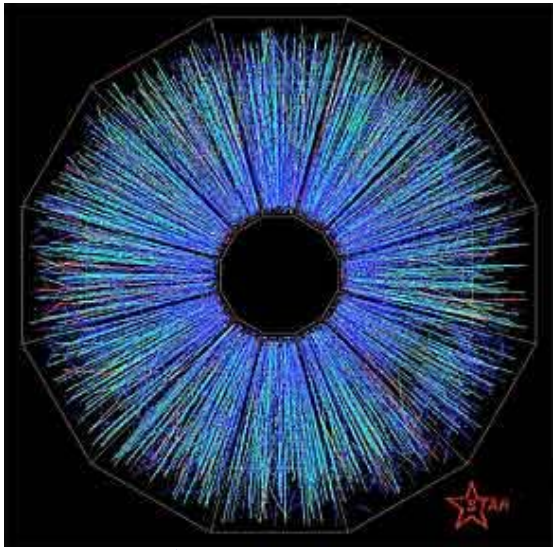
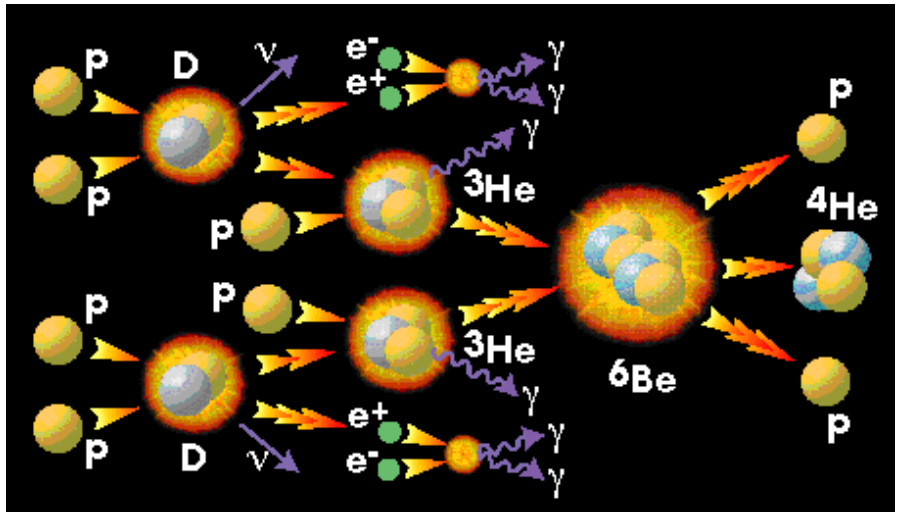
Direct Reactions in/for Nuclear Astrophysics

Carlos Bertulani
(University of Arizona)

Nuclear Astrophysics





TeV / nucleon

???

Exotic stellar site

Quark matter in compact stars, Big Bang

keV / nucleon

???

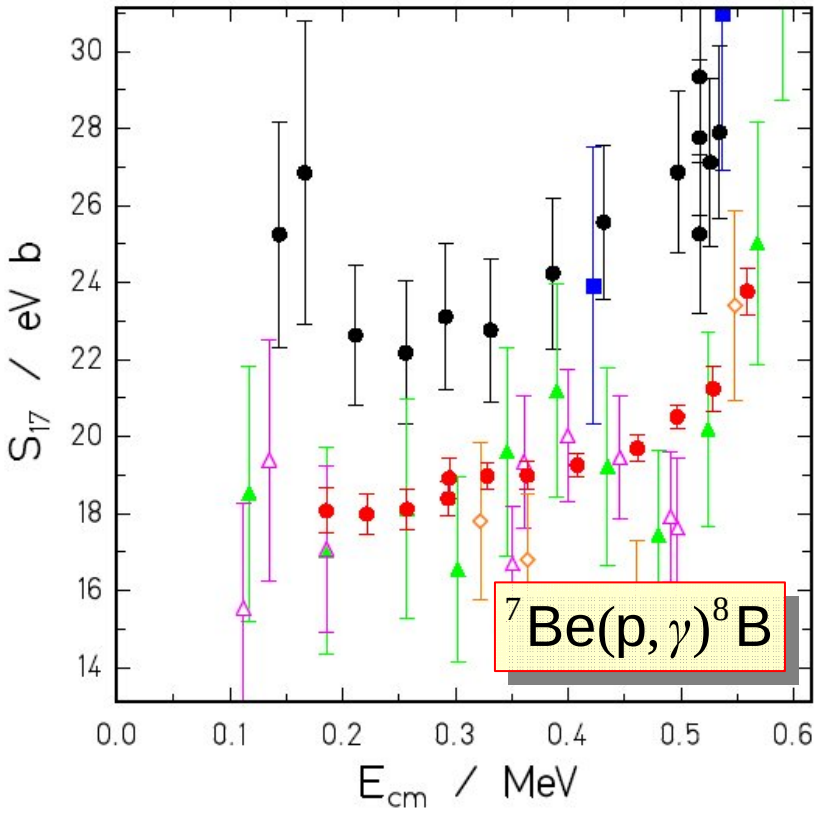
Typical stellar site

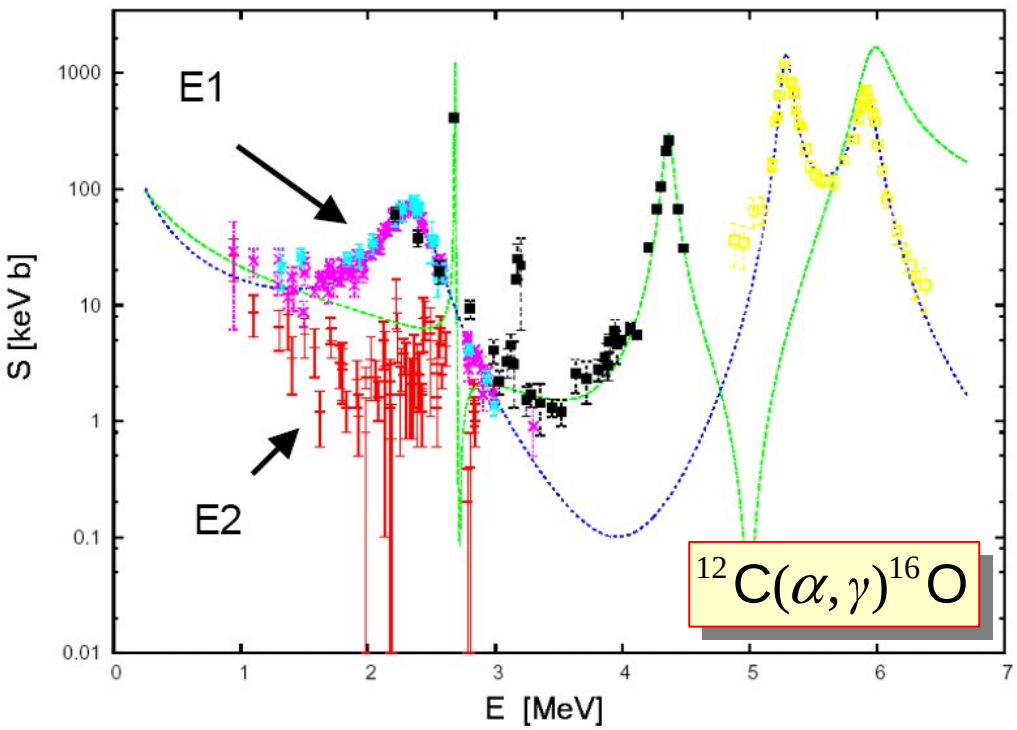
Stellar evolution

Nuclear many-body problem:
one of the hardest problems of all physics!

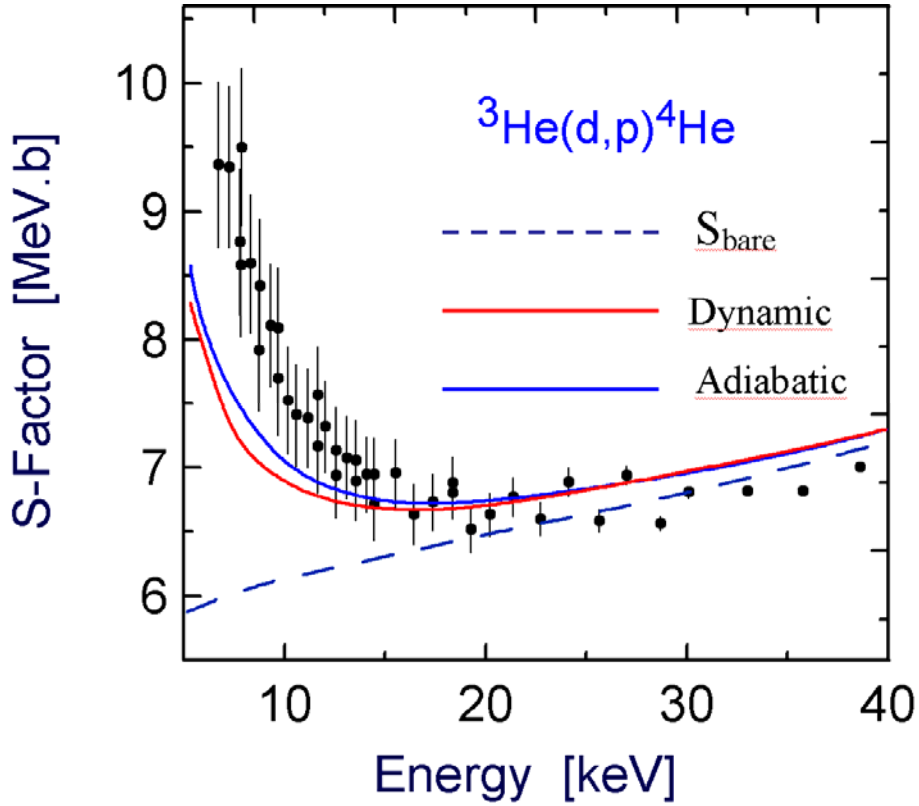
- Interactions are complicated
- Nucleons = composite particles
- Requires large computation

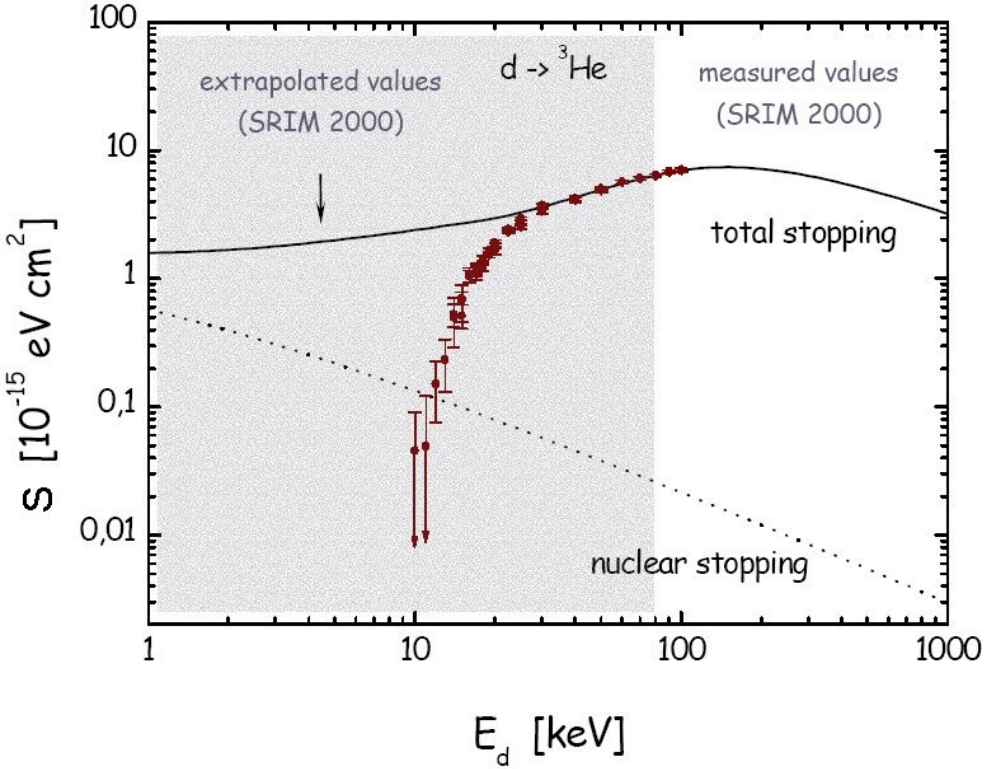
Typical problems





Electron screening: (a) in stars (theoretical)
(b) on earth (experimental+theoretical)





Stopping power tables wrong? YES

CB, de Paula, PRC 2000, 2004

Atomic, QED, or nuclear effects?

