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

???

Nuclear many-body problem: one of the hardest problems of all physics!
- Interactions are complicated
- Nucleons = composite particles
- Requires large computation

Typical stellar site
Stellar evolution
Typical problems

$S_{17}/\text{eV b}$ vs $E_{\text{cm}}/\text{MeV}$

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

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
Electron screening: (a) in stars (theoretical) (b) on earth (experimental+theoretical)

Atomic, QED, or nuclear effects? NO

CB, Balantekin, Hussein, NPA 1997

Stopping power tables wrong? YES

CB, de Paula, PRC 2000, 2004
Solutions with direct reactions at 50–200 MeV/nucleon

(A) Trojan horse $A(a=b+x,b+c)C \rightarrow A(x,c)C$  
Claudio Spitaleri, Catania 
Baur, PLB 1986

(B) ANC  Akram Mukhamedzhanov, 1991 
Talk by Bob Tribble, Tuesday

(C) Knockout reactions

\[ A + xN \rightarrow A^+ \rightarrow A^0 + \gamma \]

\[ \frac{d\sigma}{dk_z} \]  
CB, McVoy, PRC 1992  
best probe of $\psi$

\[ \text{Spectroscopic factors} \]

light target $T=^9\text{Be}, ^{12}\text{C}$  
Hansen, Tostevin, ARNPS 2003  
CB, Hansen, PRC 2004

input for nuclear reactions in astrophysics

\[ P_0 \rightarrow P_\parallel \]
Coulomb dissociation

Shoemaker-Levy comet
(easier than this)

Theory
CB, Baur, Rebel, 1986

Kiener et al., Z. Phys. 1993

\[ \sigma_{\gamma+a} = \frac{k^2_{bc}}{k^2_\gamma} \sigma_{b+c} \]

\[ \frac{d\sigma}{dE_\gamma d\Omega} = \frac{1}{E_\gamma} \sum_l \frac{dn_l(E_\gamma, \Omega)}{dE_\gamma d\Omega} \sigma_{\gamma+a \rightarrow b+c}(E_\gamma) \]
Standard calculations

1 - Use a **nuclear model**. Expand trans. dens. into multipoles

\[ \delta \rho(r) \equiv \Psi^*_{J M}(r) \Psi_{J_0 M_0}(r) = \sum_{\lambda \mu} \delta \rho_{J M; J_0 M_0}(r) \]

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

\[ \delta \rho_{\lambda \mu}^{J M; J_0 M_0}(r) = \frac{e_{\text{eff}}}{\sqrt{16\pi}} (-)^{I_C + J_0 + \lambda + j_0 + l_0 + \mu} \frac{J_0}{j} \]

\[ \times \langle J_0 M_0 \lambda \mu | J M \rangle \left\langle j_0 \frac{1}{2} \lambda 0 | j \frac{1}{2} \right\rangle \left\{ j J I_C \right\} r^2 R_{E_{x j}^*}(r) R_{l_0 j_0}^{J_0}(r) \]

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

\[ U(E, r) = \int d^3 r_1 d^3 r_2 \rho_P(r_1) \rho_T(r_2) t_{NN}(E, s) \]

3 - Plug in **DWBA amplitude**

\[ f^{(J M)}_{N \lambda \mu} = -\frac{m_{PT}}{2\pi \hbar^2} \int d^3 r d^3 R \chi^{(-)}(R) \chi^{(+)}(R) \delta \rho_{\lambda \mu}(r) U_{\lambda \mu}(R, r) Y_{\lambda \mu}(\hat{R}) \]
4 - Repeat all for **Coulomb interaction**

\[ f^{(JM)}_{C\lambda\mu} = S_{\lambda\mu}(E_x, \theta) \langle JM | r^2 Y_{\lambda\mu}(\vec{r}) | J_0 M_0 \rangle \]

5 - Add all

\[ \frac{d\sigma^J}{d\Omega dE_x} = \frac{1}{2J_0 + 1} \sum_{M} \left| \sum_{\lambda\mu} \left[ f^{(JM)}_{C\lambda\mu} + f^{(JM)}_{N\lambda\mu} \right] \right|^2 \]
Application to $^7\text{Be}(p,\gamma)^8\text{B}$

Motobayashi et al., PRL 1994

talk by Motobayashi
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 and 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 publication of 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 7Be 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 Filipponi in 1983—but Filipponi’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 9B to get meaningful measure-
and discussed the possibility that the same technique might work for \(^{8}\text{B}\) with Fred Barker, a theorist at the Australian National University, and Motobayashi.

