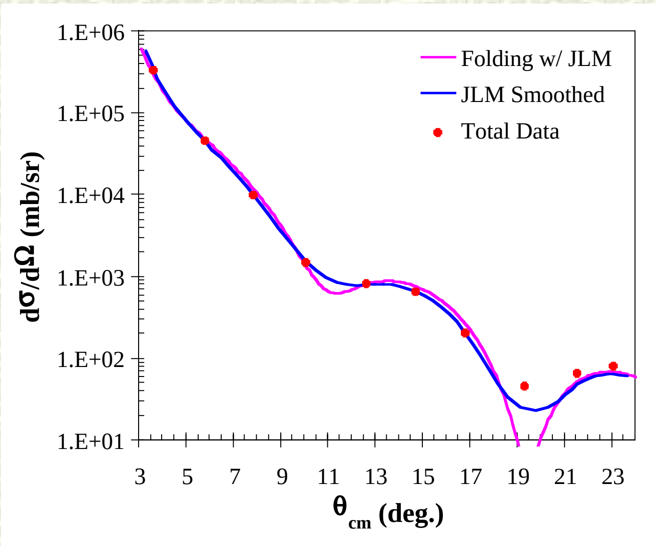


^{7}Be Elastic Scattering

Not Fits!

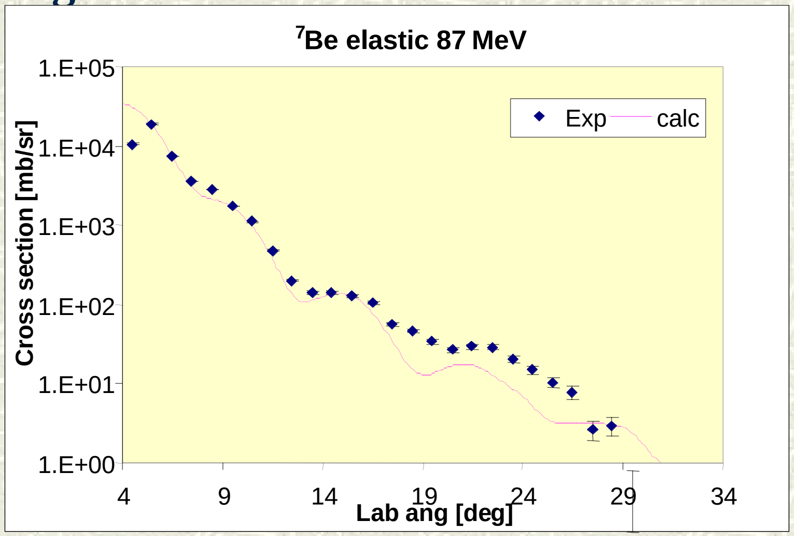


^{10}B Target

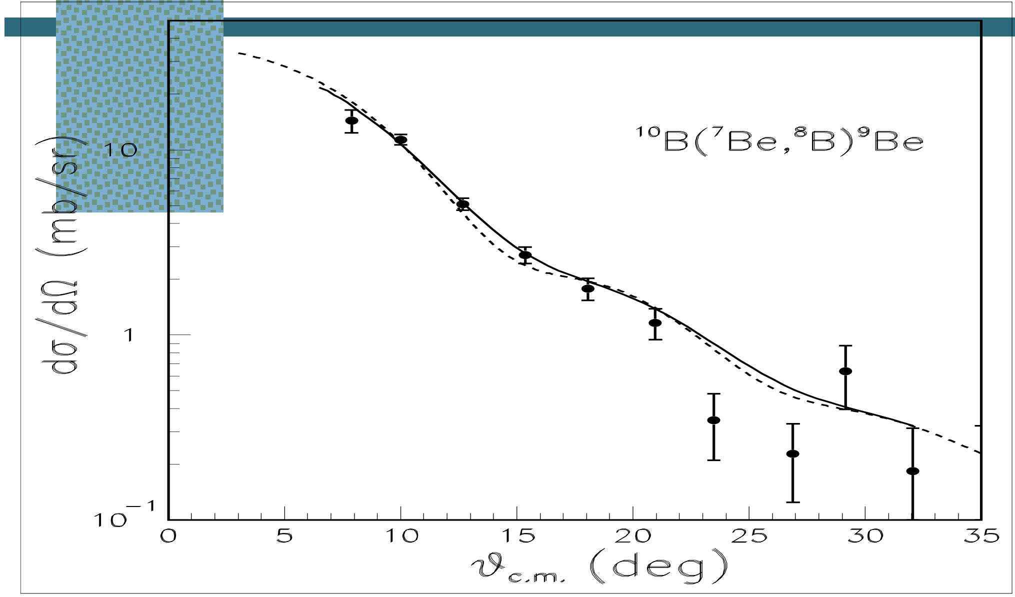


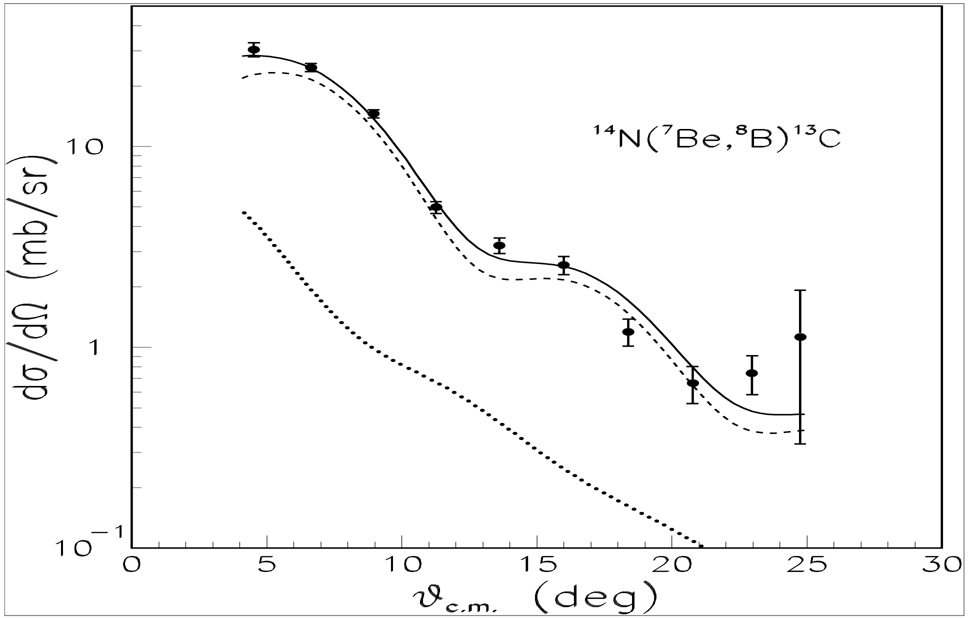
^{14}N Target

New (May 2003 exp.)



S factor for $^7Be(p, \gamma)^8B$



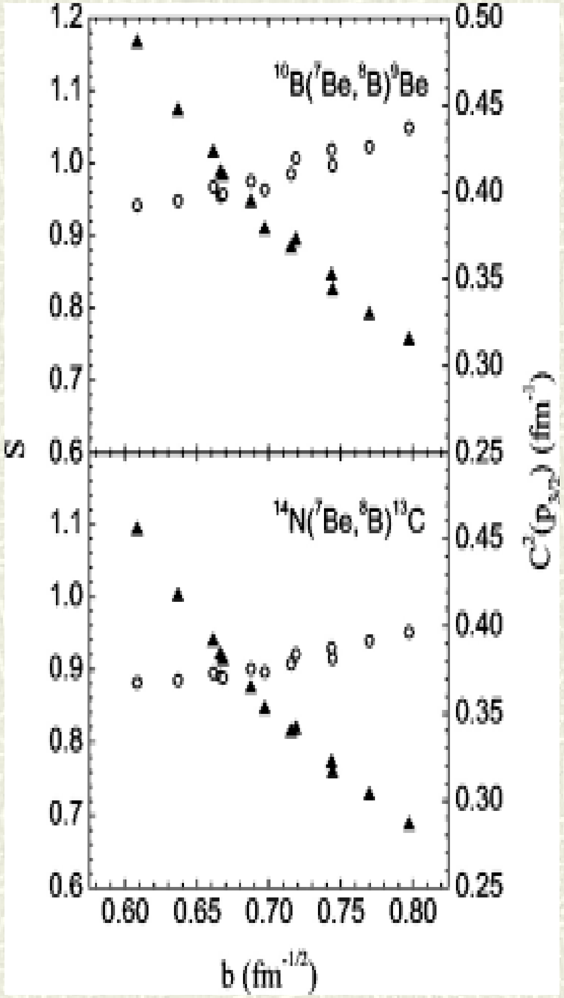


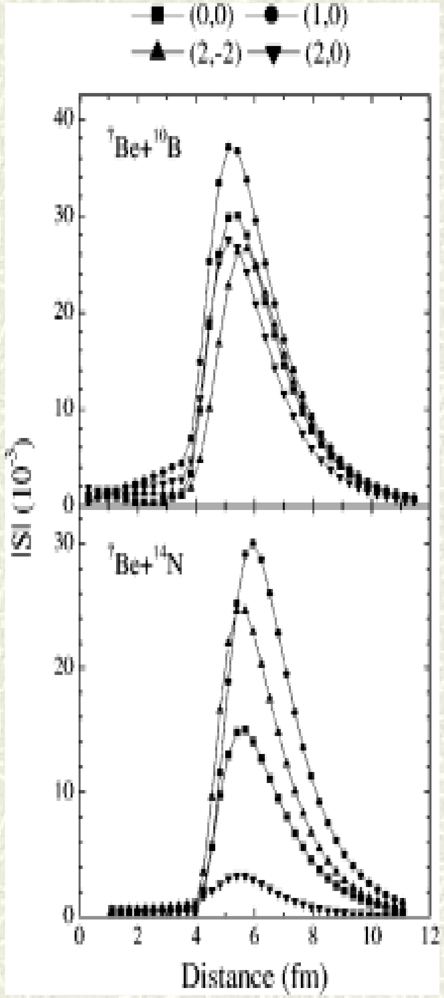
- transfer dσ/dΩ's
- dashed line gives dominant component
- solid line smoothed for angular acceptance
- Fits _ **ANC's**
- $C^2(^{10}B) = 0.410 \pm .055$ fm^{-1}
- $C^2(^{14}N) = 0.388 \pm .039$ fm^{-1}
- Astrophysical S-factor:

  S_{17}=17.3 ± 1.8 eVb

A. Azhari e.a., PRC 63 (2001)

$^{10}B(^{7}Be,^{8}B)^{9}Be$ and $^{14}N(^{7}Be,^{8}B)^{13}C$ reactions





Left Comparison of variation of calculated spectroscopic factors (triangles, left axis) and the ANC's (circles, right axis), obtained for different values of well radius and diffuseness for each target.