NO

CB, Balantekin, Hussein, NPA 1997

Solutions with direct reactions at 50-200 MeV/nucleon

(A) Trojan horse

A(a=b+x,b+c)C → A(x,c)C

Baur, PLB 1986

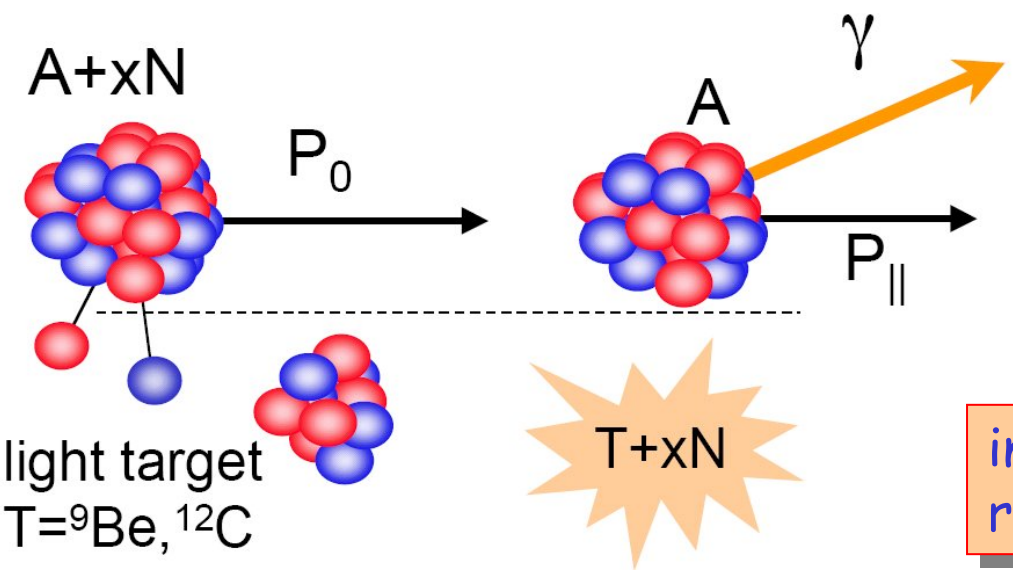
Claudio Spitaleri, Catania

(B) ANC

Akram Mukhamedzhanov, 1991

Talk by Bob Tribble, Tuesday

(C) Knockout reactions



$$\frac{d\sigma}{dk_Z}$$

CB, McVoy, PRC 1992

best probe of ψ

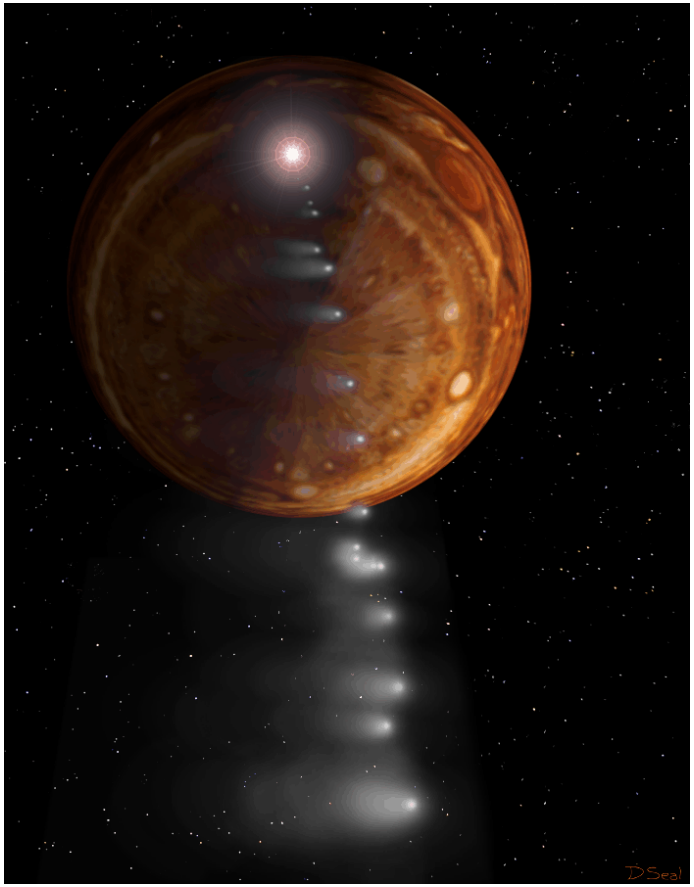
Spectroscopic factors

input for nuclear reactions in astrophysics

Hansen, Tostevin, ARNPS 2003

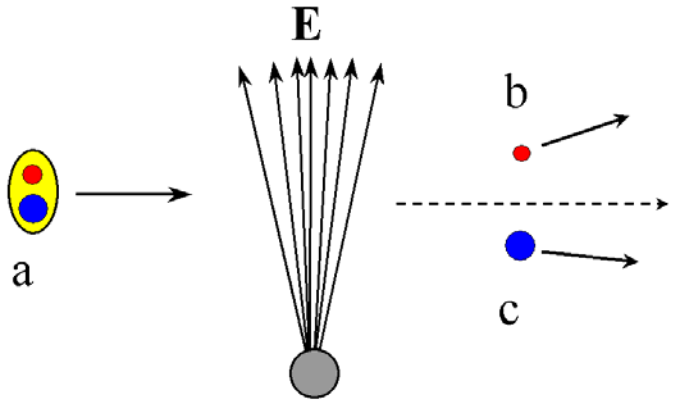
CB, Hansen, PRC 2004

Coulomb dissociation



Shoemaker-Levy comet

(easier than this)

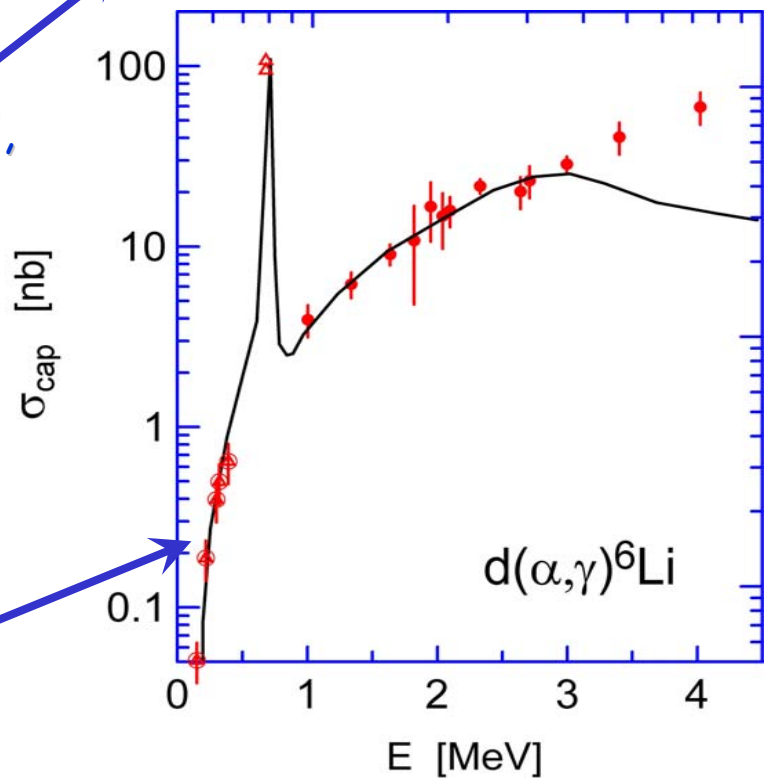


$$\sigma_{\gamma+a} = \frac{k_{bc}^2}{k_\gamma^2}\sigma_{b+c}$$

$$\frac{d\sigma}{dE_\gamma d\Omega} = \frac{1}{E_\gamma}\sum_l \frac{dn_l(E_\gamma,\Omega)}{dE_\gamma d\Omega}\sigma_{\gamma+a\to b+c}(E_\gamma)$$

Theory

CB, Baur, Rebel, 1986



Kiener et al., Z. Phys. 1993

Standard calculations

1 – Use a nuclear model. Expand trans. dens. into multipoles

$$\delta\rho(\mathbf{r}) \equiv \Psi^*_{JM}(\mathbf{r})\Psi_{J_0M_0}(\mathbf{r}) = \sum_{\lambda\mu} \delta\rho^{JM;J_0M_0}_{\lambda\mu}(r)$$

1a – e.g. a potential model (Woods Saxon + Coulomb + spin orb.)

$$\delta\rho^{JM;J_0M_0}_{\lambda\mu}(r) = \frac{e_{eff}}{\sqrt{16\pi}}(-)^{I_C+J_0+\lambda+j_0+l+l_0+\mu}\frac{\hat{J}_0\hat{\lambda}\hat{j}_0}{\hat{j}}$$

$$\times\left\langle J_0M_0\lambda\mu \middle| JM\right\rangle\left\langle j_0\frac{1}{2}\lambda 0 \middle| j\frac{1}{2}\right\rangle\begin{Bmatrix} j & J & I_C \\ J_0 & j_0 & \lambda \end{Bmatrix} r^2 R^{J*}_{E_x lj}(r) R^{J_0}_{l_0 j_0}(r)$$

2 – Use an optical potential, or build from folding (M3Y, JLM, etc.)

$$U(E,\mathbf{r}) = \int d^3r_1 d^3r_2\, \rho_P(\mathbf{r}_1)\rho_T(\mathbf{r}_2)t_{NN}(E,s)$$

3 – Plug in DWBA amplitude

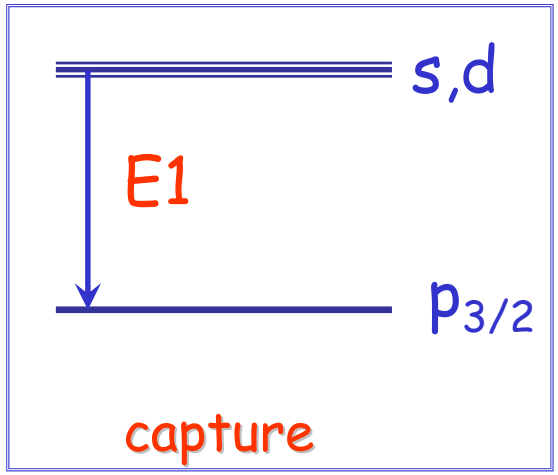
$$f^{(JM)}_{N\lambda\mu} = -\frac{m_{PT}}{2\pi\hbar^2}\int d^3r d^3R\, \chi^{(-)*}(\mathbf{R})\chi^{(+)}(\mathbf{R})\delta\rho_{\lambda\mu}(r)U_{\lambda\mu}(R,r)Y_{\lambda\mu}(\hat{\mathbf{R}})$$

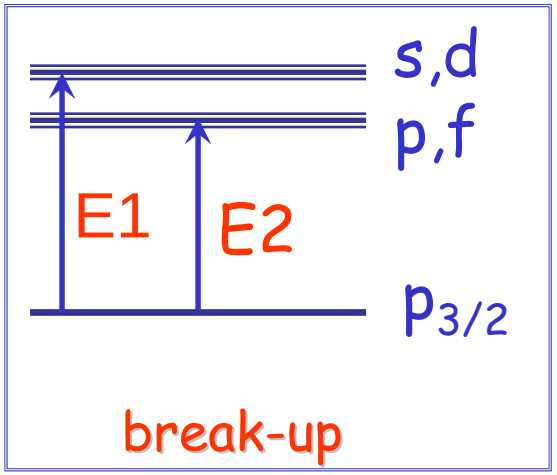
4 - Repeat all for Coulomb interaction

$$f_{C\lambda\mu}^{(JM)} = S_{\lambda\mu}(E_x,\theta)\left\langle JM \middle| r^{\lambda} Y_{\lambda\mu}(\hat{\mathbf{r}}) \middle| J_0 M_0 \right\rangle$$