Indeed, the rate of the reaction in which \(^{8}\text{B}\) absorbs a photon and decays into \(^{7}\text{Be}\) 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 \(^{8}\text{B}\) 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 \(^{8}\text{B}\)

They also calculated that if the E2 component is indeed sizable, the experiment would have indicated a reaction rate so slow 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 mis-scaled 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 + neutrino
- proton + electron + proton → deuterium + neutrino
**Nuclear interaction:**

\[ \text{^7Be}(p, \gamma)^8\text{B} \]

from

\[ ^8\text{B} + \text{Pb} \rightarrow p + ^7\text{Be} + \text{Pb} \]

50 MeV/nucleon

Data: Kikuchi, PLB 97
Calc: C.B., NPA 1998
### Higher order transitions

#### Continuum discretization

#### Quantum States

\[ |\varphi_0\rangle = e^{-iE_0 t/\hbar} |\varphi_0\rangle, \quad E_0 = -B \]

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

#### Energy Levels

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<th>p-waves</th>
<th>d-waves</th>
<th>f-waves</th>
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#### Breakup Pathways

- **Ground state**
- **Breakup threshold**

- **Photon absorbed here**
- **Breakup occurs here**

The diagram illustrates the transition between different energy levels and the processes involved in the breakup of a system.
Higher order transitions + E1-E2 interference

\[ ^8 \text{B} + \text{Pb} \rightarrow p^+ \text{Be} + \text{Pb} \]


- 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 distributions

Esbensen, Bertsch, NPA 1996

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

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

\[
U = V_0 (2E - V_0)
\]

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

\[
R = (b, z)
\]

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

\[
f_{\alpha}(Q) = -\frac{ik}{2\pi} \int \! db \ e^{iQ \cdot b} \left[ S_{\alpha}(b, z = \infty) - \delta_{\alpha, 0} \right]
\]

\[
Q = K'_{\perp} - K_{\perp}; \quad \alpha = jlJM
\]

Relativistic CDCC
\( ^8 \text{B} \) dissociation on lead at 50 MeV/nucleon

\[ \varepsilon \frac{d\sigma}{d\theta} \text{[b/rad]} \]

\[ E = 0.5 - 0.75 \text{ MeV} \]

\[ E = 1.25 - 1.5 \text{ MeV} \]

Data: Kikuchi et al, 1997

Perturbation theory, R-CDC, NR-CDC, with non-relativistic \( V_0 \)

Relativistic corrections

4-10% effect

Data: Davids et al, 2002
Summary on CD method for $^7\text{Be}(p,\gamma)^8\text{B}$

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

$S_{17}(0) = 18 \pm 1.1 \text{ eV.b}$
Attempts for $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

see also contribution by C. Angulo


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

80 MeV/nucleon
Trying to reconcile structure and reactions

What do we need?

\[ g(r) = \left\langle \Psi^{(A)} \left| \hat{\Phi}^{(A-a)} \Phi^{(a)} \delta(r - r_{A-a,a}) \right\rangle \right. \]

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

What can we do in practice?