Right *S*-matrix calculations for the transfer reactions as a function of separation distance. Calculations were performed for several values of (L_X ,Δl), where $L_X = l_{Projectile} - l_{Target}$ and $\Delta l = L_{out} - L_{in}$

Neutron transfer – $^{14}N(^{7}Li,^{8}Li)^{13}C$

Study mirror reaction – neutron transfer with stable beam to obtain information on ^{8}Li

Use charge symmetry ^{8}Li - ^{8}B

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **67**, 062801(R) (2003)

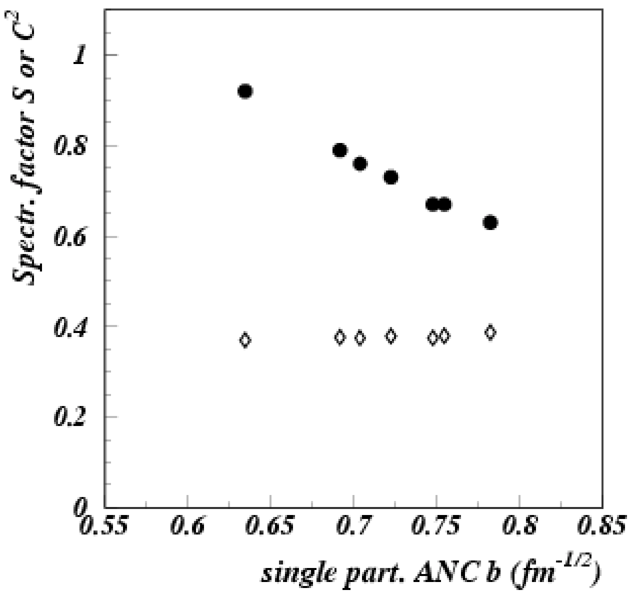


FIG. 1. The angular distribution for the $^{13}C(^{7}Li,^{8}Li)^{12}C$ reaction. The data are shown as points, and the solid line is the best fit. The $p_{1/2}\rightarrow p_{1/2}$ component is shown as a dotted line, and the $p_{1/2}\rightarrow p_{3/2}$ component is the dashed line.

TABLE II. The results of the present study for different optical model parameters used for the DWBA calculations. The entrance/exit channel combinations refer to the potentials in Table I. See text for further explanation.

Poten... (entra...					
POT1					
POT2					
POT1					
POT1					
Avera...					
Avera...					
Fit/av...					
Fit/fit					
POT1/$^{7}Li+^{12}C$	0.370	0.044	0.118	2.5	0–30
POT1/$^{6}Li+^{13}C$	0.409	0.047	0.115	2.9	0–30
POT1/JLM-WS	0.408	0.047	0.114	3.0	0–30
weighted average	0.384	0.048	0.125		

Result:

$C^2_{tot}(^{8}B) = 0.455 \pm 0.047\ fm^{-1}$

$S_{17}(0) = 17.6 \pm 1.7$ eV b

LT e.a., PRC 67, June 2003

Transfer reactions

Transfer reactions for nuclear astrophysics:

C. Rolfs, Nucl. Phys. A217, 29 (1973)

ANC method:

LD Blokhintsev, I Borbely, and EI Dolinskii, Fiz. Elem. Chastits At. Nucl. 8, 1189 (1977) + some

HM Xu, CA Gagliardi, RE Tribble, AM Mukhamedzhanov and NK Timofeyuk, Phys Rev Lett. 73, 2027 (1994) + many

Reactions studied (TAMU):

$^{10}B(^{7}Be,^{8}B)^{9}Be$ and $^{14}N(^{7}Be,^{8}B)^{13}C$ for S_{17}

$^{14}N(^{11}C,^{12}N)^{13}C$ for $^{11}C(p,\gamma)^{12}N$

$^{14}N(^{13}N,^{14}O)^{13}C$ for $^{13}N(p,\gamma)^{14}O$

Also $^{13}C(^{7}Li,^{8}Li)^{12}C$ - mirror to $(^{7}Be,^{8}B)$ reaction for S_{17}

$^{14}N(^{17}F,^{18}Ne)^{13}C$ w. HRIBF Oak Ridge for $^{17}F(p,\gamma)^{18}Ne$

Others (Beijing, RIKEN, Kolkata, etc...):

$d(^{7}Be,^{8}B)n$, $^{12}C(d,p)^{13}C$, $d(^{8}B,^{9}C)n$ ...

Other tests

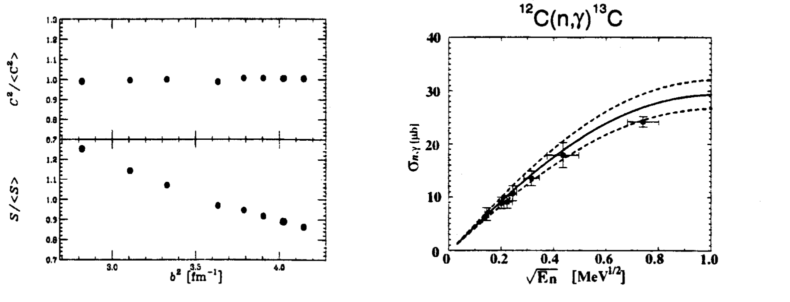


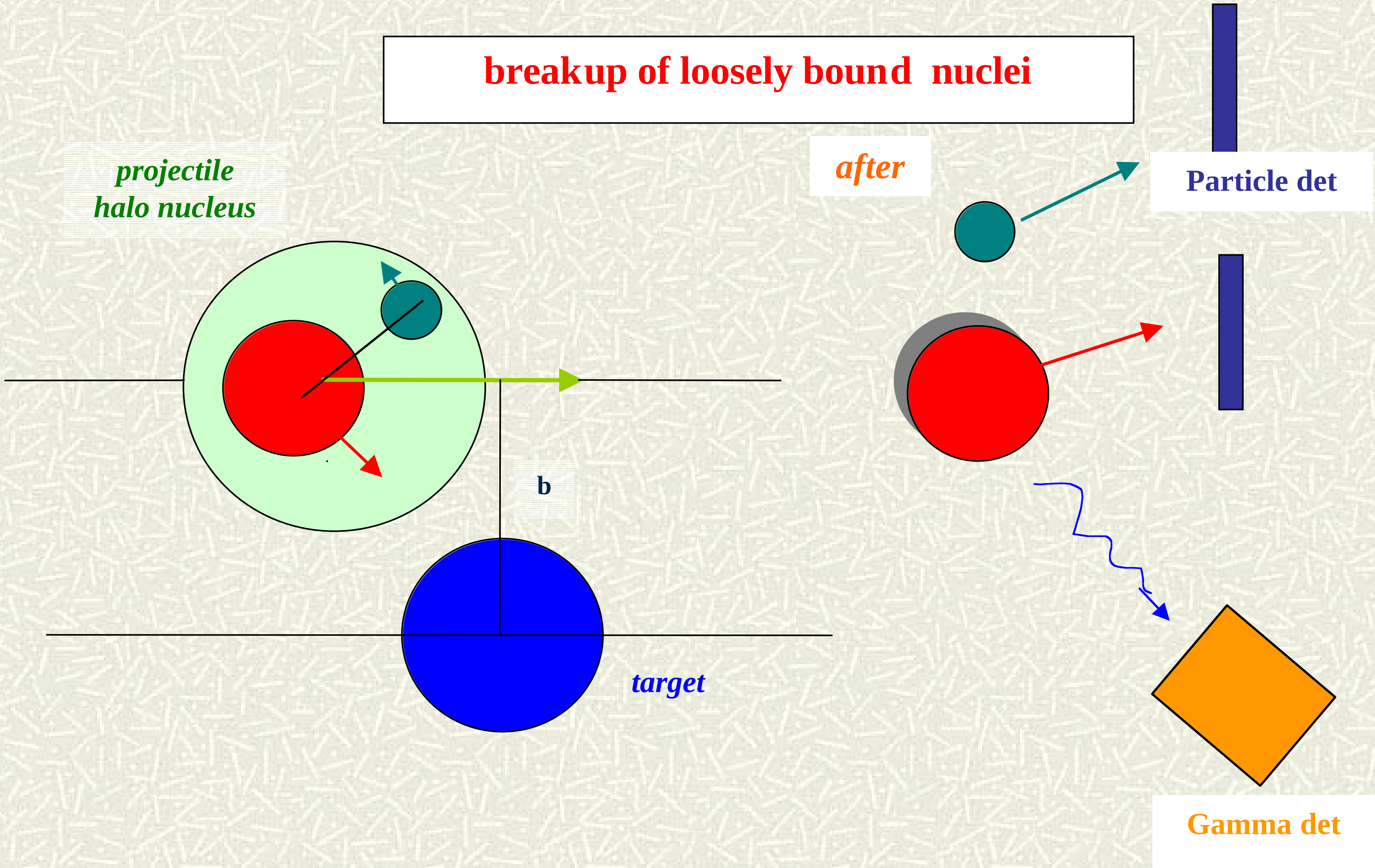
Figure 3. The variation of the spectroscopic factor S (lower panel) and the ANC C (upper panel) as a function of the single asymptotic amplitude ANC b^2.