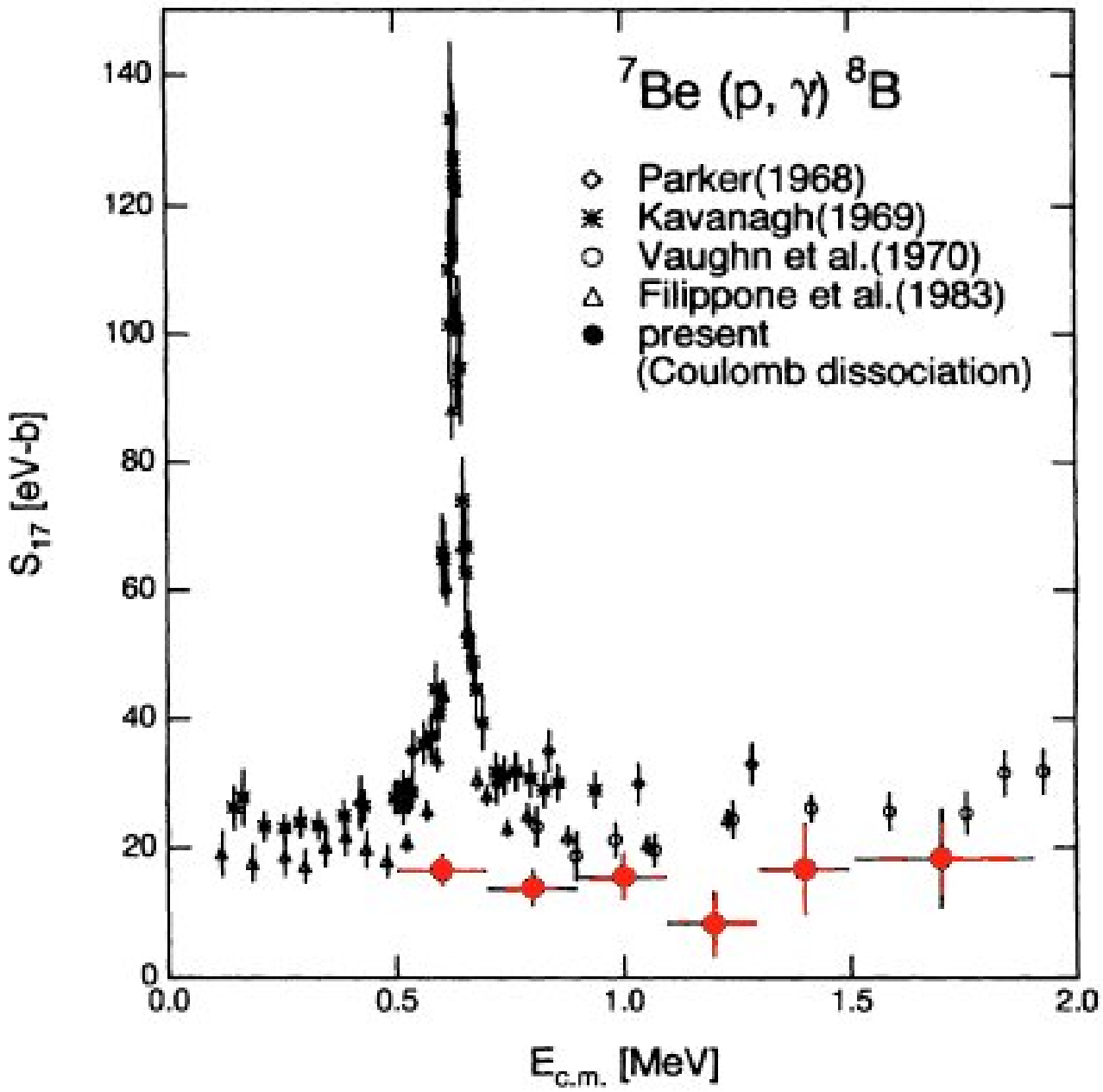
5 - Add all

$$\frac{d\sigma^J}{d\Omega dE_x} = \frac{1}{2J_0+1}\sum_M \left| \sum_{\lambda\mu} \left[f_{C\lambda\mu}^{(JM)} + f_{N\lambda\mu}^{(JM)} \right] \right|^2$$





Application to $^7Be(p,\gamma)^8B$



Motobayashi et al, PRL 1994

talk by Motobayashi

Discussions with John Bahcall, 1994

RESEARCH NEWS

SCIENCE • VOL. 266 • 18 NOVEMBER 1994

Electronic Battle Over Solar Neutrinos

An elusive measurement of a key solar reaction has prompted a fierce dispute, with attacks and counter-attacks circulating electronically well before the measurement was published

One of the problems facing physics in these days of electronic communication is keeping up with the back-and-forth, as results and theories are kicked around even before they are formally published. Witness the 14 November issue of *Physical Review Letters*, which includes a new and unique experimental determination of what has been called by astrophysicists "the most important nuclear measurement there is"—the rate at which beryllium-7 in the sun will fuse with a proton to become boron-8, which will later emit a high-energy neutrino.

The experiment that produced these results was done at Japan's Institute of Physical and Chemical Research (RIKEN) by a group led by Tohru Motobayashi of Rikkyo University in Tokyo and Moshe Gai of the University of Connecticut. The measurement is crucial to understanding the long-standing "solar neutrino problem," which is the discrepancy between the flux of solar neutrinos as predicted by theoretical models of the sun

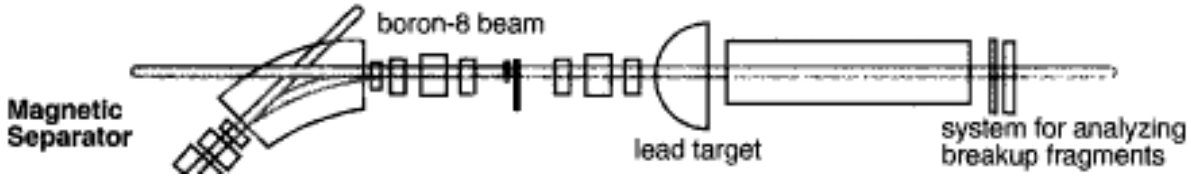
the 1960s, was erected in the Homestake gold mine in South Dakota by Ray Davis, who was then at Brookhaven National Laboratory on Long Island. That detector has spotted only a third of the solar neutrinos it was predicted to find. The Kamiokande detector in Japan, which came on line in 1987, has detected only half the predicted flux. The two newest detectors, both using gallium as the target for the neutrinos, recently reported seeing only two thirds of the expected number of neutrinos.

The most exciting explanation proposed so far for the discrepancy between experiment and theory is that neutrinos "oscillate" into a neutrino species that the experiments cannot detect. If it's true, it would be a Nobel-caliber revelation, but so far no pub-

the two gallium experiments can also see the much more plentiful low-energy neutrinos from the fusion of protons into deuterium.)

A handful of attempts have been made to measure this reaction rate in the laboratory by bombarding a target of ^{7}Be with a beam of protons. The two best measurements have come from physicists now at the California Institute of Technology—Ralph Kavanagh in 1969 and Brad Filippone in 1983—but Filippone's experiment came up with a reaction rate 25% lower than Kavanagh's. "John Bahcall has been beating on people's heads for 20 years to get a better measurement of [the reaction rate]," says Yale University nuclear physicist Peter Parker.

One difficulty, says Moshe Gai, is that to create enough ^{8}B to get meaningful measure-



and discussed the possibility that the same technique might work for ^{8}B with Fred Barker, a theorist at the Australian National University, and Motobayashi.

Indeed, the rate of the reaction in which ^{8}B absorbs a photon and decays into ^{7}Be and a proton, says Gai, is a million times higher than its inverse. "What nature has provided is an amplifier," says Gai. Carlos Bertulani of the Federal University of Rio de Janiero demonstrated theoretically that a measurement of the dissociation of ^{8}B would provide them with an accurate guide to calculate the rate of the reaction in which it is created. "All you need is an accelerator which provides you with ion beams at medium energies," says Bertulani. "Anybody could do it. It's just that nobody believed such a thing could be useful."

The experiment was done in March 1992 using the accelerator at RIKEN. Gai, Motobayashi and his student Naohito Iwasa, and their colleagues bombarded a target of beryllium with a beam of carbon-12 atoms and then used a magnetic field to sift out ^{8}B

They also calculated that if the E2 component is indeed sizable, the experiment would have indicated a reaction rate so low as to either dramatically change the solar neutrino problem or, as some physicists took it, to imply that the RIKEN method simply didn't work.

Shoppa and Langanke's paper appeared in April and represented the first journal publication of the RIKEN data. As it turned out, however, the RIKEN preprint had incorrect error bars, and that problem was compounded when the two Caltech theorists miscaled the data in their article—"our stupidity," concedes Langanke. When Bertulani and Gai later realized that the Caltech paper not only had errors in the data but did not take into account what they considered the relevant parameters of the RIKEN experimental setup, they now redid it and concluded

NEUTRINO-PRODUCING REACTIONS IN THE SUN

proton + proton → deuterium + positron + neu

proton + electron + proton → deuterium + neutrino

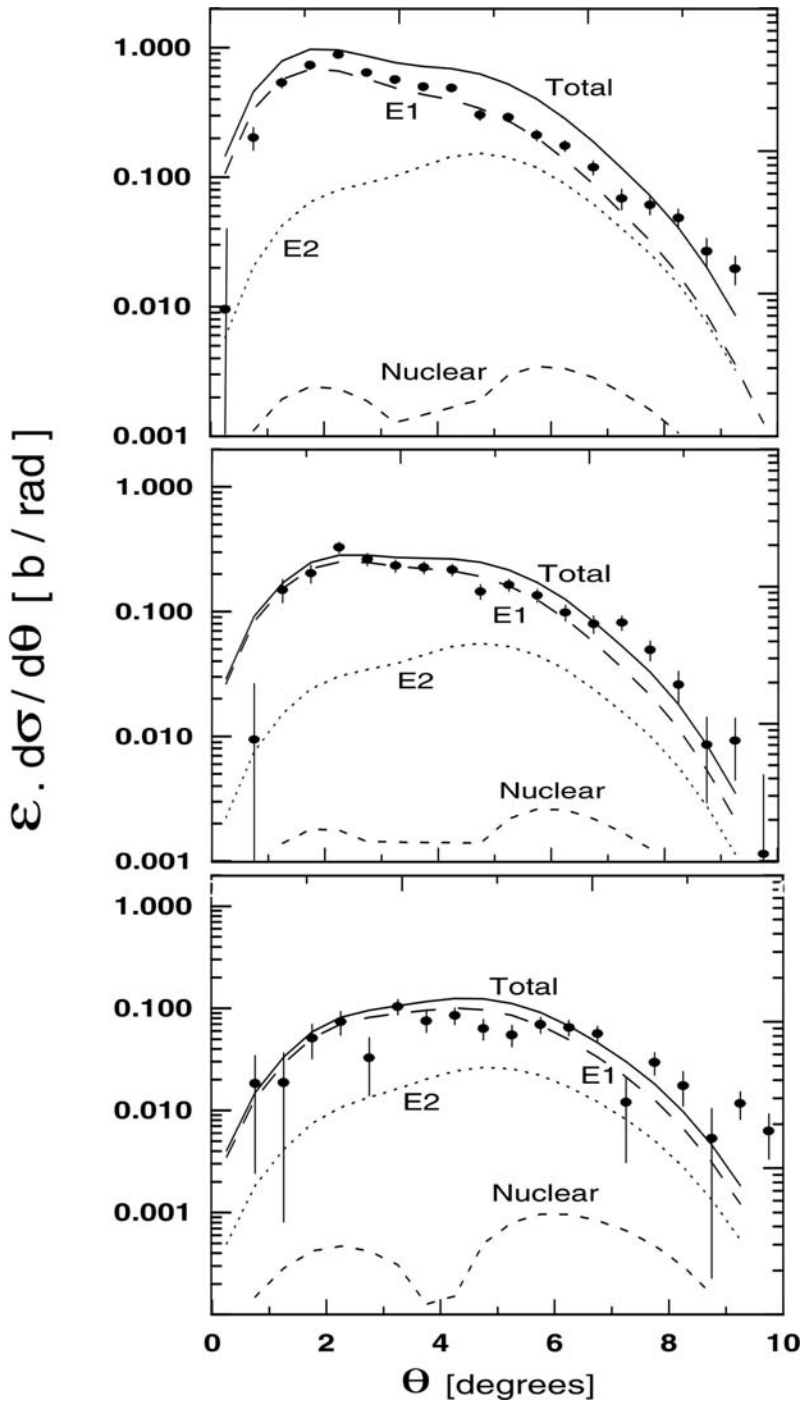
Nuclear interaction:

$^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$

from

$^{8}\mathrm{B} + \mathrm{Pb} \rightarrow p + {}^{7}\mathrm{Be} + \mathrm{Pb}$

50 MeV/nucleon



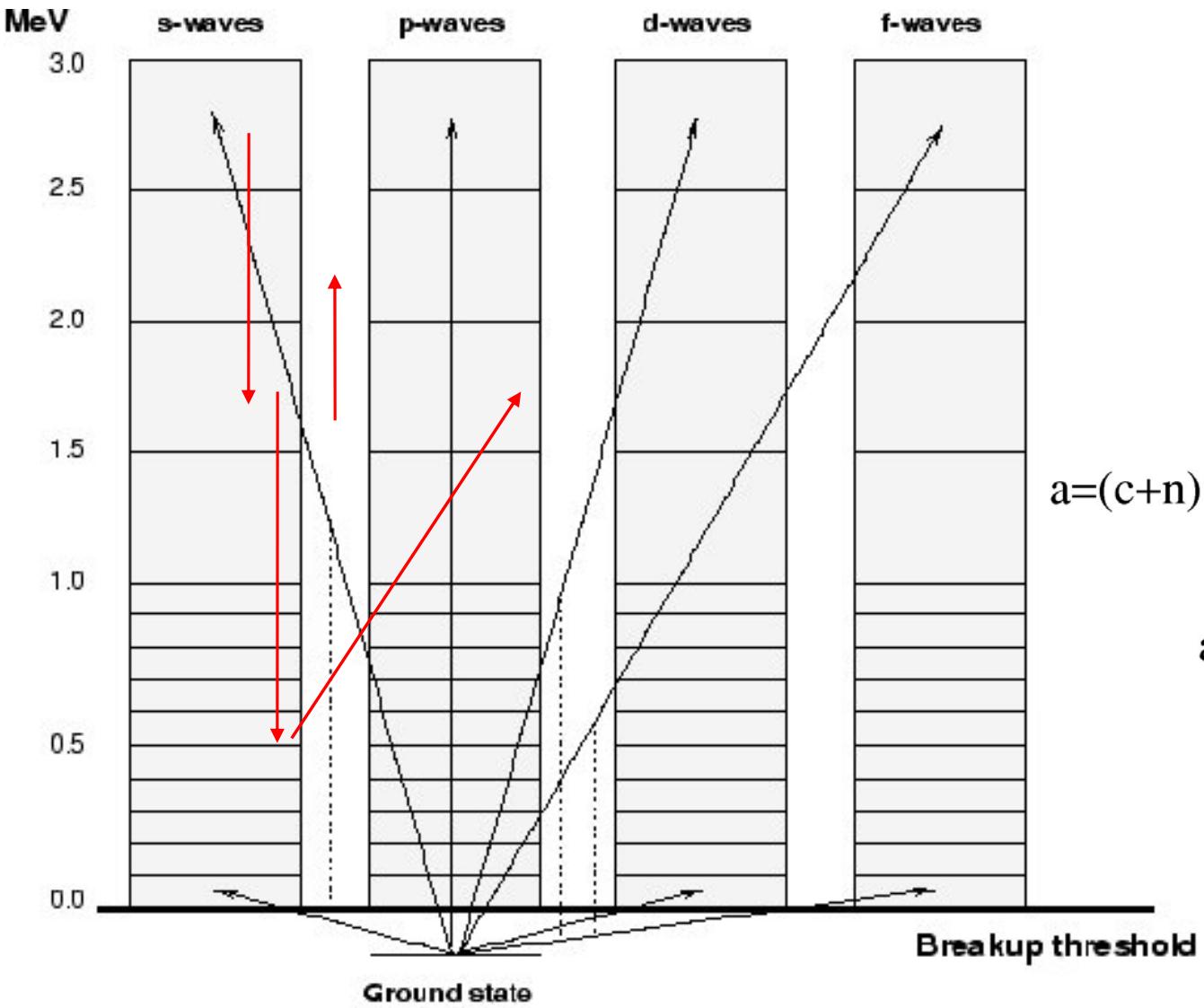
Data: Kikuchi, PLB 97
Calc: C.B., NPA 1998

