The Electron Screening Effect in Nuclear Astrophysics

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As we have seen in previous talks there are several open issues which need a strong contribution from experimental nuclear astrophysics

- Understand energy production in stars
- BBN
- Nucleosynthesis
- Explosive phenomena
The main problem in the charged particle cross section measurements at astrophysical energies is the presence of the Coulomb barrier between the interacting nuclei. It determines an exponential drop in the abundance curve.

Reactions occur through the tunnel effect:

\[ E_{\text{coul}} \sim Z_1 Z_2 \text{ (MeV)} \]

\[ E_{\text{kin}} \sim kT \text{ (keV)} \]

Coulomb potential

nuclear well

\[ E_{\text{coul}} \sim Z_1 Z_2 \]

\[ V \]

\[ E_{\text{kin}} \sim kT \]

\[ \text{tunneling probability} \]

\[ P \propto \exp(-2\pi\eta) \]

\[ 2\pi\eta = \text{GAMOW factor} \]

in numerical units:

\[ 2\pi\eta = 31.29 Z_1 Z_2 (\mu/E)^{1/2} \]

\[ \mu \text{ in amu and } E_{\text{cm}} \text{ in keV} \]
In general, their direct evaluation is severely hindered and in some cases even beyond present technical possibilities.

Possible solutions: underground measurements, extrapolations.

Gamow energies

\[ \sigma \text{ in the range nano-picobarn} \]
Experimental procedure

Bare Nucleus Astrophysical $S(E)$-factor is introduced. Energies (Gamow energies) could be estimated by extrapolating measurements performed at higher energies.
The **DANGER OF EXTRAPOLATION** ...

large uncertainties in the extrapolation!

Necessary is **Maximize the signal-to-noise ratio**

**SOLUTIONS**

- **IMPROVEMENTS TO INCREASE**
  - **NUMBER OF DETECTED PARTICLES**
  - $4\pi$ detectors
  - New accelerator at high beam intensity

- **IMPROVEMENTS TO REDUCE**
  - **THE BACKGROUND**
  - Use of laboratory with natural shield - (underground physics)
  - Use of magnetic apparatus (Recoil Mass Separator)
The electron screening effect must be taken into account


In the accurate measurements for the determination of nuclear cross-sections at the Gamow energy, in laboratory, enhancement $f_{\text{lab}}(E)$ -factor in the astrophysical $S_b(E)$ -factor has been found

$$S_{Sh} \propto S_b \cdot e^{-\frac{\pi \eta U_e}{E}}$$

$^3\text{He} + ^2\text{H} \rightarrow p + ^4\text{He}$
Electron Screening

At astrophysical energies the presence of electron clouds must be taken into account in laboratory experiments.

The atomic electron cloud surrounding the nucleus acts as a screening potential $U_e$

- Phenomenological approach
  
  $$U_e = \frac{Z_1 Z_2 e^2}{R_a}$$
  
  $$R_a \approx \frac{R_B}{Z_1}$$
  
  $R_B$: raggio di Bohr

- Adiabatic approximation

Adiabatic approximation (low velocity case)

If $v_p \ll v_B = Z \alpha c$ (low velocity case) the electrons continuously rearrange their orbits while projectile and target approach each other, i.e. the electron wave function re-adjust itself continuously at any time it is an eigenfunction of the two-center Hamiltonian.

\[
\text{In this approximation the electron screening potential is}
\]

\[
U_{ad} = E^{(1)} + E^{(2)} - E^\oplus
\]

with $E(i)$ electronic binding energy of the $i$-th atom and $E^\oplus$ the electronic binding energy of the compound nucleus.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energy (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}(d,p)^4\text{He}$</td>
<td>119</td>
</tr>
<tr>
<td>$^7\text{Li}(p,a)^4\text{He}$</td>
<td>186</td>
</tr>
<tr>
<td>$^6\text{Li}(d,a)^4\text{He}$</td>
<td>186</td>
</tr>
</tbody>
</table>
Electron screening in the laboratory

Direct Measurements

\[ ^3\text{He} + ^2\text{H} \rightarrow p + ^4\text{He} \]

Stellar Screening ≠ Laboratory Screening

Experimental Data (Shielded)

Extrapolation of \( S_b \) (Bare)

Autofitting procedure

Correction for stellar screening (Debye-Hückel theory)