Figure 4. The (n,γ) cross sections as a function of $\sqrt{E_n}$. The points indicate the experimental data [3]. The solid line is the deduced cross sections with the ANC mean value and the dashed lines shows the range of the systematic error.

Test of the ANC Method via (d,p) Reaction
12C(d,p)13C*(1/2+), E=11.8 MeV
N. Imai, N. Aoi, S. Kubono et al.,
Nucl. Phys. A688, 281c (2001)

A. Stromich, B. Steinmetz, R. Bangert, B. Gonsior, M. Roth and P. von Brentano, Phys. Rev. C 16, 2193 (1977).

Breakup


breakup of loosely bound nuclei
projectile
halo nucleus
after
Particle det
b
target
Gamma det

Spectroscopic factors vs. ANCs

Assume configuration mixing for the projectile wave fct.

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

With s.p. wave fct asymptotic behavior

$$\varphi_{nlj} \to b_{nlj} \frac{W_{-\eta,l+1/2}(2\kappa r)}{r}$$

for the peripheral region, ***r>R$_N$*** the overlap integral is

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

The ANC formulation avoids the dependence on the choice of the geometry of the proton binding potential *(r_0,a)* *and is better than spectroscopic factor for halo nuclei where geometry is unknown and speculative at best!*

Reaction model: 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 (^8B, ^9C, ^{11}Be, ^{14}B, ^{15}C, etc…) 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

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

If the reaction is peripheral we can reverse the process: use experimental data to extract spectroscopic factors or ANCs!

For ^8B and ^9C: $1p_{3/2}$ and $1p_{1/2}$ mixing and write:

$$\sigma_{\exp} = (S_{p_{3/2}} + S_{p_{1/2}})\sigma_{sp}(p_j) = (C^2_{p_{3/2}} + C^2_{p_{1/2}})\frac{\sigma_{sp}}{b_p^2}$$

and extract either the sum of spectroscopic factors, or the sum of the ANCs.

For ^8B we correct for core excitation contribution using GSI data at 936 MeV/u (D. Cortina-Gil et al., Phys. Lett. B529, 36 (2002) - GSI data):

$$\frac{C_e^2 / b_e^2}{C_g^2 / b_g^2} \approx \frac{C_e^2}{C_g^2} \approx \frac{S_e}{S_g} = 0.16\,(4)$$

Spectroscopic factors vs. ANCs (cont'd)

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:

$^7Be(p,\gamma)^8B$ - solar neutrino problem!!

from ^8B breakup at E/A= 30 –1000 MeV/u.

from p transfer @ 12MeV/u

and $^8B(p,\gamma)^9C$ - hot pp chains!

from ^9C breakup at 285 MeV/u.

Also: $^{14}C(n,\gamma)^{15}C$ – neutron source Inhomogeneous Big Bang

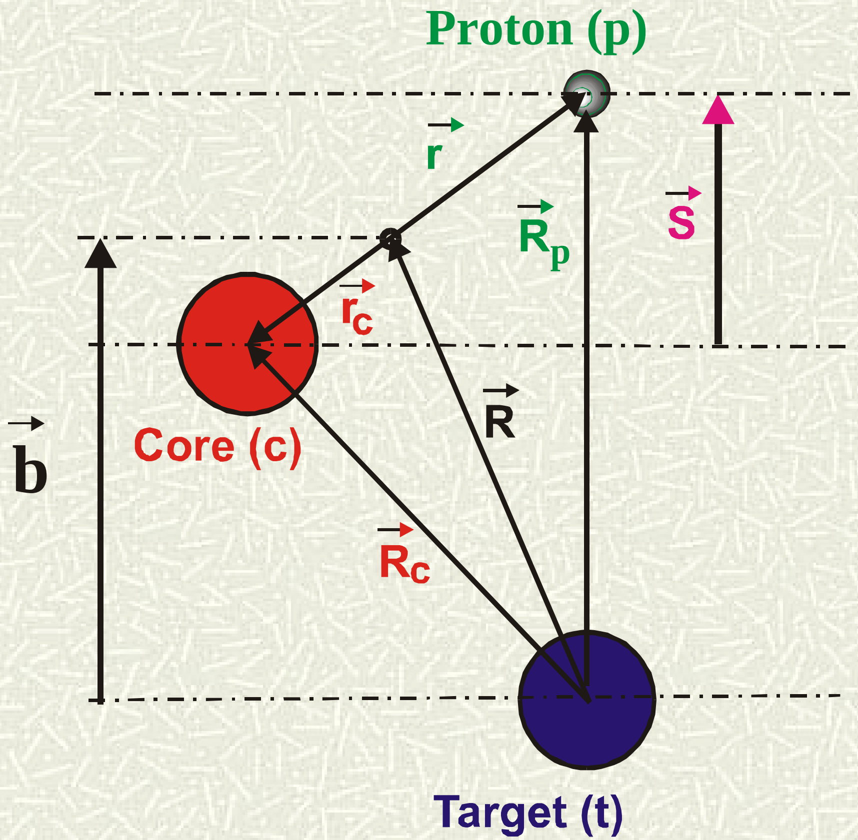
from ^{15}C breakup at 54 and 62 MeV/u.

Coordinates and parameters used in the Glauber model calculations

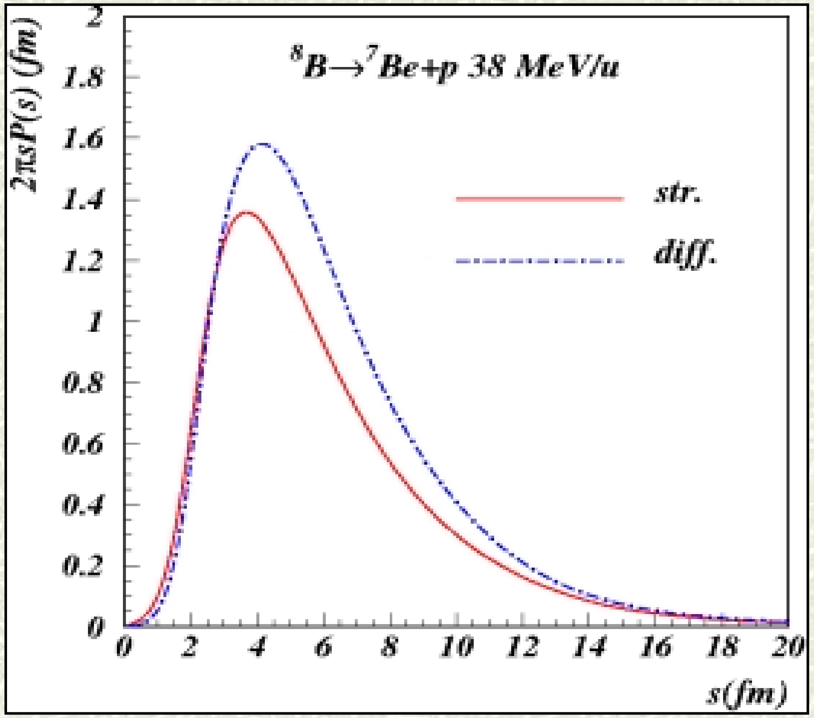
^{8}B S_p=0.137 MeV

^{9}C S_p=1.296 MeV

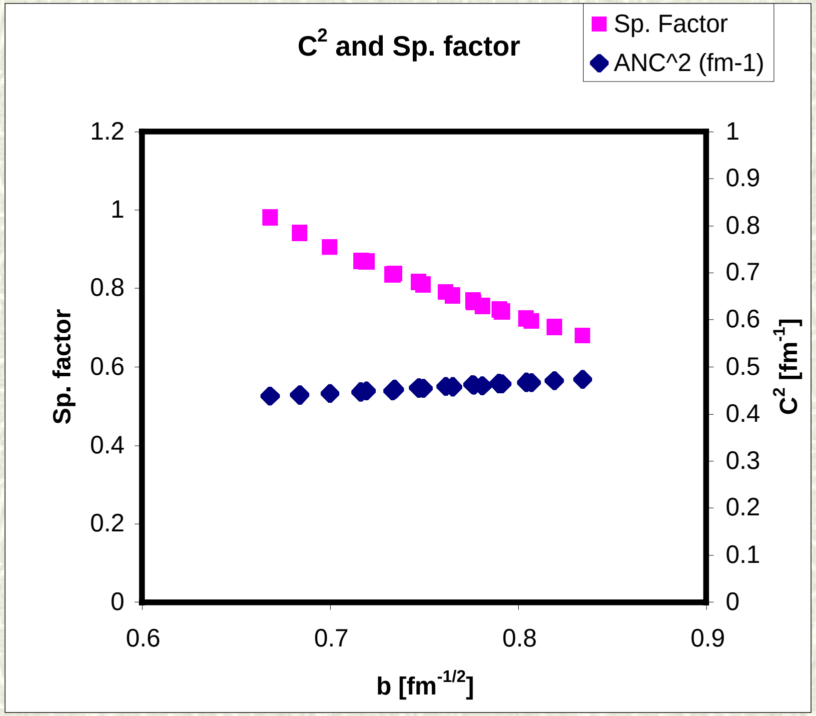
For S-matrix calc we used potentials from double folding with JLM effective interactions, as tested before for elastic scattering (L. Trache e.a. – PRC 61, 024612 (2000)).