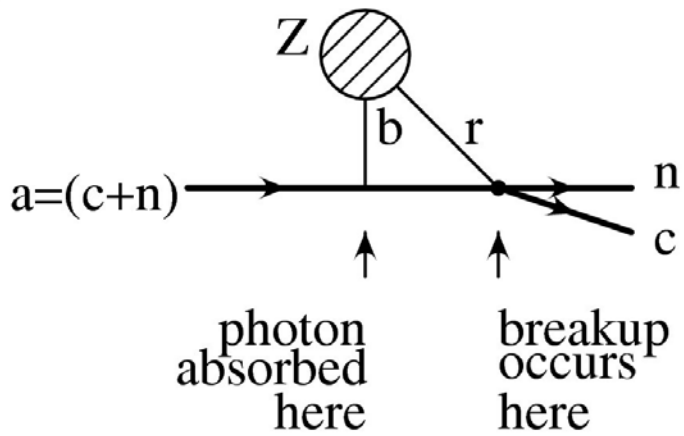
Higher order transitions

Continuum discretization

$$\left|\varphi_0\right\rangle = e^{-iE_0 t/\hbar}\left|\varphi_0\right\rangle, \qquad E_0 = -B$$

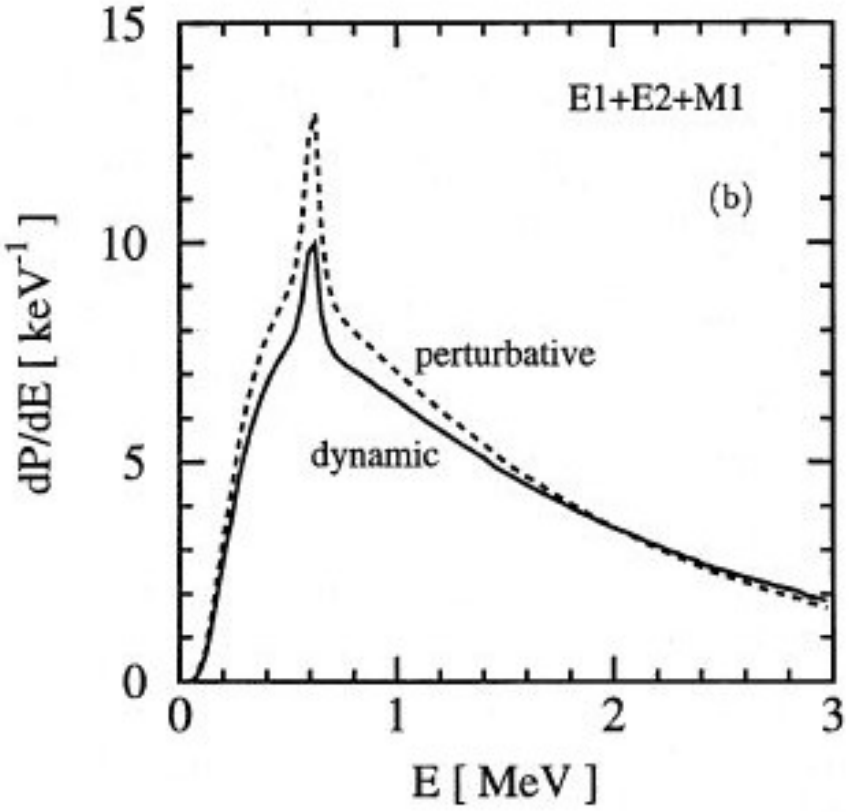
$$\left|\varphi_{jlm}\right\rangle = e^{-iE_j t/\hbar}\int \Gamma_j(E)\left|E, lm\right\rangle dE$$

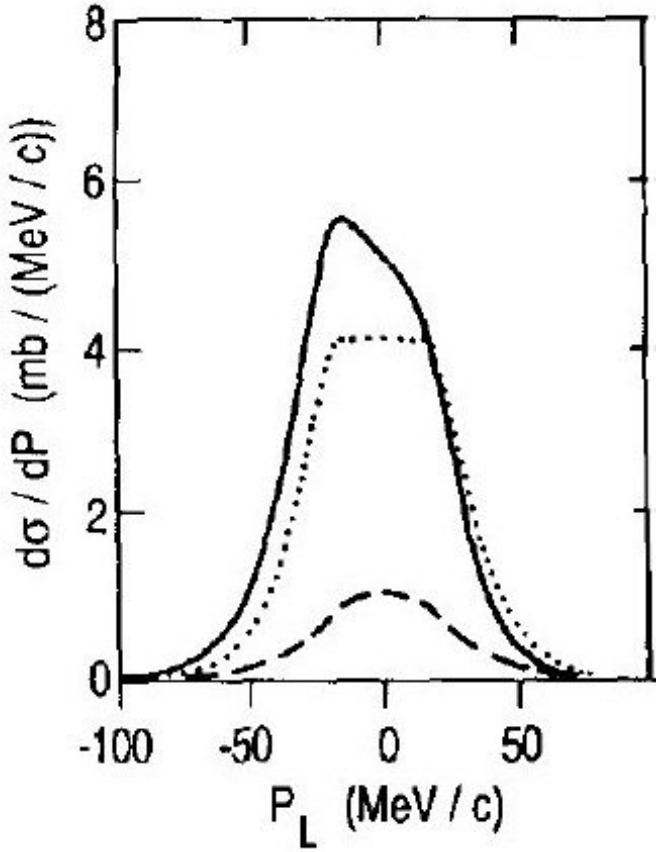




Higher order transitions + E1-E2 interference

$^{8}\mathrm{B} + \mathrm{Pb} \rightarrow p + {}^{7}\mathrm{Be} + \mathrm{Pb}$





C.B., Z. Phys. 1996

- small effect higher-order transitions in $d\sigma / d\Omega dE$
- small E1-E2 interference in $d\sigma / d\Omega dE$

- but large E1-E2 interference in momentum distirbutions

Esbensen, Bertsch, NPA 1996

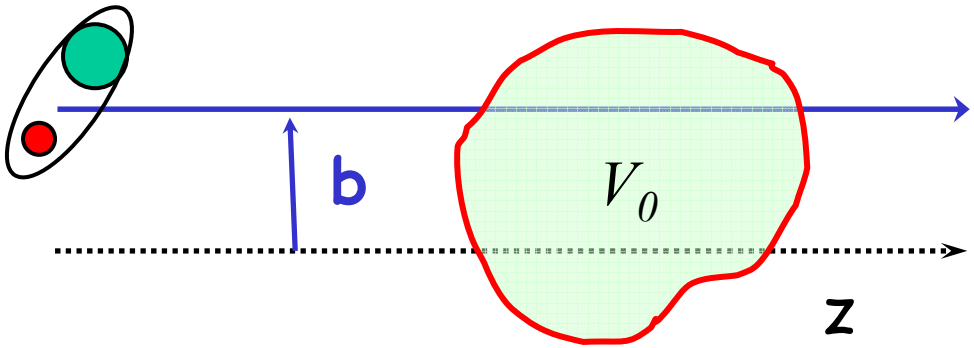
Used by Davids, PRL 1999 to filter E2 from $S_{17}(0)$

Relativistic effects

CB, PRL 2005

$$\left[\nabla^2 + k^2 - U\right]\Psi(\mathbf{R},\mathbf{r}) = 0$$

$$U = V_0\left(2E - V_0\right)$$



$$\Psi(\mathbf{R},\mathbf{r}) = \sum_\alpha S_\alpha(\mathbf{b},z)\, e^{ik_\alpha z}\, \phi_\alpha(\mathbf{r}),$$

$$\mathbf{R} = (\mathbf{b}, z)$$

$$U \approx 2V_0 E$$

$$\nabla^2 S << ik_z \partial_z S$$

Eikonal

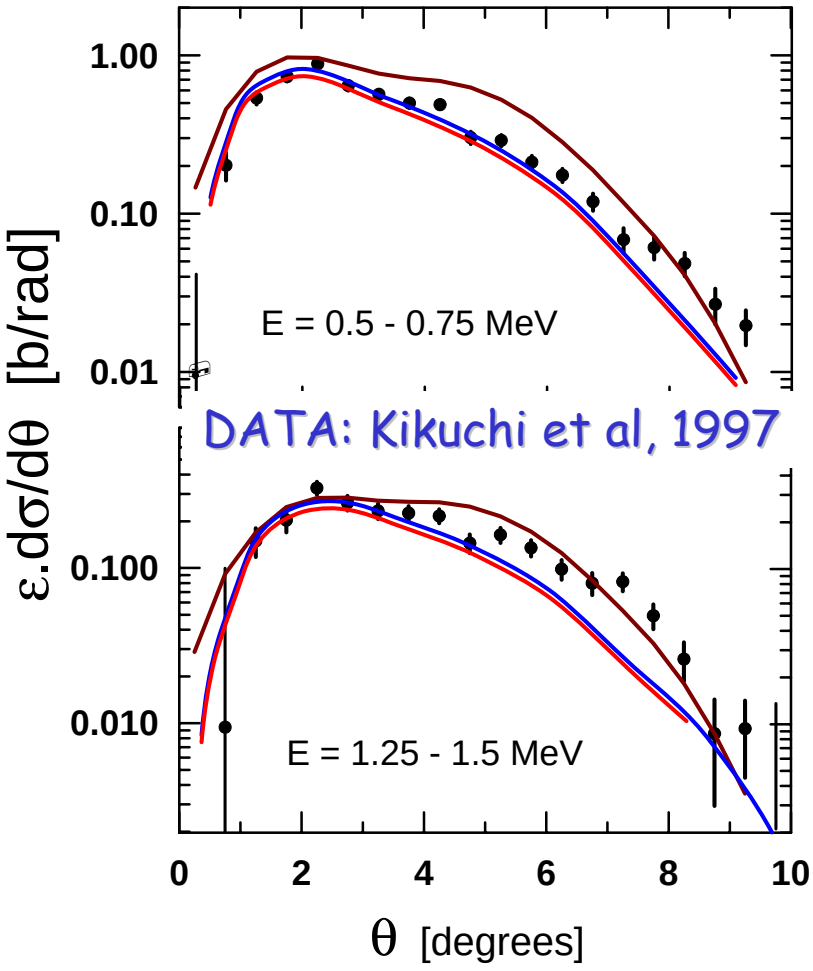
$$iv\partial_z S_\alpha(\mathbf{b},z) = \sum_\beta V_{\alpha\beta}(\mathbf{b},z) S_\beta(\mathbf{b},z)\, e^{i(k_\beta - k_\alpha)z}$$