An experimental measurement of \( U_e \) allows:

- a determination of \( S_b \) (applications)
- to study electron screening in laboratory conditions and then in stellar plasma
Values of $U_e$ were estimated for several reactions by means of comparison between direct data and extrapolations. A systematic discrepancy was observed in the data:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$U_e$ (exp)</th>
<th>$U_e$ (ad)</th>
<th>$U_e$ (calc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6Li(d,^3He)$</td>
<td>20 eV</td>
<td>186 eV</td>
<td>300 ± 160 eV</td>
</tr>
<tr>
<td>$^7Li(p,^3He)$</td>
<td>20 eV</td>
<td>300 ± 160 eV</td>
<td>440 ± 80 eV</td>
</tr>
</tbody>
</table>

Works made in a long campaign by Rolfs' group.

Possible explanations:

- lack of knowledge for energy loss at $E<100$ keV;
- extrapolation of $S_b(E)$ at astrophysical energies;
- theoretical models of electron screening (atomic physics).
IN SUMMARY...

To avoid extrapolations, experimental techniques were improved;

To extract from direct (shielded) measurements the bare astrophysical $S_b(E)$-factor, extrapolation were performed at higher energy.

After improving measurements (at very low energies), electron screening effects were discovered;


$^3\text{He} + ^2\text{H} \rightarrow p + ^4\text{He}$
Can a metallic environment simulate stellar plasma?


Study of electron screening for D(d,p)t in deuterated targets (Ti, Al, Zr) “the plasma of the poor”

\[ U_e (D\text{-metal}) \sim 10-30 \text{ times than in } U_e (D\text{-gas}) \]

Systematic study (58 samples) of Ue in D(d,p)t in deuterated metals

• Electron screening potential was measured for d(d,p)t reaction with deuterons implanted in metals
• Large values (Ue\gg\text{adiabatic approx.}) were measured
• Several years of work of Claus’ group in Bochum (with Catanese contaminants), Berlin, Japan and other places
A more enhanced screening effect is seen in metals (blue) \((U_{ad}=30 \text{ eV})\)

Raiola et al. EPJ A, 2002 & 2004
Debye length

\[ R_{\text{Debye}} = \left( \frac{\epsilon_0 kT}{n \rho_a e^2} \right)^{1/2} \]

Helmholtz potential

\[ U_e = \frac{Z_1 Z_2 e^2}{R_{\text{Debye}}} \quad \iff \quad U_e \propto T^{-1/2} \]

**Example:**

\[ T = 293 \ K \]
\[ n = 1 \]
\[ U_e = 300 \ eV \]
\[ \rho_a = 6 \times 10^{22} \ cm^{-3} \]

**Idea:** quasi-free electrons in a metal could simulate free electrons in stellar plasma (classical picture).
Electron screening in stars is rather different than in lab ... and to assume stellar plasma behaves like “poor plasma” in metals is just a hypothesis.

**Up to now:** Correction of the reaction rate for stellar screening (Debye-Hückel theory)

\[ U_e = \frac{Z_1 Z_2 e^2}{R_{\text{Debye}}} \]

\[ f_{\text{star}} \propto \langle \sigma v \rangle \ e^{\frac{\pi \eta U_e}{E}} \]

i.e. it is assumed a correction to the bare nucleus reaction rate which depends on stellar plasma conditions.
NEW METHODS ARE NECESSARY

-to measure cross sections at never reached energies

-to retrieve information on electron screening effect when ultra-low energy measurements are available.

INDIRECT METHODS ARE NEEDED
Main Indirect Methods

a) - Coulomb dissociation
to study radiative capture reactions

b) - Asymptotic Normalization Coefficients (Anc) ... to extract direct capture cross sections using peripheral transfer reactions

c) - Beta Delay decays studies and other methods

d) - The Trojan Horse Method (THM)
to extract charged particle reaction cross sections using the quasi-free mechanism...
Trojan Horse Method (outlook)

Main application:
Charged particle bare nucleus cross section measurements at astrophysical energies

Basic idea:
It is possible to extract astrophysically the relevant two-body cross section $\sigma$

$$B + x \rightarrow C + D$$

from quasi-free contribution of an appropriate three-body reaction

$$A + B \rightarrow C + D + S$$

SEE SILVIO'S LECTURE
Trojan Horse Method (outlook)

Main application: Charged particle bare nucleus cross section measurements at astrophysical energies

Basic idea:
- The A nucleus presents a strong cluster structure: $A = x \oplus S$ clusters.
- It is possible to extract astrophysically the relevant two-body cross section $\sigma_{B + x \rightarrow C + D}$ from quasi-free contribution of an appropriate three-body reaction $B + x^+ \rightarrow C + D + S$.
- The $x$ cluster (participant) interacts with the nucleus $B$.
- The $S$ cluster acts as a spectator (it doesn't take part to the reaction).