Check for peripherality of breakup

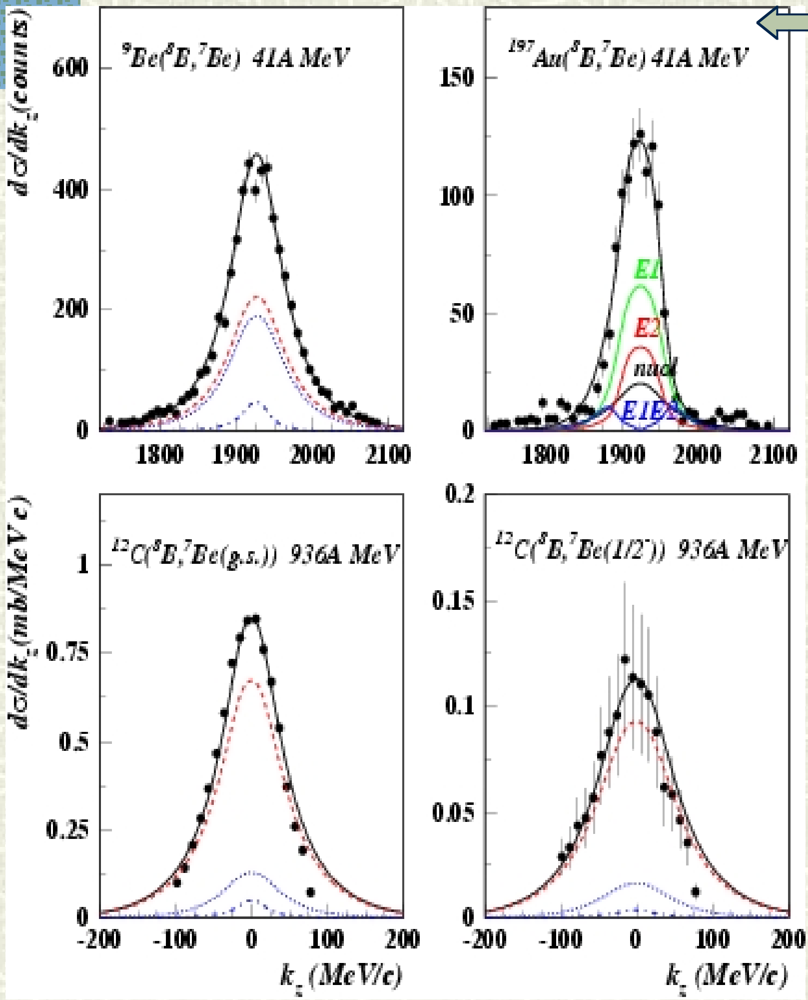


Breakup probabilities vs distance



Spectroscopic factors vs ANC for ^8B breakup at 38 MeV/u (GANIL data, Negoita ea, PRC 54 (1996)

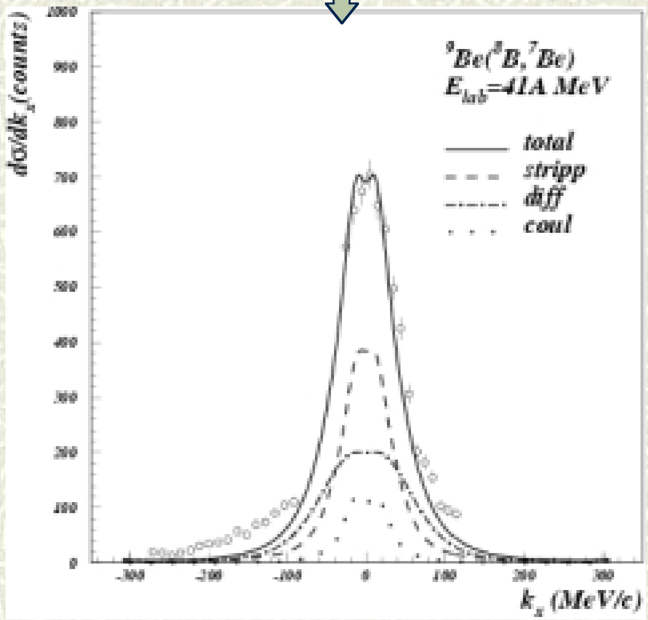
^{8}B breakup – momentum distributions



Parallel momentum distributions

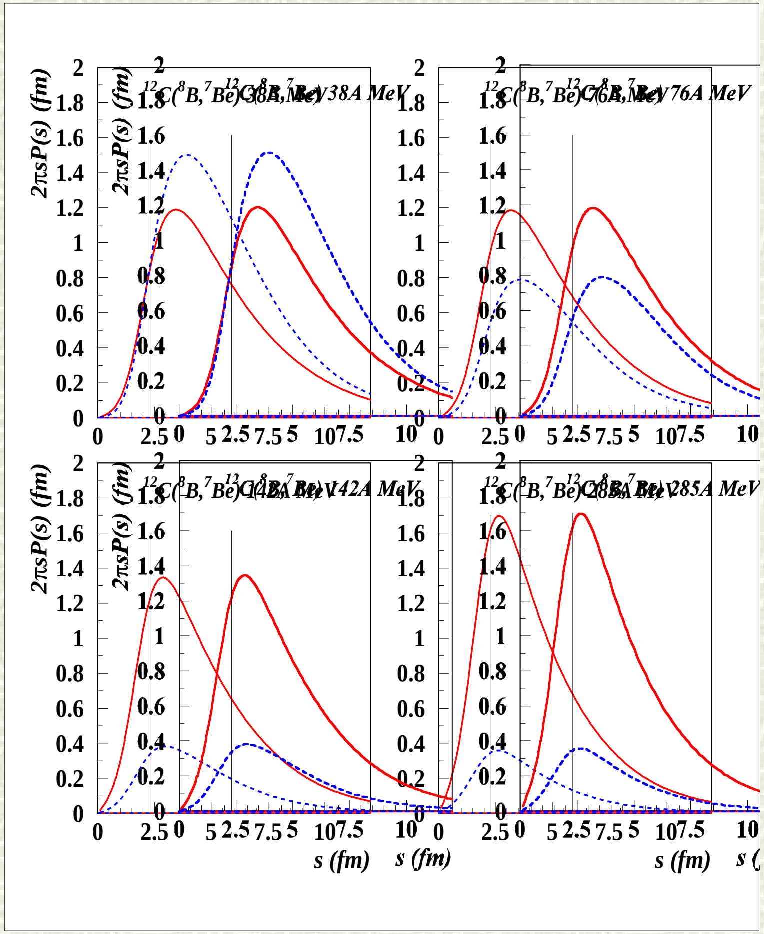
J. H. Kelley et al., PRL 77 (1996) and D. Cortina-Gil et al., Nucl. Phys. A720 (2003)

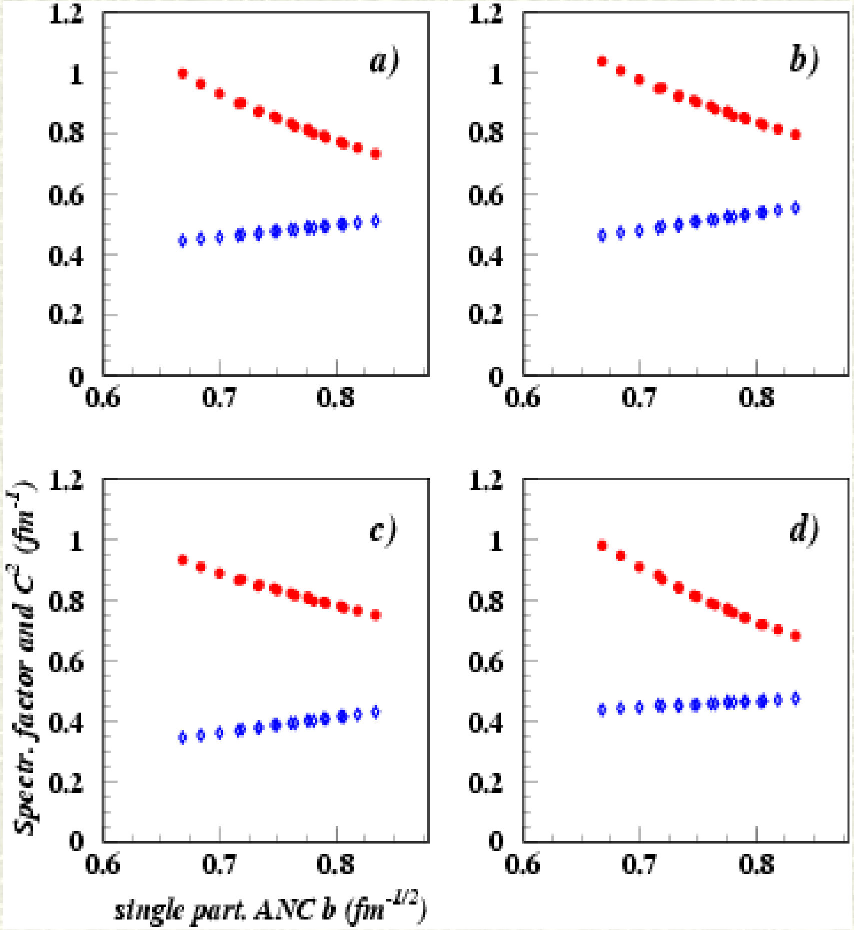
Transverse momentum distribution



How peripheral?!