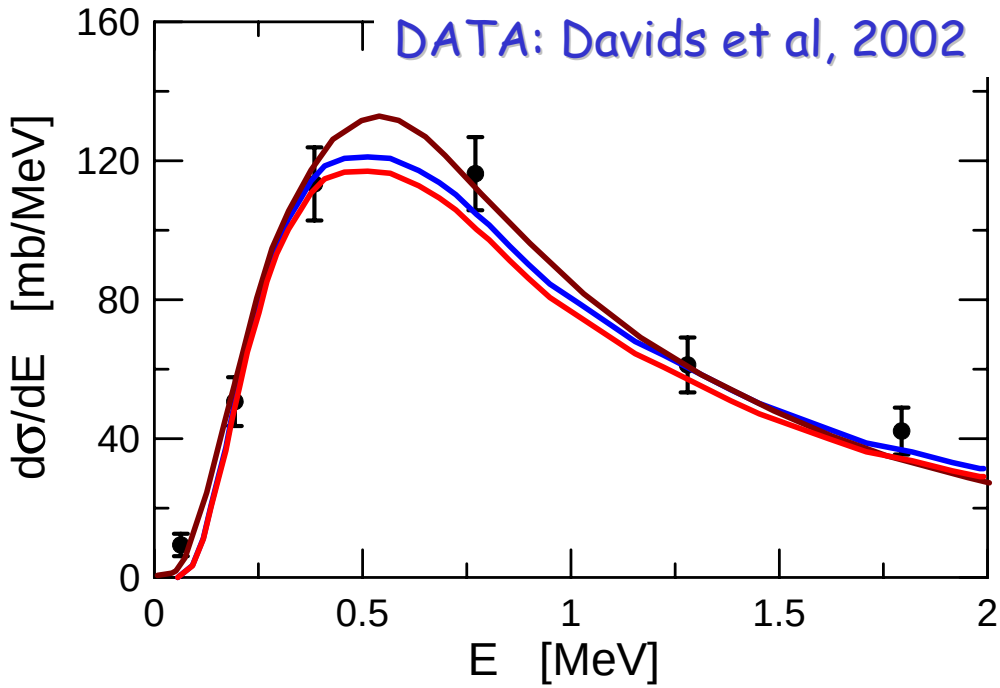
$$f_\alpha(\mathbf{Q}) = -\frac{ik}{2\pi}\int d\mathbf{b}\; e^{i\mathbf{Q}.\mathbf{b}}\left[S_\alpha(\mathbf{b}, z=\infty) - \delta_{\alpha,0}\right]$$

$$\mathbf{Q} = \mathbf{K}'_\perp - \mathbf{K}_\perp; \qquad \alpha = jlJM$$

Relativistic CDCC

^{8}B dissociation on lead at 50 MeV/nucleon





perturbation theory

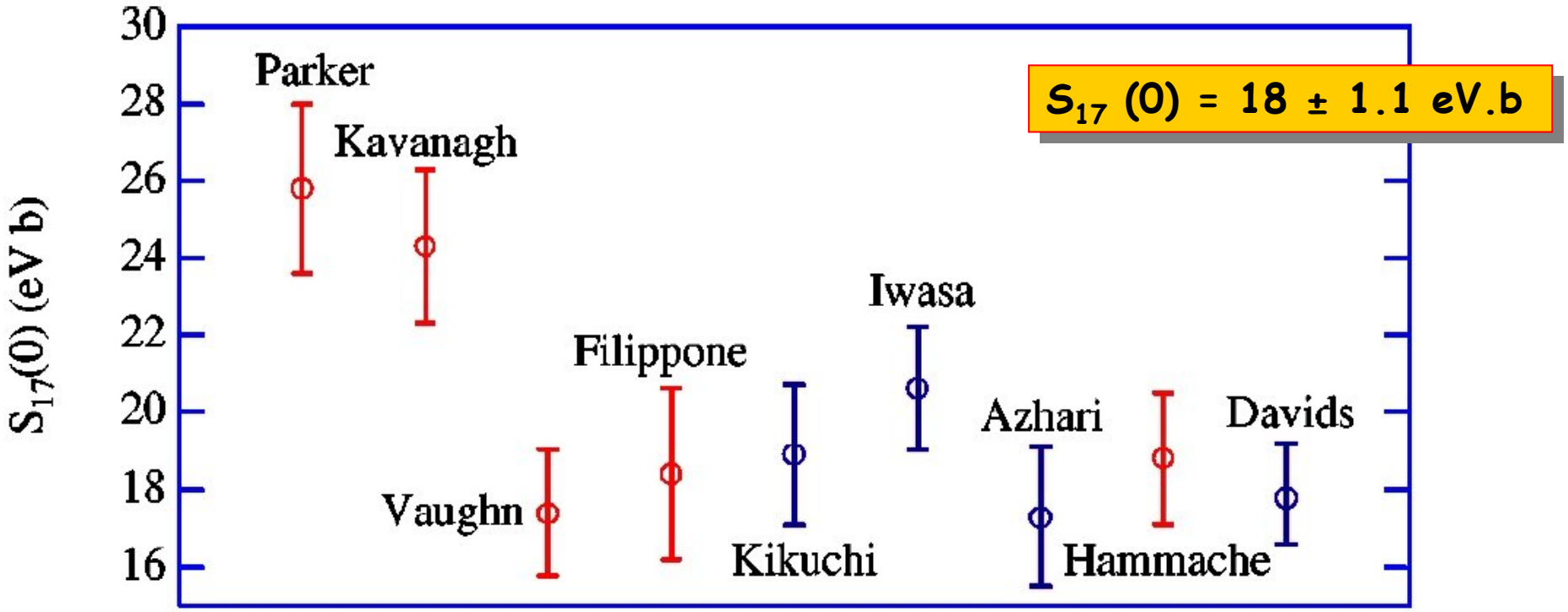
R-CDCC

NR-CDCC
with non-relativistic V_0

relativistic corrections

4-10% effect

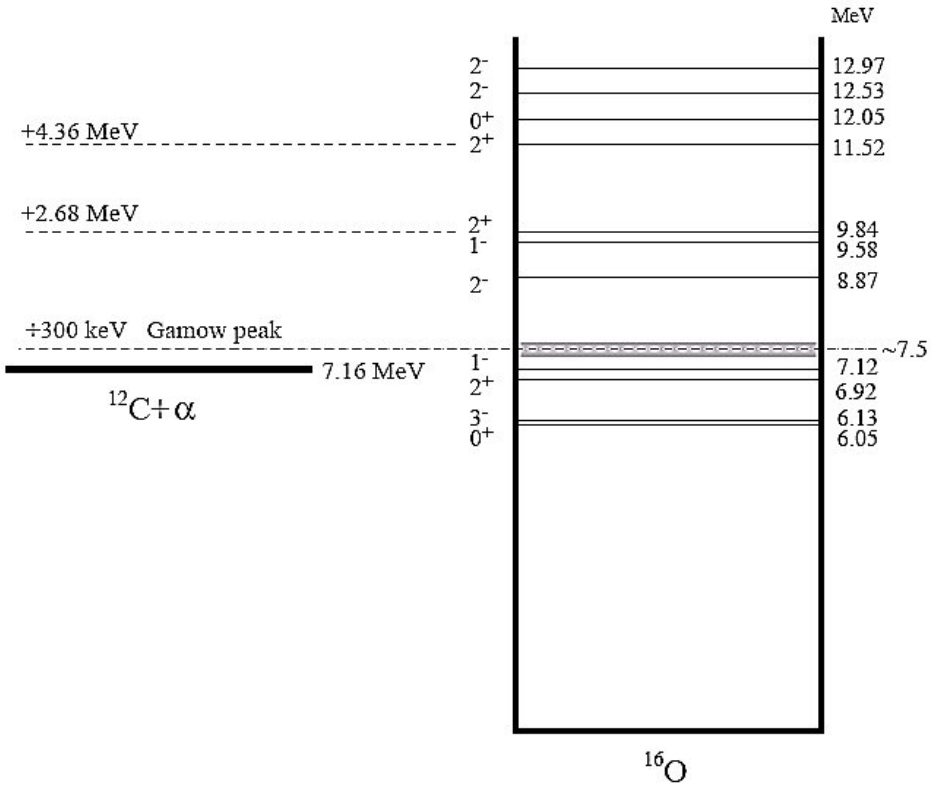
Summary on CD method for $^{7}Be(p,\gamma)^{8}B$

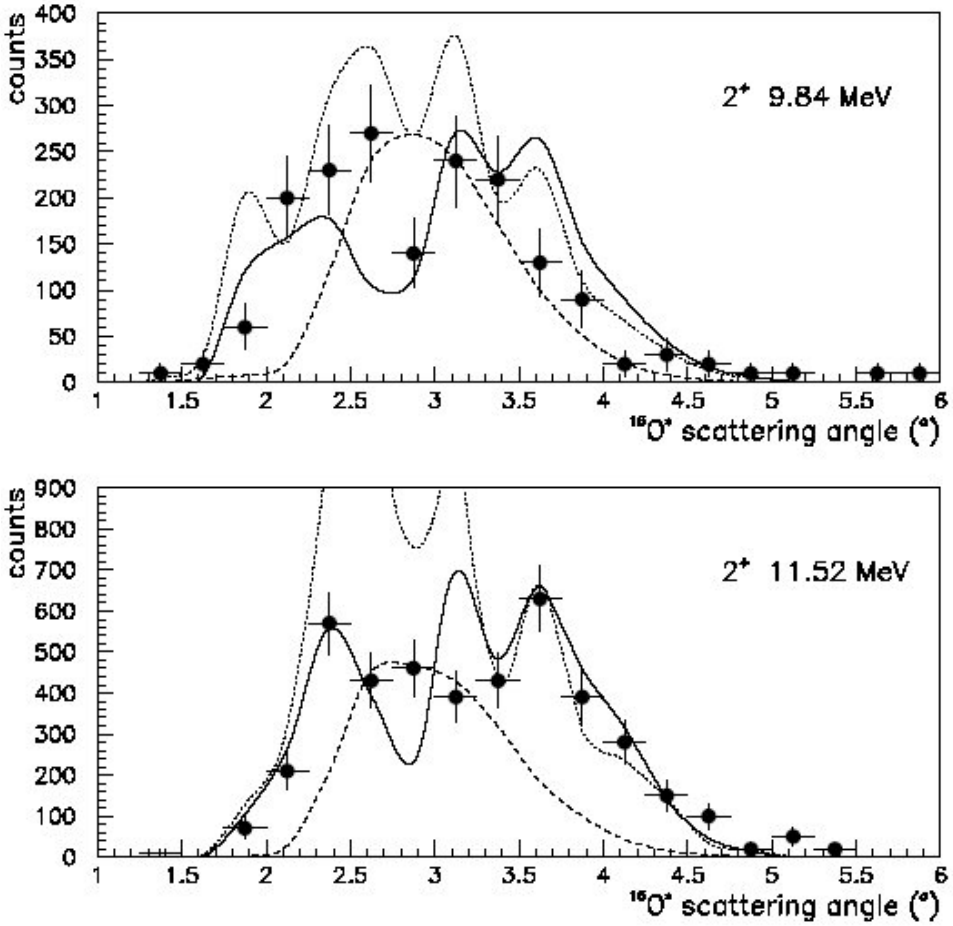


CD method has proven useful to extract $S_{17}(0)$ **(and other S-factors)**

Attempts for $^{12}C(\alpha,\gamma)^{16}O$

see also contribution by **C. Angulo**





dotted: nuclear

dashed: Coulomb

solid: nuclear + Coulomb + interf.

Fleurot, PhD Thesis, 2002

$$^{16}O + Pb \rightarrow \alpha + ^{12}C + Pb$$

80 MeV/nucleon

Trying to reconcile structure and reactions

What do we need?

$$g(r) = \left\langle \Psi^{(A)} \middle| \hat{\mathcal{A}}\, \Phi^{(A-a)} \Phi^{(a)} \delta(r - r_{A-a,a}) \right\rangle$$

$$g_l(r \to \infty) \sim I_l(r) - S_l O_l(r)$$

What can we do in practice?

$$\int dr' \left[H(r,r') - EN(r,r') \right] g(r') = 0 \quad \text{all } r$$

Hill-Wheeler, 1953

$$\begin{Bmatrix} H \\ N \end{Bmatrix}(r,r') = \left\langle \hat{\mathcal{A}}\, \Phi^{(A-a)} \Phi^{(a)}(r') \middle| \begin{Bmatrix} H \\ N \end{Bmatrix} \middle| \hat{\mathcal{A}}\, \Phi^{(A-a)} \Phi^{(a)}(r) \right\rangle$$

e.g. NCSM

What are the effective interactions in $H = T + \frac{1}{2}\sum v_{ik}$??