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

Hill-Wheeler, 1953

\[ \begin{pmatrix} H \\ N \end{pmatrix} (r,r') = \left\langle \hat{\Phi}^{(A-a)} \Phi^{(a)} (r') \left| \begin{pmatrix} H \\ N \end{pmatrix} \right| \hat{\Phi}^{(A-a)} \Phi^{(a)} (r) \right\rangle \]

e.g. NCSM

talk by C. Forssen

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

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

$R_{ij}(r) \rightarrow C_{ij} \frac{W_{-\eta, l+1/2}(r)}{r}$
Knockout reactions with NCSM

\[
\frac{d\sigma_{\text{strip}}}{d^2k_C^\perp} = \frac{1}{2\pi} \sum_m \frac{C^2S_{lj}}{(2l+1)} \int d^2b_n \left[1 - \left| S_n(b_n) \right|^2\right] \int dz \left| \int d^2r_\perp e^{-ik_c^\perp \cdot r} S_C(b_C) \phi_{\text{NCSM}}^{ljm}(r) \right|^2
\]

CD Bonn

\[ ^8\text{B} (41 \text{ MeV/nucleon}) + ^9\text{Be} \rightarrow ^7\text{Be} + X \]

\[ ^8\text{B} (41 \text{ MeV/nucleon}) + ^9\text{Be} \rightarrow ^7\text{Be} + X \]

With NCSM wavefunctions (10 $\hbar\omega$)

- $l=1, j=1/2, I_{^7\text{Be}}=3/2$: $C^2S=0.085$
- $l=1, j=3/2, I_{^7\text{Be}}=1/2$: $C^2S=0.280$
- $l=1, j=3/2, I_{^7\text{Be}}=3/2$: $C^2S=0.958$
\( ^8B \text{ (938 MeV/nucleon)} + ^{12}C \rightarrow ^7Be + X \)

\[ \sigma_{\text{str}} = 99.39 \text{ mb} \]

\[ \text{exp} = 94 \pm 9 \text{ mb} \]

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

\[ \sigma_{\text{str}} = 15.31 \text{ mb} \]

\[ \text{exp} = 12 \pm 3 \text{ mb} \]

DATA: Cortinal-Gil et al, 2002
$^7\text{Be}(p,g)^8\text{B}$ S-factor with NCSM

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

CD-Bonn 2000 $10\hbar\Omega \hbar\omega=12 \text{ MeV}$

$S_{17} = 22 \pm 1 \text{ eV.b}$
Future: Charge Exchange

\[ \left( \langle B \sigma \tau \rangle A \right)^2 \]

\( e^- + (Z,A) \rightarrow (Z-1, A) + \nu_e \) needed for \( A \sim 50-60 \)

Obtained from

\( (p,n) \ (n,p) \ (d,^2\text{He}) \ldots (Z, Z\pm 1) \)

based on

- Tadeucci et al, NPA 1981
- Lenske, Wolter, Bohlen, PRL 1989
- CB, NPA 1993

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

Remco Zegers - MSU
Electron-ion collider ELISE (GSI) skins and halos

$\sigma_{ee'}(q)$

soft multipole vibrations

$^{11}\text{Li}$

$\Delta r_{np}$
very strong dependence on effective range expansion parameters, \( a_l, r_l \)

CB, PLB 2005

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

Ershov, PRC 2005
Reconciling Nuclear Physics with QCD

\[ T = \frac{C_0}{T^{(0)}} + \frac{C_0}{T^{(1)}} + \frac{C_0}{T^{(2)}} + \frac{C_0}{T^{(3)}} \]

\[ T(k) \sim \frac{1}{\frac{1}{a} - \frac{1}{2} r_0 k^2 + \ldots - i k} \]

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

\[ c_\eta^2 p (\cot \delta - i) + \alpha m H(\eta) = -\frac{1}{a_C} + r_0 p^2 / 2 + \ldots \]

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

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

CB, Hammer, van Kolck, 2002

Kong, Ravndal, 2000

in progress
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 Collider) and electron-positron storage rings. The electric and magnetic fields generated by these machines are very intense, and the electric and magnetic forces are very large. The factor $\gamma$, which is $(1-\frac{\beta^2}{c^2})^{-1/2}$, is very large (on the order of $10^3$) in relativistic heavy-ion colliders.

Theory