(a, b, c) - @ 76A, 142A MeV, 285A MeV on C
(d) @285A MeV on Pb



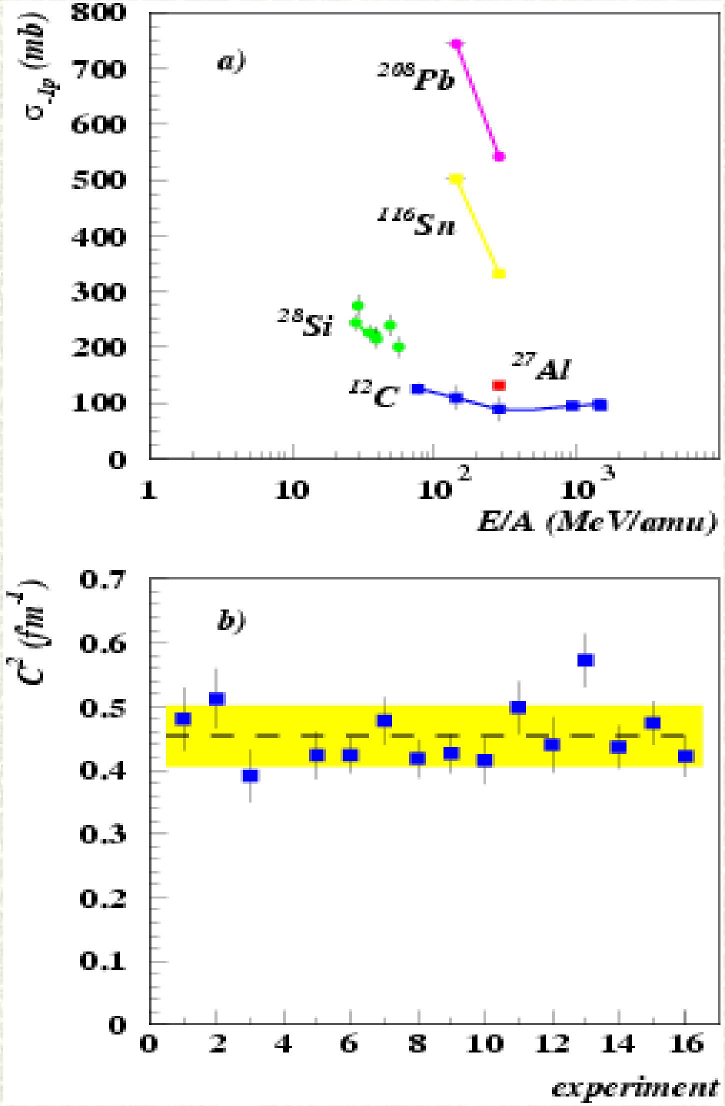


^{8}B breakup with JLM effective interaction

Use data from:

Exp	Target	E/A	Ref
1-4	C	76 142,285, 936	[1] [2] [3]
5	Al	285	[2]
6-12	Si	28-56	[4,5]
13,14	Sn	142,285	[2]
15,16	Pb	142,285	[2]

[1] J. Enders e.a., Phys Rev C 67, 064302 (2003)
[2] B. Blank et al, Nucl Phys A624, 242 (1997)
[3] D. Cortina-Gil e a, EuroPhys J. 10A, 49 (2001).
[4] F. Negoita et al, Phys Rev C 54, 1787 (1996))
[5] R. E. Warner et al. – BAPS 47, 59 (2002).



Result

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

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

and using:

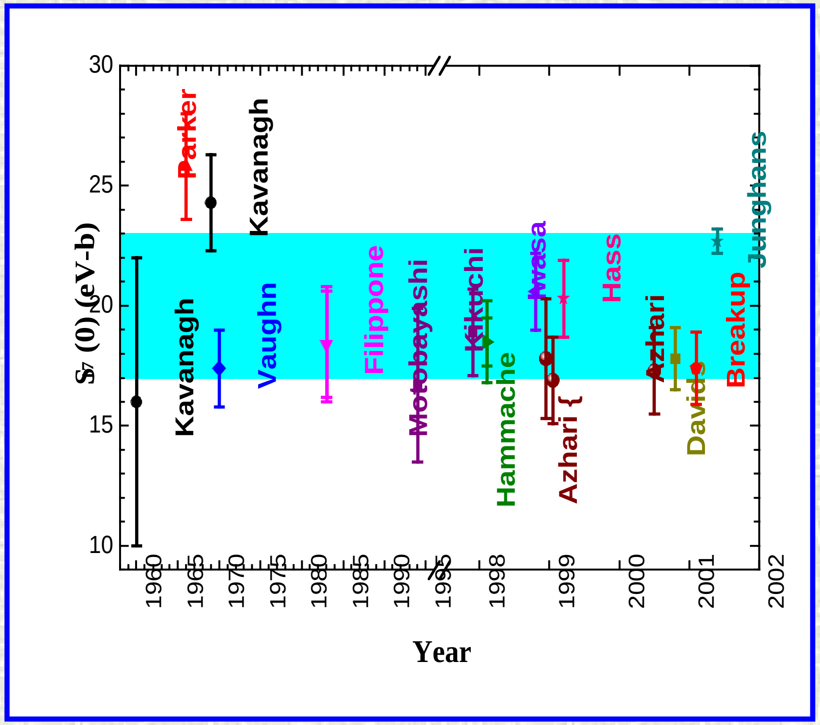
$$S_{17}(0) = \frac{38.6 \text{ eV b}}{\text{fm}^{-1}} \left(C^2_{p_{3/2}} + C^2_{p_{1/2}}\right)$$

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

(L.T., F. C. et al. Phys Rev Lett 87, 271102 (2001))

In agreement with most indirect and direct measurement results, but one … (figure).

Go to extend and test the calculations using …



Various effective interactions

A. Glaubermodel 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, ^{8}B, ^{11}C and ^{13}N on ^{12}C, ^{14}N)

$$V[W](R) = N_V[N_W]\int d\vec{r}_1 d\vec{r}_2 \rho(r_1)\rho(r_2) v_{eff}(\rho, E, \vec{s}), \vec{s} = \vec{r}_1 + \vec{R} - \vec{r}_2$$

$$\chi(b) = -\frac{1}{\hbar v}\int dz V(b,z) + high \quad order \quad corr.$$

***found no renorm for imaginary pot Nw=1.0* at 10 MeV/u. Assumed correct at all energies !!!**

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

Various effective interactions (cont'd)

B. Glauber model calc in the optical limit

Use three ranges for interactions, to check the sensitivity:

3) zero-range μ_0

4) "standard" μ=1.5 fm for all terms

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

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

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

Test how the calculations reproduce other observables: reaction cross-sections (p, ^{7}Be and ^{8}B on a ^{12}C target) and total cross sections (p on ^{12}C).

No new parameters!!!

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

Data from:

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

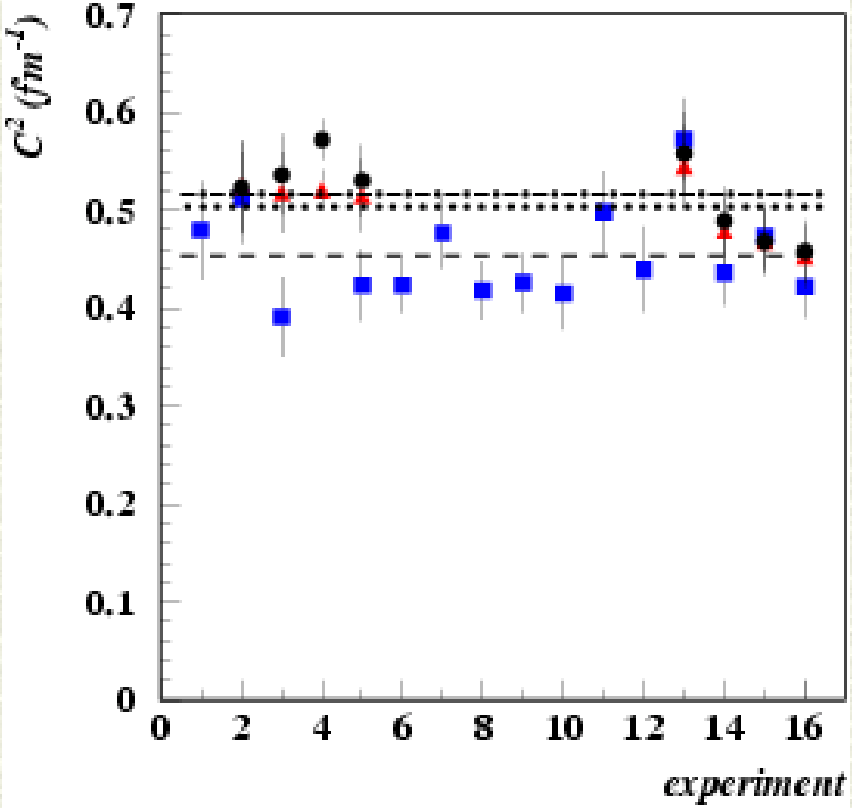
B. Blank et al, Nucl Phys A624, 242 (1997)

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

D. Cortina-Gil e a, EuroPhys J. 10A, 49 (2001).

R. E. Warner et al. – BAPS 47, 59 (2002).

J. Enders e.a., Phys Rev C 67, 064302 (2003)



Summary of results:

The calculations with 3 different effective nucleon-nucleon interactions are kept and shown:

JLM (blue squares),

"standard" μ=1.5 fm (black points) and

Ray (red triangles).