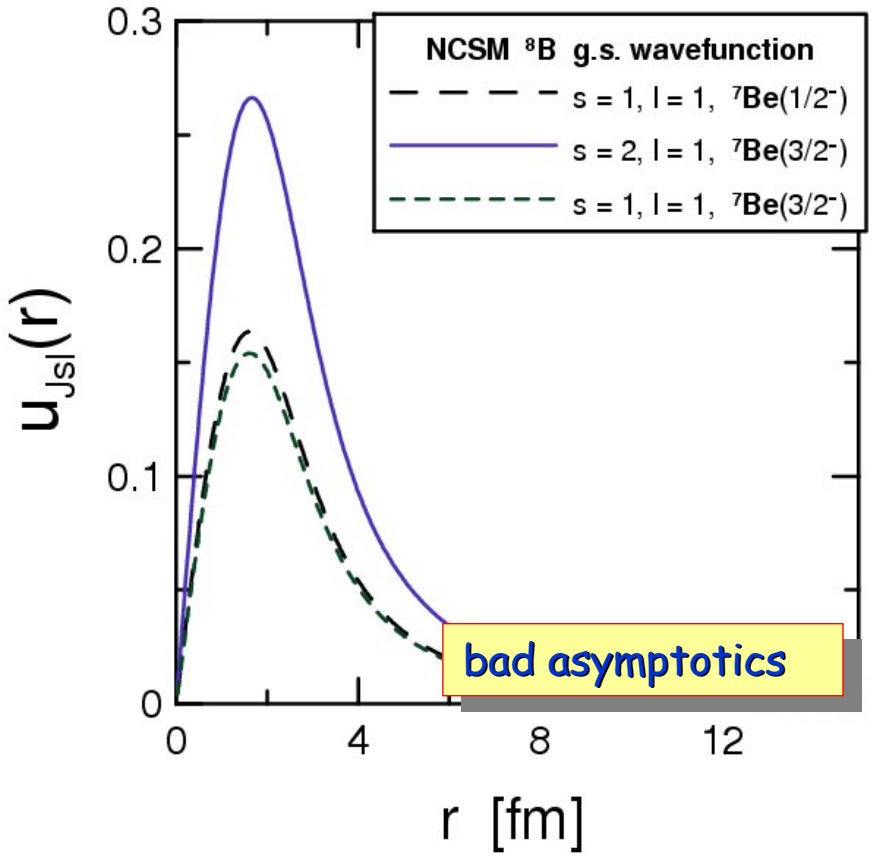
talk by C. Forssen

MANY YEARS OF INVESTIGATION

Many-body bound state

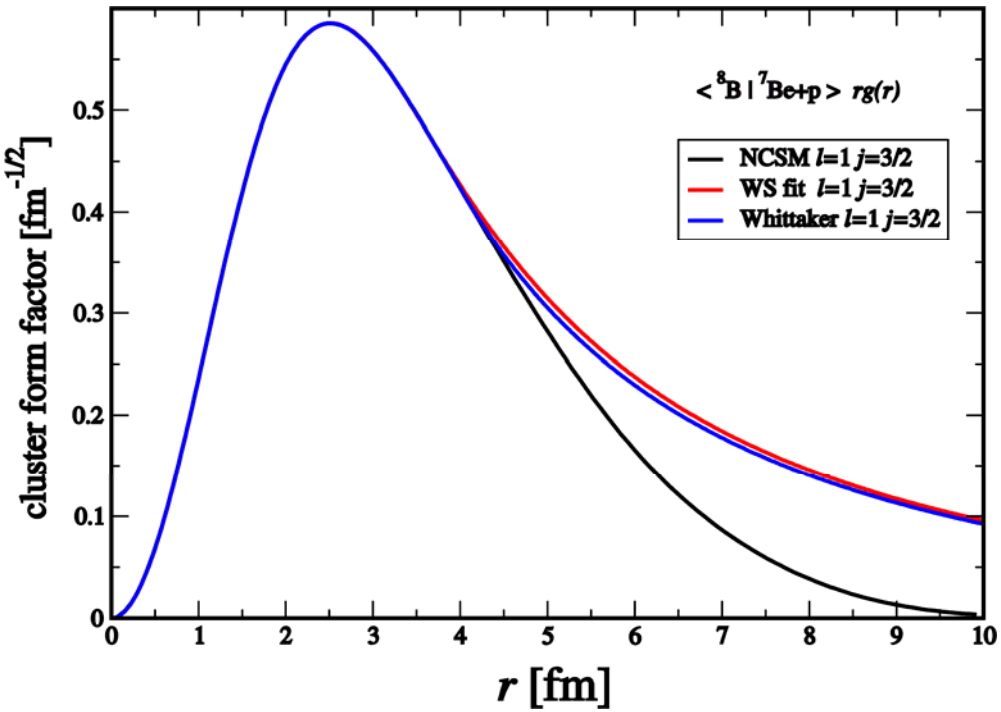
Navratil, C.B., Caurier, PLB 2005

PRC 2006



No-Core-Shell-Model

(with correction for asymptotics)

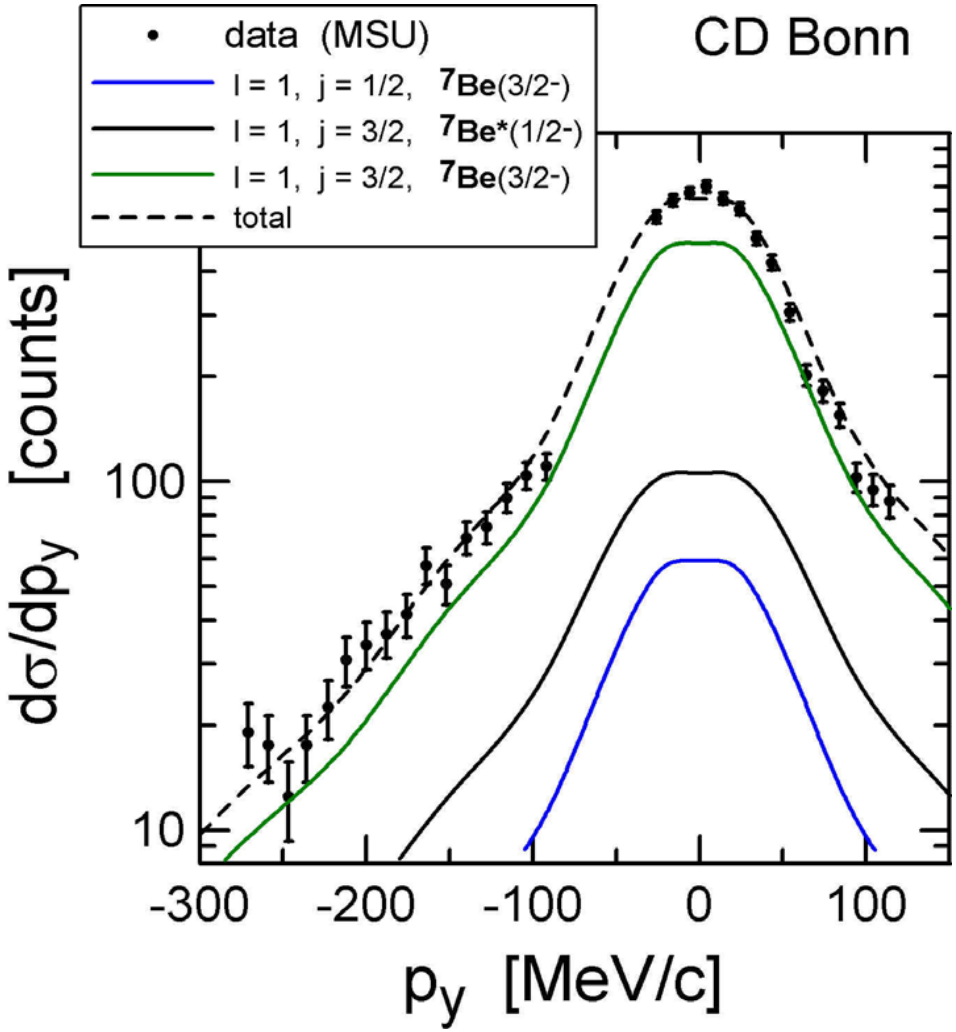


Fix: correct Coulomb tail at large *r*'s

$$R_{lj}(r) \rightarrow C_{lj} \frac{W_{-\eta,l+1/2}(r)}{r}$$

Knockout reactions with NCSM

$$\frac{d\sigma_{strip}}{d^2k_C^{\perp}} = \frac{1}{2\pi}\sum_m \frac{C^2 S_{lj}}{(2l+1)} \int d^2b_n \left[1 - \left|S_n(\mathbf{b}_n)\right|^2\right] \int dz \left| \int d^2r_{\perp}\, e^{-i\mathbf{k}_C^{\perp}\cdot\mathbf{r}}\, S_C(\mathbf{b}_C)\, \phi_{NCSM}^{ljm}(\mathbf{r}) \right|^2$$



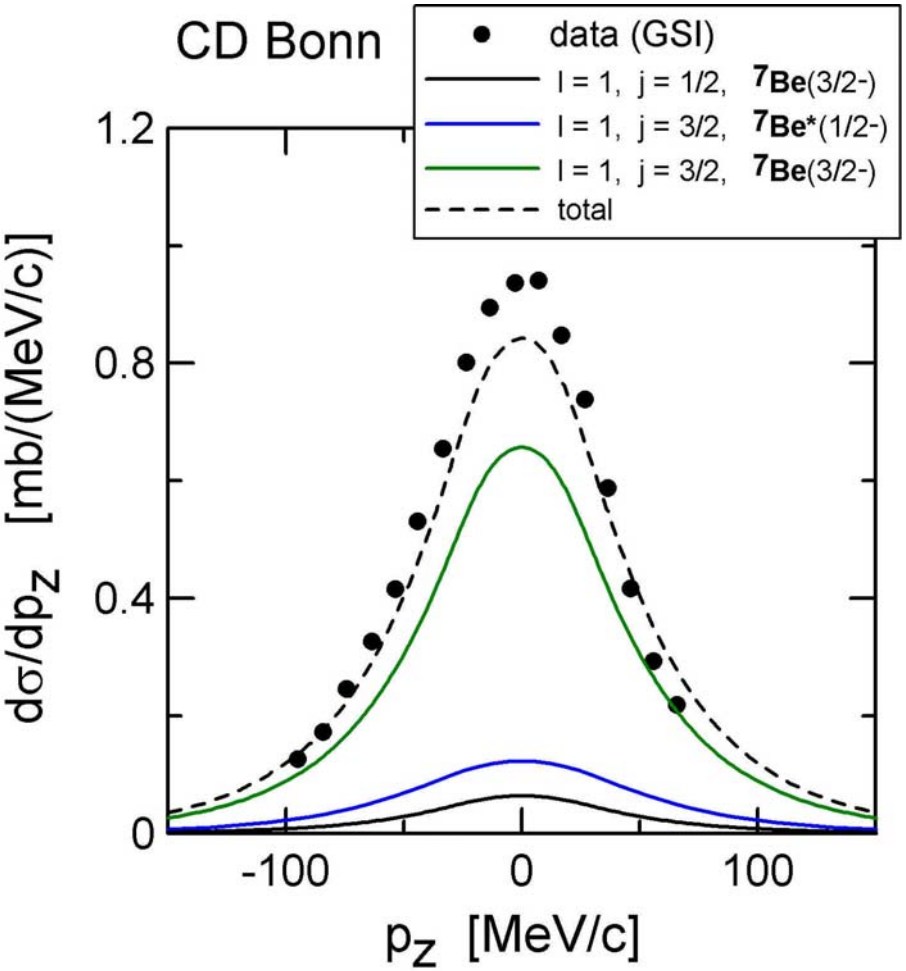
^{8}B (41 MeV/nucleon) + ^{9}Be → ^{7}Be + X

^{8}B (41 MeV/nucleon) + ^{9}Be → ^{7}Be + X

With NCSM wavefunctions (10 ħω)

- l=1, j=1/2, I_{7Be}=3/2: C^2S=0.085
- l=1, j=3/2, I_{7Be}=1/2: C^2S=0.280
- l=1, j=3/2, I_{7Be}=3/2: C^2S=0.958

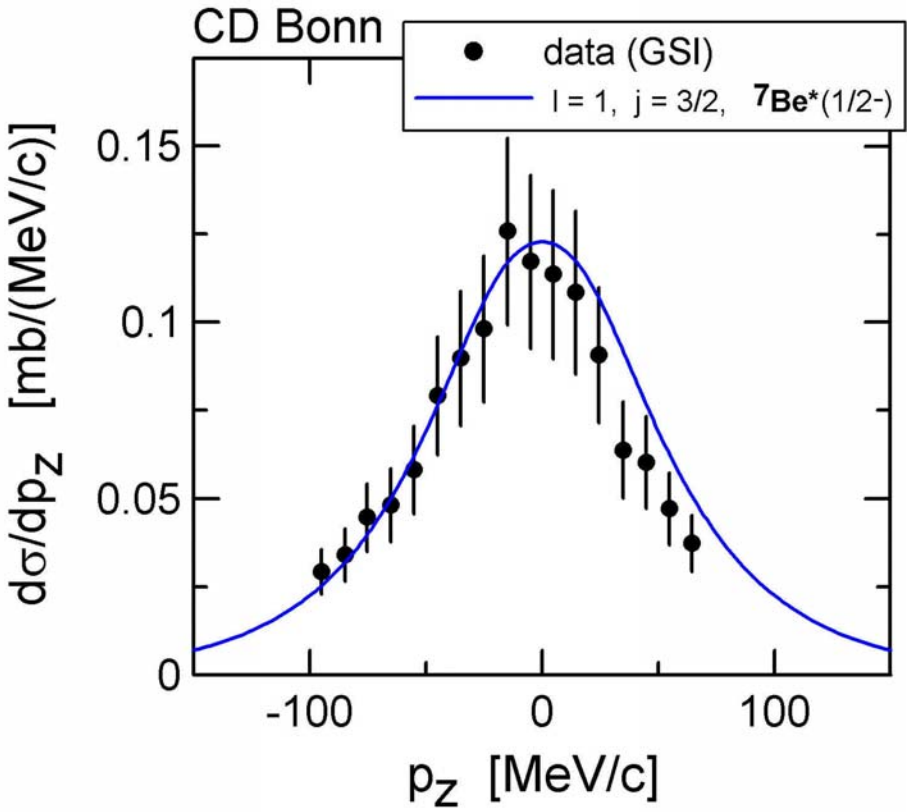
^{8}B (938 MeV/nucleon) + $^{12}C \rightarrow {}^{7}Be$ + X



σ_{str} = 99.39 mb

exp = 94 ± 9 mb

^{8}B (938 MeV/nucleon) + $^{12}C \rightarrow {}^{7}Be + \gamma$ + X

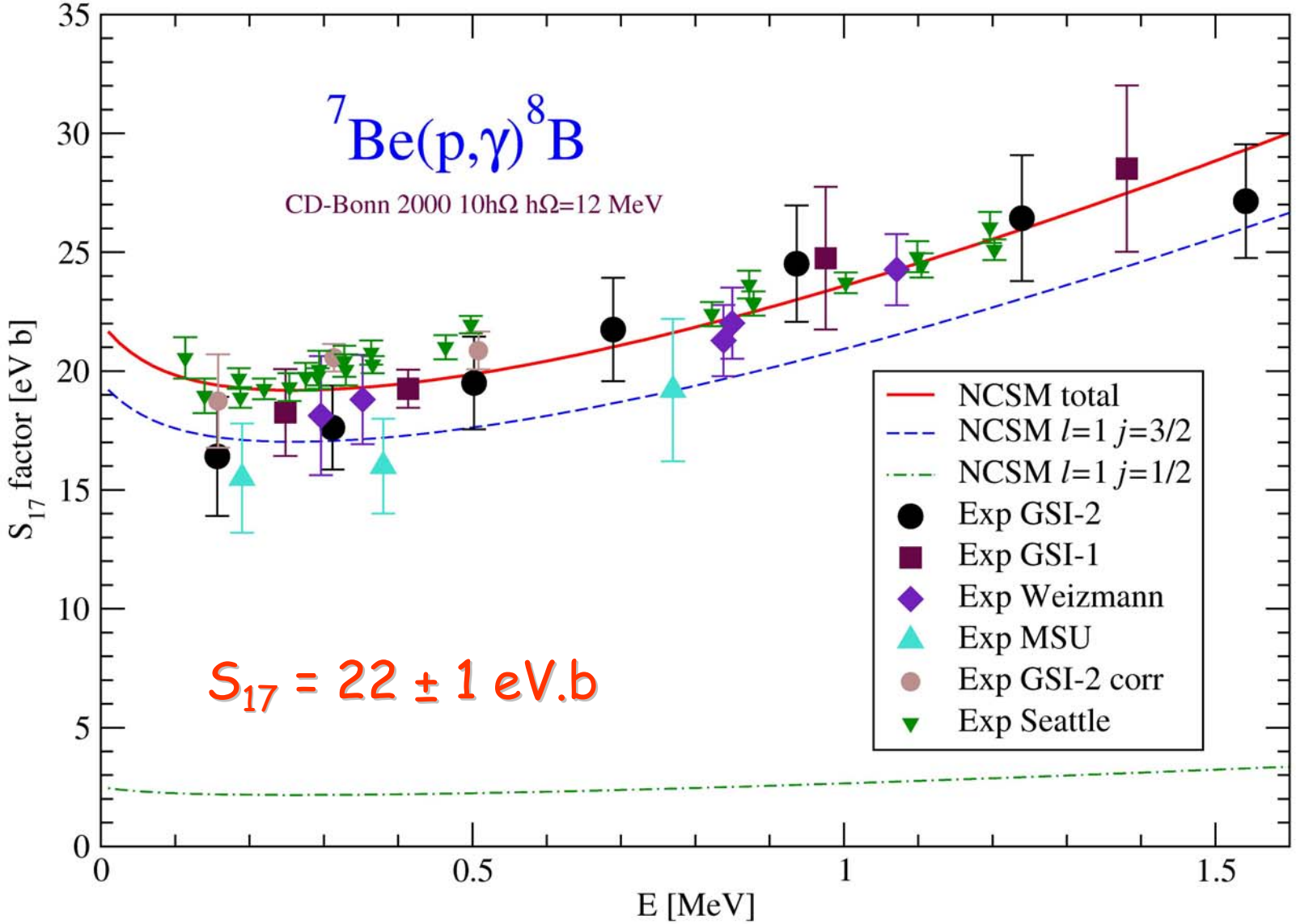


σ_{str} = 15.31 mb

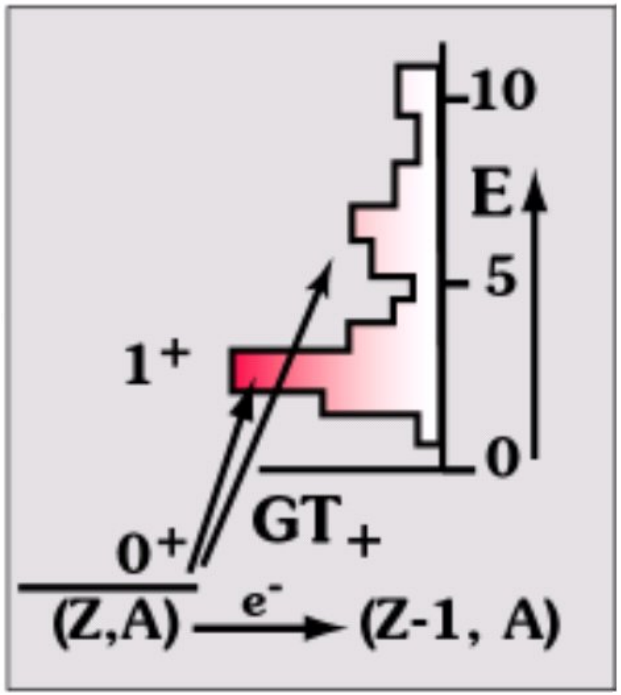
exp = 12 ± 3 mb

DATA: Cortinal-Gil et al, 2002

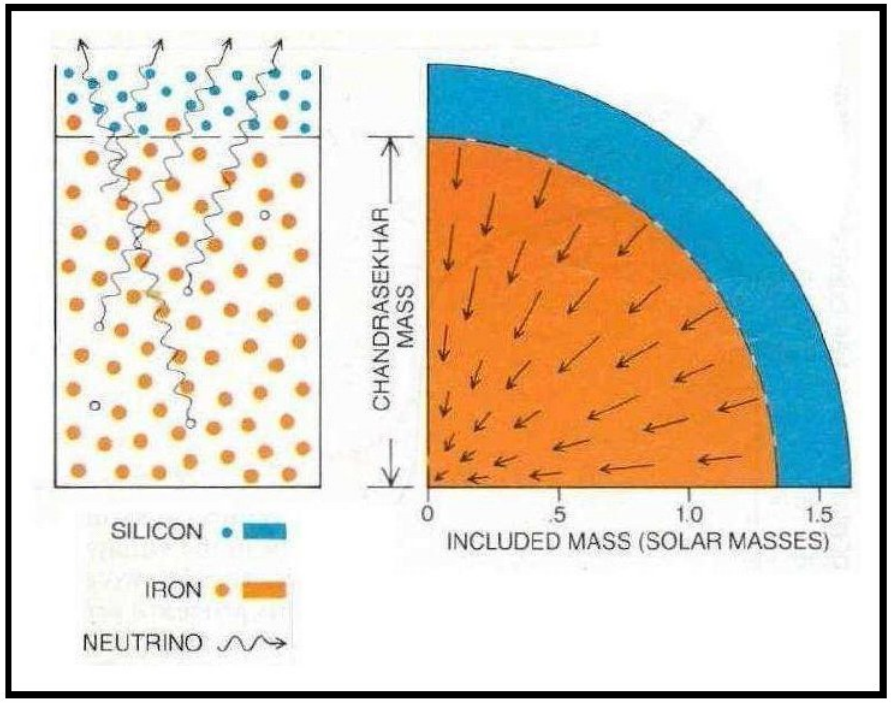
$^7Be(p,g)^8B$ S-factor with NCSM



Future: Charge Exchange



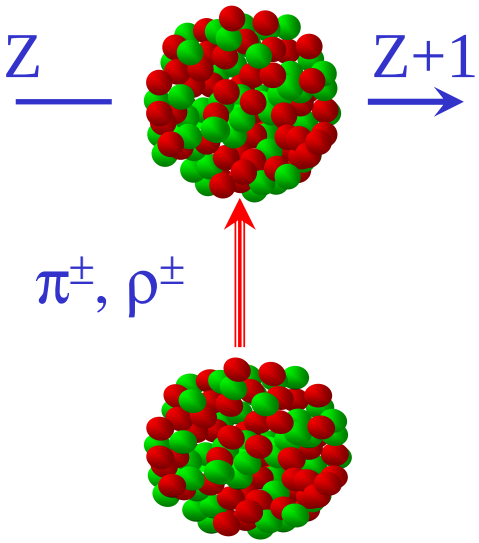
$$\left|\langle B \| \sigma\tau \| A \rangle\right|^2$$



e- + (Z,A) → (Z-1, A) + ν_e needed for A~50-60

Obtained from

(p,n) (n,p) (d,^{2}He) ... (Z, Z±1)



based on Tadeucci et al, NPA 1981

$$\frac{d\sigma}{d\Omega}(\theta \sim 0^0) = \cdots \left|\langle b \| \sigma\tau \| a \rangle\right|^2 \left|\langle B \| \sigma\tau \| A \rangle\right|^2$$

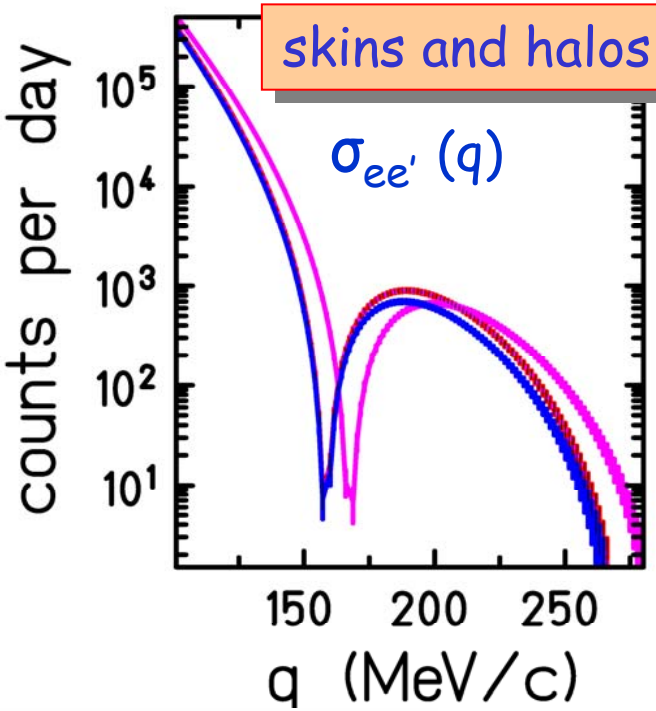
Lenske, Wolter, Bohlen, PRL 1989
CB, NPA 1993

Remco Zegers - MSU

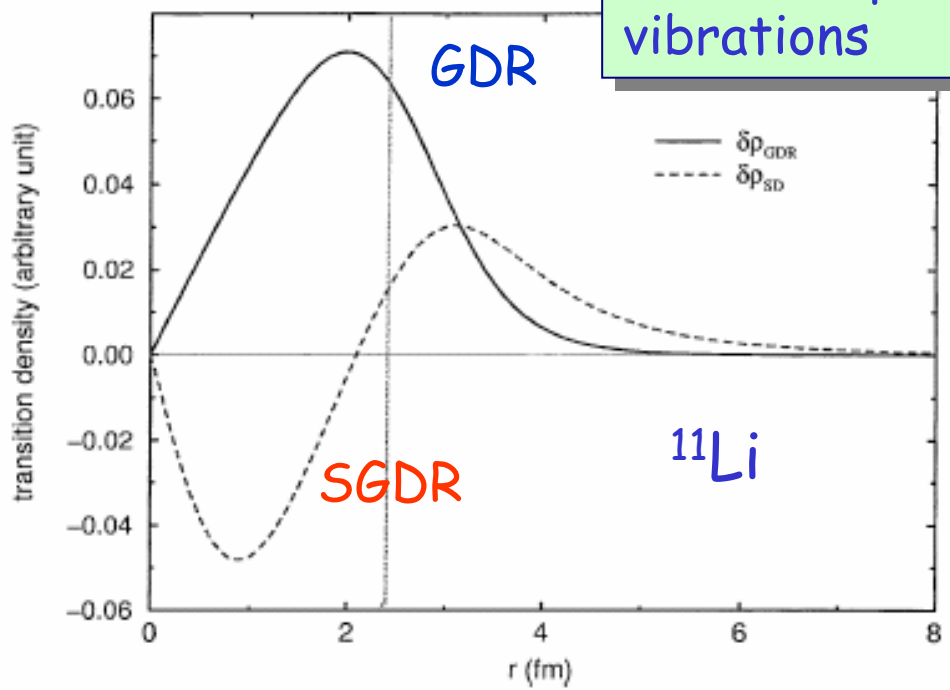
Electron-ion collider ELISe (GSI)