S_{17} astrophysical factor (ours)

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

- **JLM S_{17}=17.4±2.1 eVb** no weights
- **"standard" S_{17}=19.6±1.2 eVb**
- **Ray S_{17}=20.0±1.6 eVb**
- Franey-Love S_{17}=20.7±2.2 eVb
- **Average first 3:**

S_{17}=18.9±2.0 eVb

(all points, no weights)

For comparison:

〈 (^{7}Be,^{8}B) proton transfer at 12 MeV/u

(A. Azhari e.a., Phys Rev C 63, 055803 (2001))

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

$S_{17}(0) = 17.3 \pm 1.8$ eV•b

〈 ^{13}C(^{7}Li,^{8}Li)^{12}C at 9 MeV/u

(LT e.a., PRC 66, June 2003))

$C^2_{tot} = 0.455 \pm 0.047$ fm^{-1}

$S_{17}(0) = 17.6 \pm 1.7$ eV•b

Status of S_{17} determinations (direct)

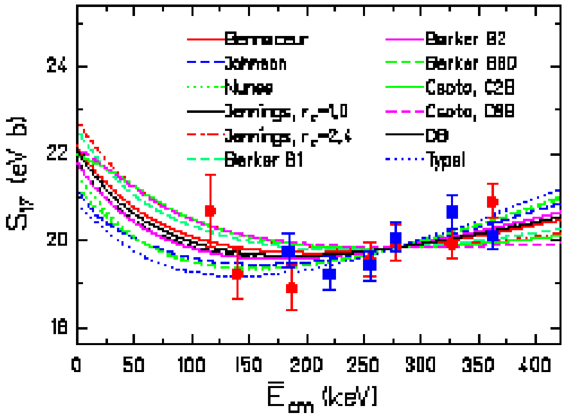


FIG. 16: Fits of 12 different theories to the BE3 data below the resonance - see [42].

TABLE VI: $S_{17}(20)$ and $S_{17}(0)$ (in eV b) from fitting our data with $\bar{E}_{cm} \leq 362$ keV with different models, as in Fig. 16 and ref. [42].

Model	$S_{17}(20)$	$S_{17}(0)$
Nunes	20.8	21.4
Johnson	20.5	21.2
Bennaceur	21.5	22.2
Barker B80	20.7	21.2
Barker B1	21.8	22.6
Barker B2	21.1	21.8
Csoto C2B	21.7	22.0
Csoto C8B	21.8	22.1
Jennings $r_c = 2.4$ fm	22.0	22.8
Jennings $r_c = 1.0$ fm	21.1	21.8
Typel	20.3	20.8
Descouvemont	21.4	22.1

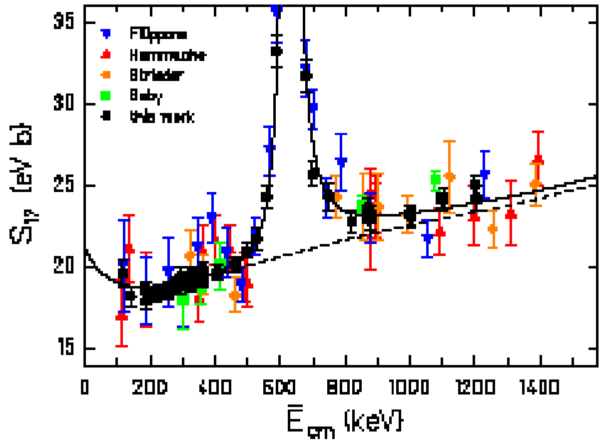


FIG. 18: S-factor data from direct experiments, all normalized to a common value of $S_{17}(0)$ (the mean DB best-fit value of 21.1 eV b - see Table VII). The error bars shown are relative, and do not include scale-factor uncertainties. Solid curve: DB plus a 1^+ resonance with parameters determined from fitting our BE1 data. Dashed curve: DB only. Calculations and data are normalized in the energy range $\bar{E}_{cm} \leq 1200$ keV.

from A. Junghans et al, nucl-exp/0308003

Status of S_{17} determinations (cont'd)

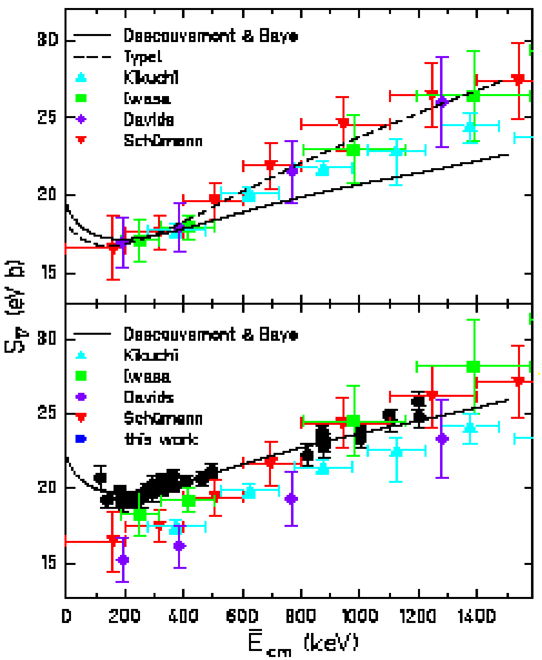


FIG. 19: E1 ^{7}Be(p,γ)^{8}B S-factors inferred from Coulomb dissociation (CD) experiments. Bottom panel: absolute CD S-factors, together with our direct results (with the 1^+ resonance subtracted) and the best-fit DB curve to our direct low-energy data. Top panel: CD data plotted with a common normalization based on the mean value of 19.3 eV b for $S_{17}(0)$ determined by fitting each data set to the DB theory below 400 keV. Solid curve: DB calculation; dashed curve: Typel calculation. The experimental error bars shown in all cases are relative, and do not include scale-factor uncertainties.

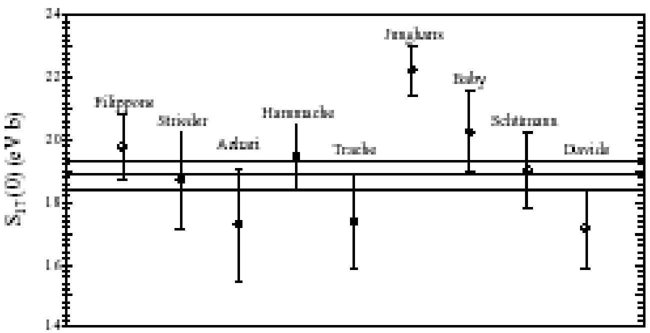


FIG. 6: Zero energy astrophysical S factors for the ^{7}Be$(p,\gamma)^8$B reaction based on experimental measurements at relative energies < 400 keV extrapolated with a potential model constrained by ^{7}Be + p elastic scattering data. The 1σ total uncertainties include extrapolation contributions evaluated individually for each measurement as explained in the text. Also shown are the ANC results of Azhari *et al.* and Trache *et al.* A weighted mean of eight of these nine measurements yields 18.9 ± 0.5 eV b (1σ), with $\chi^2 = 5.8$ for seven degrees of freedom. This weighted average and its 68% confidence level band are also depicted.

$S_{17}(0)=18.9 \pm 0.5(1\sigma)$ eV b

$S_{17}(0)=21.4 \pm 0.5(\text{exp}) \pm 0.6(\text{theor})$ eV b

B. Davids and S. Typel, nucl-th/0304054

A. Junghans e.a., nucl-ex/0308003

^{9}C_ ^{8}B+p breakup for ^{8}B(p,γ)^{9}C

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 $^{8}B(p,\gamma)^{9}C(\alpha,p)^{12}N(p,\gamma)^{13}O(\beta^{+}\nu)^{13}N(p,\gamma)^{14}O$.

Use breakup of ^{9}C->^{8}B+p at intermediate energies to obtain ^{8}B(p,γ)^{9}C at astrophysical energies.

Analyze existing data from

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

^{9}C @285 MeV/u on C, Al, Sn and Pb targets

Find new reaction rate:

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

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

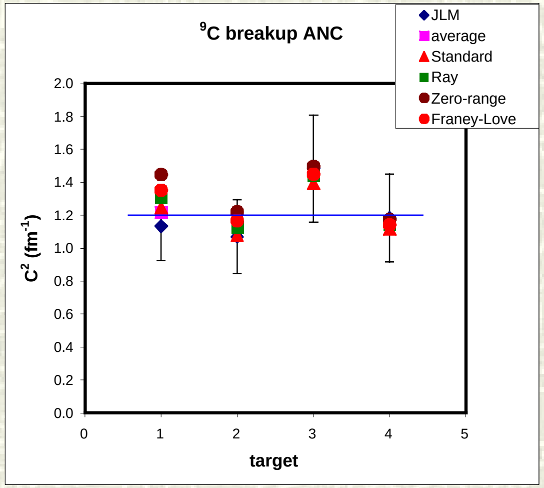


Figure. The results of similar calculations for ^{9}C.

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

and $S_{18}(E)=47.3-15.1E+7.34E^2$ eVb (E in MeV)

Other 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.