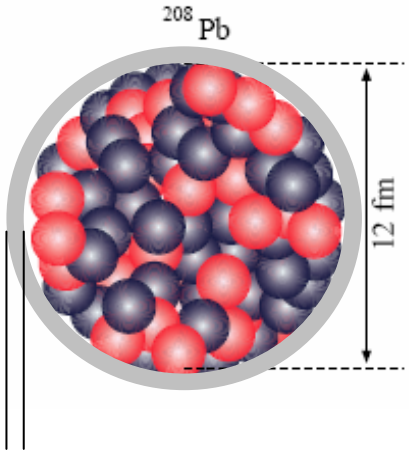
H.Simon@gsi.de

skins and halos

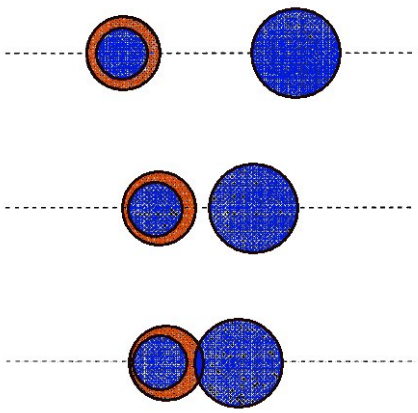


soft multipole vibrations



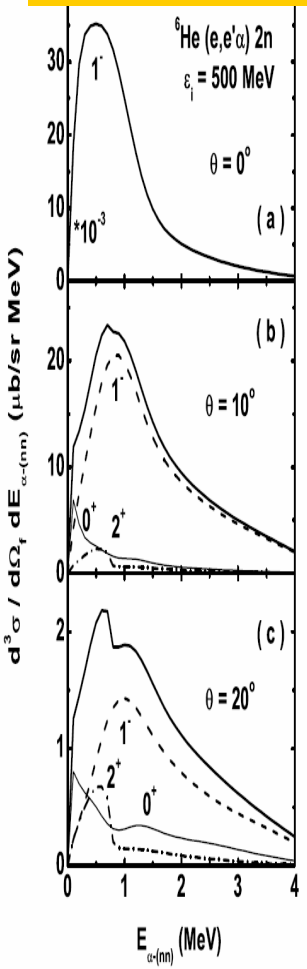


$\Delta\, r_{np}$



Electron-ion collider ELISe (GSI)

H.Simon@gsi.de

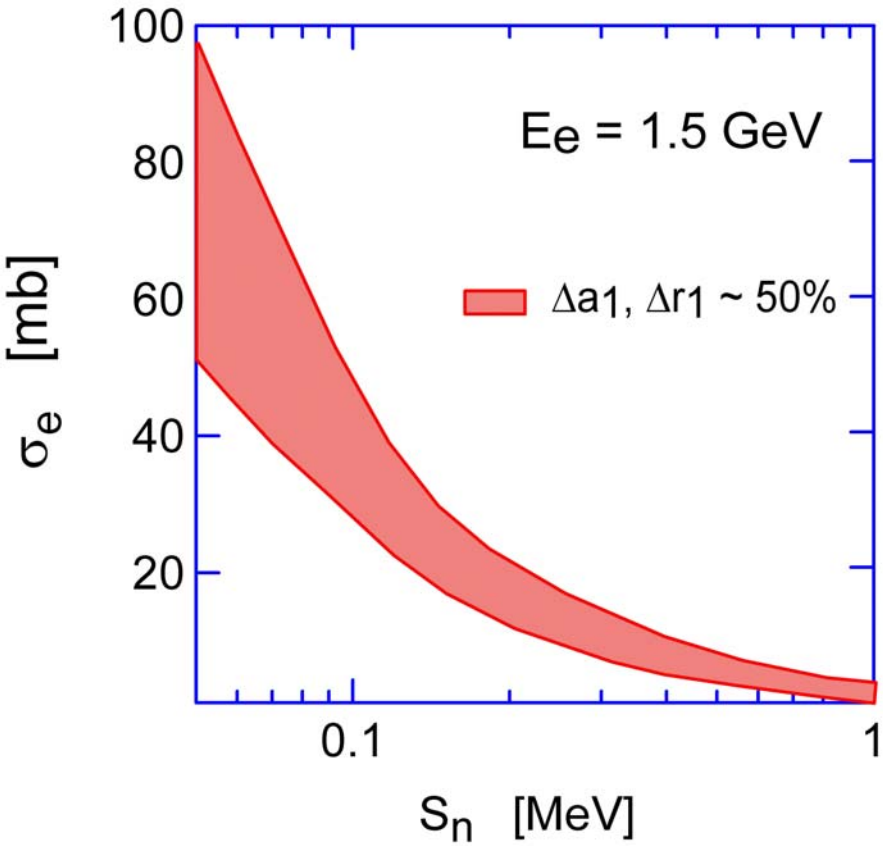


$$\frac{d\sigma}{dE_e d\Omega} \sim |f_l(q)|^2$$

$$f_l \equiv f_l(q, S_n, a_l, r_l)$$

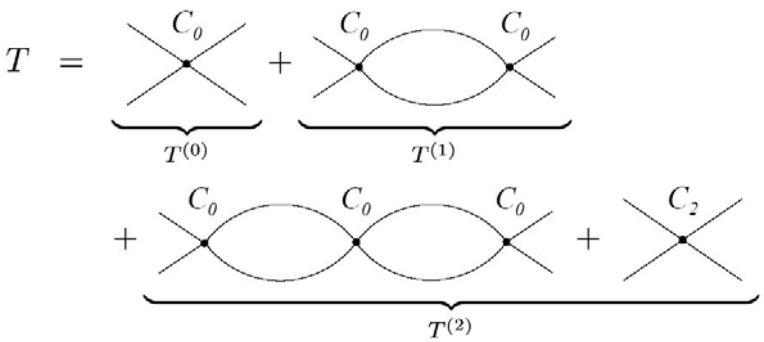
very strong dependence on effective range expansion parameters, a_l, r_l

CB, PLB 2005



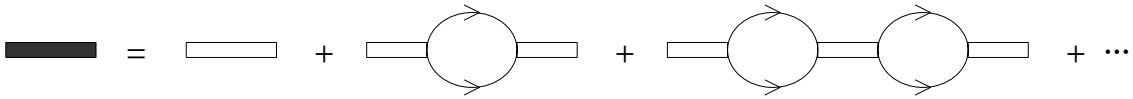
Ershov, PRC 2005

Reconciling Nuclear Physics with QCD



van Kolck, 1997
Gegelia, 1998
Kaplan, Savage, Wise, 1998

$$T(k) \sim \frac{1}{\frac{1}{a} - \frac{1}{2} r_0 k^2 + \ldots - ik}$$



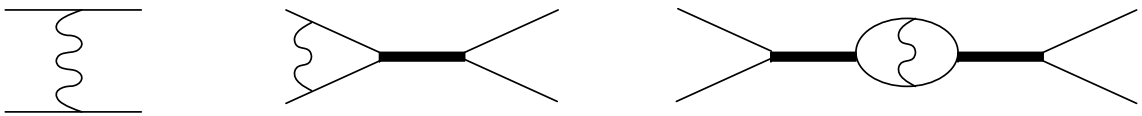
CB, Hammer, van Kolck, 2002

$n + {}^4He$

$$S(E) \sim \frac{1}{E - E_R + i\Gamma(E)/2}$$

Kong, Ravndal, 2000

$$c_\eta^2 p(\cot\delta - i) + \alpha m H(\eta)$$
$$= -1/a_C + r_0 p^2/2 + \cdots$$



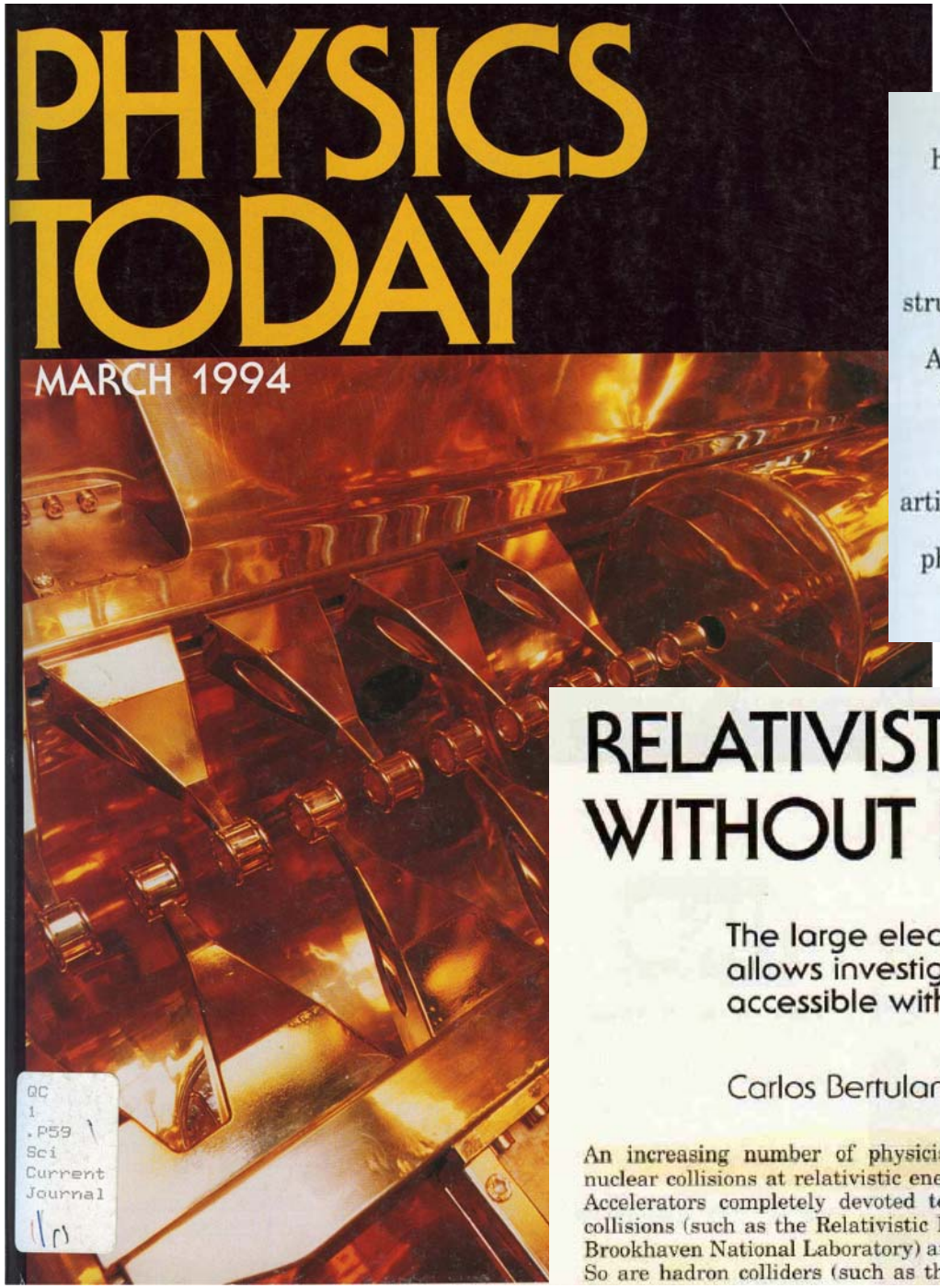
in progress

$$R_{\alpha\alpha'} = \sum_\lambda \frac{\gamma_{\lambda\alpha}\gamma_{\lambda\alpha'}}{E_\lambda - E}$$

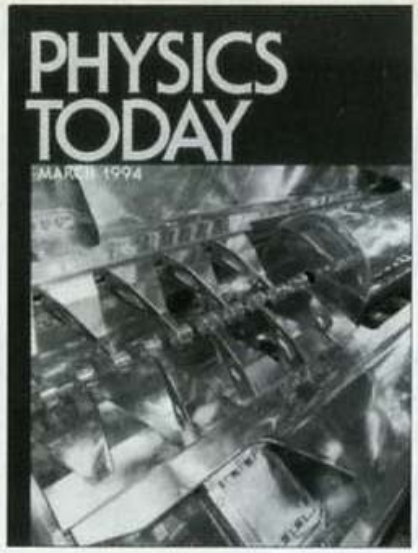
Summary

- Problems in nuclear astrophysics
  - Screening: confusing
  - too small cross sections
  - Many reactions will never be measured directly
- Using direct reactions
  - Coulomb excitation
  - Charge-exchange
  - Knockout & transfer reactions, …
  - Need ISOL and fragmentation facilities
- Needed theory
  - reactions in general
  - bridge internal (structure) to external (reactions)
  - understand Nuc. Phys. from fundamental theory QCD

and for the LHC …



COVER: Inside of a compact high-frequency linear accelerator for heavy ions developed at the Technical University of Munich and at GSI in Darmstadt, Germany. The polished copper structure uses a quadrupole field to focus highly charged ions. Accelerators of this design at GSI and CERN bring ions up to high enough energies that the main accelerators can take them to relativistic energies. In their article on page 22, Carlos Bertulani and Gerhard Baur discuss the physics one can probe by colliding relativistic heavy ions without nuclear contact.



RELATIVISTIC HEAVY-ION PHYSICS WITHOUT NUCLEAR CONTACT

The large electromagnetic field generated by a fast heavy nucleus allows investigation of new electromagnetic processes not accessible with real photons.

Carlos Bertulani and Gerhard Baur

An increasing number of physicists are investigating nuclear collisions at relativistic energies. (See figure 1.) Accelerators completely devoted to the study of these collisions (such as the Relativistic Heavy Ion Collider at Brookhaven National Laboratory) are under construction. So are hadron colliders (such as the Large Hadron Col-

mately by $b/\gamma v$ and that the electric (or magnetic) field during this time interval is very intense: $E \simeq \gamma Ze/b^2$. The factor γ, which is $(1 - v^2/c^2)^{-1/2}$, is very large (on the order of 10^4–10^7) in relativistic heavy-ion colliders.

Theory