NEW: Coulomb dissoc at RIKEN – Motobayashi et al., unpublished, gives a higher value S_{18}=77±15 eV·b. (disagrees)
NEWER: breakup at MSU (Enders ea, PRC 67, 064301 (2003)) agrees: C^2=1.27±0.10 fm^{-1}.

Conclusions

- **Reliable spectroscopic information can be extracted from one-nucleon breakup reactions (as per GANIL, GSI, MSU, RIKEN results).**
- **A better 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).**
- **The validity of the method is wider than for the ^{8}B, ^{9}C and ^{15}C cases discussed above.**
- **Very difficult or even impossible direct measurements for nuclear astrophysics 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.**

  Can be done with:

  - few part/sec.

  - cocktail beams.

Everywhere !?!

ANC "stability" vs *l* and S_n

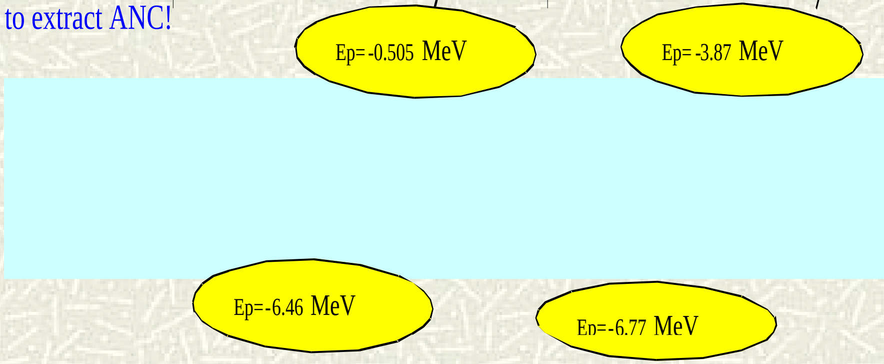
4. Results for ^{11}Be, ^{14}B, ^{15}C – ANCs and halo rms radii

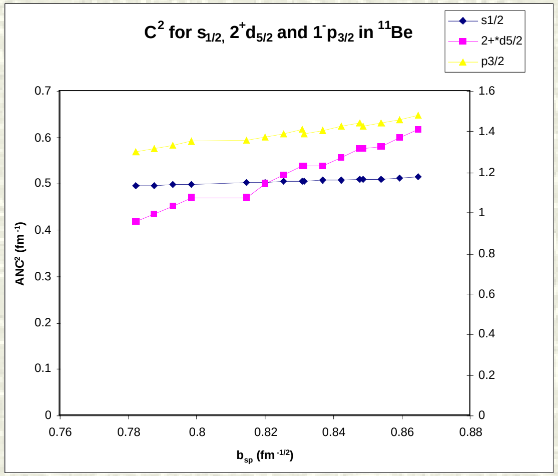
$$\psi(^{11}Be\, g.s.) = S_g^{1/2}\left|^{10}Be \otimes 2s_{1/2}\right\rangle + S_{e1}^{1/2}\left|^{10}Be(2^+) \otimes 1d_{5/2}\right\rangle$$

$$and\ + S_{e2}^{1/2}\left|^{10}Be(1^-) \otimes 1p_{3/2}\right\rangle + S_{e3}^{1/2}\left|^{10}Be(2^-) \otimes 1p_{3/2}\right\rangle + \ldots$$

Spectroscopic factors are not known!

If the process is peripheral we can reverse the process: use experimental data to extract ANC!





data from Aumann et al, **PRL 84**, 35 (2000) ^{11}Be @60 MeV/u on ^{9}Be

Gamma-ray coinc allow to determine the core excitation contributions

breakup cross sect: 203(31) mb, 16(4), 17(4) and 23(6), respectively

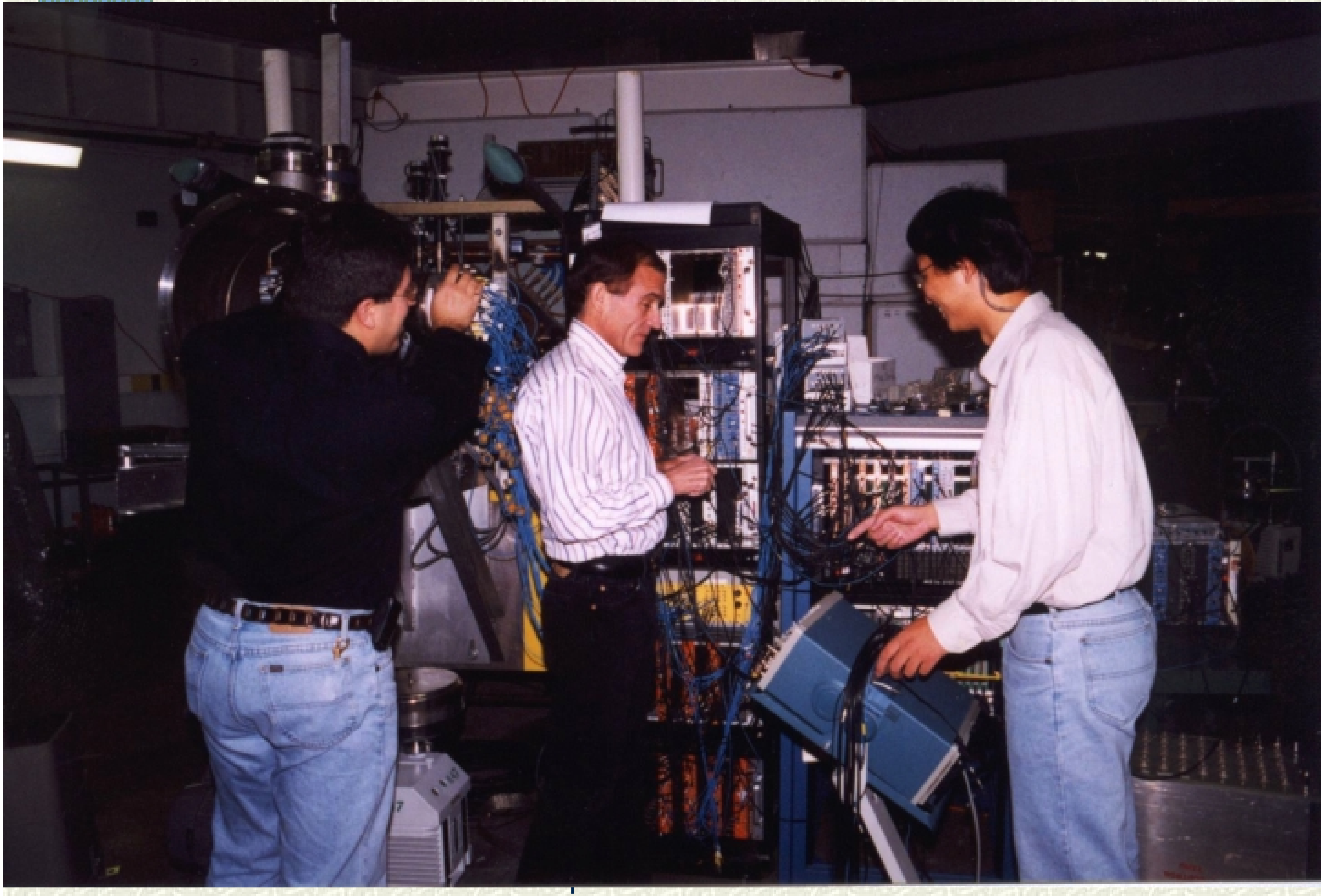
lead to ANCs:

$C^2(2s_{1/2})$=0.505 fm^{-1}($\pm$1.2%) and $C^2(1d_{5/2})$=0.105 fm^{-1} ($\pm$11%) (% uncert from calculations only)

$C^2(1^-\otimes 1p_{3/2})$=1.95 fm^{-1}($\pm$7.6%) and $C^2(2^-\otimes 1p_{3/2})$=2.97 fm^{-1} ($\pm$7.8%)

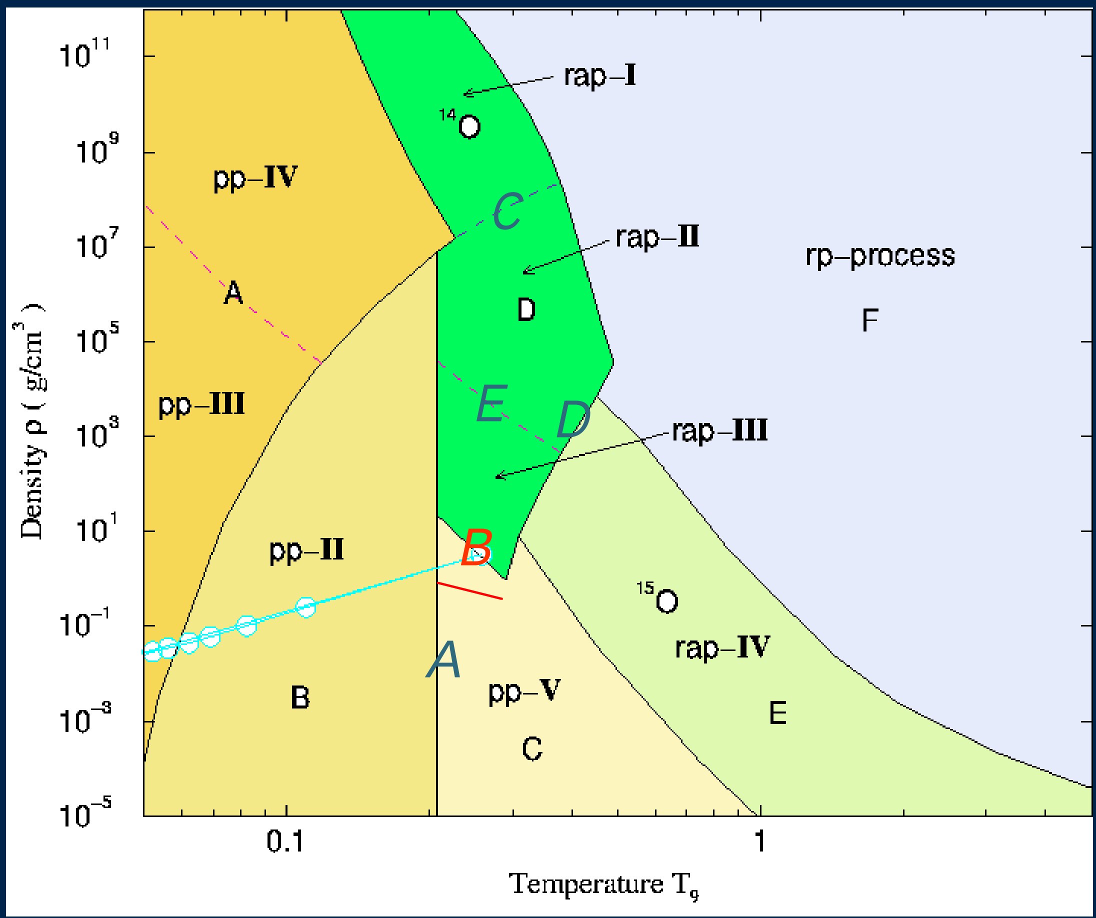
And to a rms halo radius: $\langle r^2\rangle^{1/2}$=6.26(46) fm (all uncertainties included).

$\langle r^2\rangle^{1/2}$=2.6*R(^{10}Be)



Hot p-p chains

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



- $^{7}Be(\alpha,\gamma)$=$^{7}Be(e^{-},\nu)$ ★
- $^{11}C(p,\gamma)$=$^{11}C(\beta^{+}\nu)$
- $^{7}Be(p,\gamma)$=$^{8}B(\gamma,p)$
- $^{11}C(p,\gamma)$=$^{12}N(\gamma,p)$
- $^{12}N(p,\gamma)$=$^{12}N(\beta^{+}\nu)$
- T_9<0.4, DC is dominant
- Rap-II, III can operate with lower densities
- The implication to the scenario of Pop III star evolution relies on new calculations with the latest rates

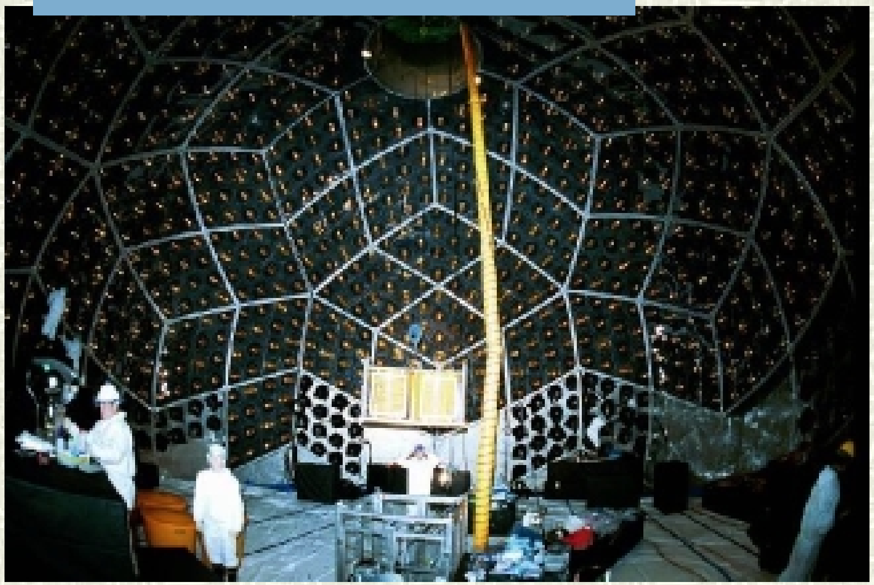
Spectroscopic factors vs Asymptotic Normalization Coefficients from breakup and transfer reactions with loosely bound nuclei

Livius Trache
Texas A&M University

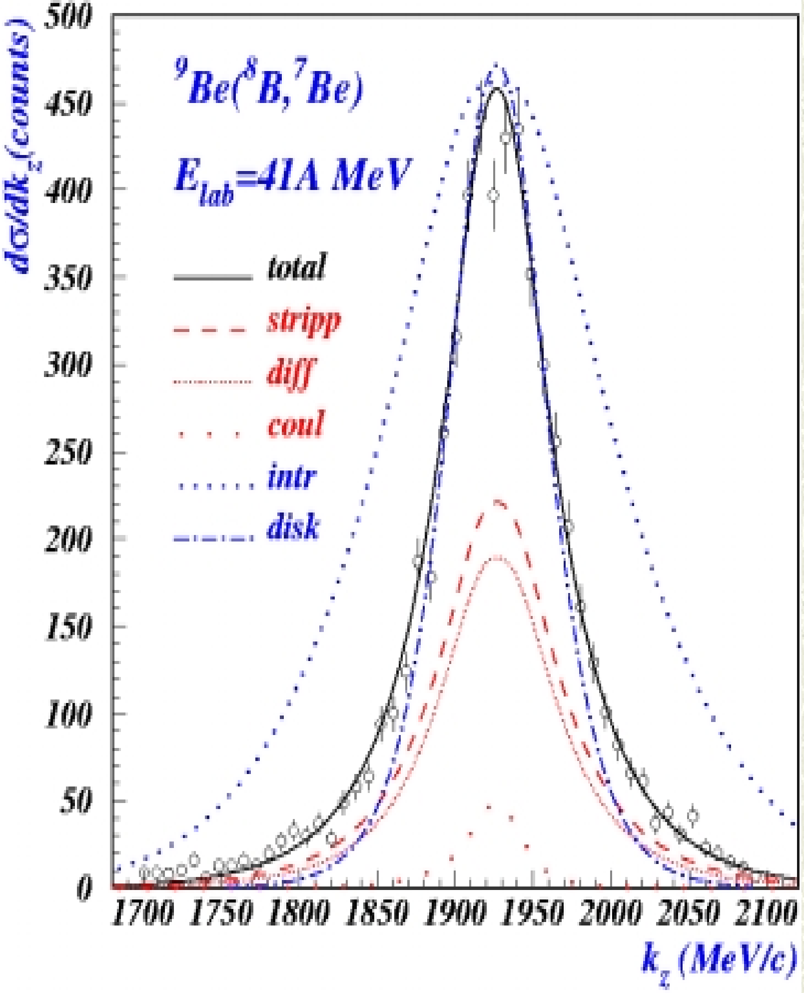
Trento, March 2004

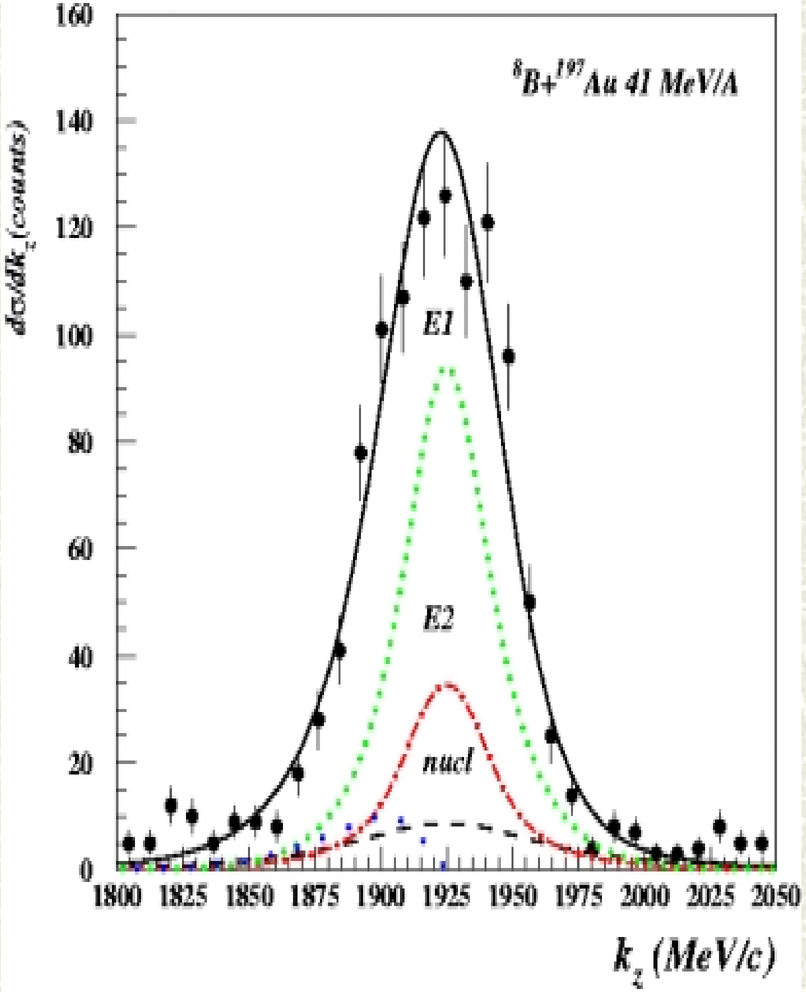
Questions

Tools to seek answers



Parallel momentum distributions





MSU data: JH Kelley et al, PRL 77, 5020 (1996)