SEE SILVIO'S LECTURE
Results for Lithium I

$U_e = 340 \pm 50 \text{ eV}$

$U_{ad} = 186 \text{ eV}$

$S_0 = 16.9 \text{ MeV b}$


- No screening effect at $E < 100 \text{ keV}$ for indirect data;
- Direct and indirect methods are complementary;
- Independent determination of $S_b(E)$ and $U_e$;
- Previous extrapolations of $S_b$ are confirmed.
Results for Lithium II (see talk Lamia)

\[ S_b(E) \text{ (keV b)} \]

\[ E_{cm}(\text{MeV})^{1} \]

\[ ^7\text{Li} + p \rightarrow \alpha + \alpha \]

- Previous extrapolations of \( S_b(E) \) are confirmed;
- Independent measurement of \( U_e \).

\[ U_e = 425 \pm 60 \text{ eV} \]
\[ U_{ad} = 186 \text{ eV} \]
\[ S_0 = 53 \pm 5 \text{ keV b} \]

- Pizzone R.G. et al.: 2003, A.& A.. 9, 435
RESULTS FOR LITHIUM III
(see Talk Lamia)

L. Lamia et al., in press on APJ (2013)

\[ U_e = 355 \pm 100 \text{ eV} \]
\[ U_{ad} = 186 \text{ eV} \]
\[ S_0 = 3.44 \pm 0.35 \text{ MeV b} \]
Results for d(d,p)t

\[ U_e = 13.2 \pm 2 \text{ eV} \]
\[ U_{ad} = 14 \text{ eV} \]
\[ S_0 = 57.4 \pm 1.8 \text{ keV b} \]

Only case in agreement with adiabatic limit, investigation still going on.

RESULTS FOR $^9$Be(p,\(\alpha\))^6Li

\[ S(E) \text{ (MeV b)} \]

\[ E_{\text{c.m.}} \text{ (MeV)} \]

$U_e=676 \pm 86 \text{ eV}$

$U_{ad}=240 \text{ eV}$

$S_0=21 \pm 0.8 \text{ MeV b}$

Q. Wen et al., PHYS. REV. C 78, 035805 (2008)
Results for $^{11}$B$^+$ p

$U_e = 472 \pm 160$ eV
$U_{ad} = 340$ eV
$S_0 = 2.07 \pm 0.41$ MeV b

For the $^3$He(d,p)$^4$He case (La Cognata et al. 2005):

<table>
<thead>
<tr>
<th>$U_e^{(\text{theo})}$</th>
<th>$U_e^{(\text{THM})}$ $^3$He+d</th>
<th>$U_e^{(\text{Dir})}$ $^3$He+d</th>
</tr>
</thead>
<tbody>
<tr>
<td>115 eV</td>
<td>155 ± 15 eV</td>
<td>175 ± 30 eV</td>
</tr>
</tbody>
</table>

The reaction $^3$He(d,p)$^4$He is important for primordial nucleosynthesis as well as stellar one.
Summary for reactions on the examined isotopes:

Previous extrapolations for bare nucleus S(E)-factor as well as the electron screening potential are confirmed (statistical error only)

Systematic Discrepancy with adiabatic limit as in direct data

Isotopic effect confirmed

Still very active field of research

New possibility: plasma physics, lasers applications …

The best is yet to come!!
• References

• Assemaub et al., Z. Phys. A, 327, 461-468
• C. Bertulani’s Lecture
• F. Striede et al., Naturwissenschaften, 88, 2001
• R.G. Pizzone et al., Nucl. Phys. A, 834, 673c
• S. Cherubini’s Lecture
We have the pleasure to announce the “7th European Summer School on Experimental Nuclear Astrophysics (Santa Tecla School)”, devoted to the education of young Ph.D. students and young researchers. The school belongs to the European Network of Nuclear Astrophysics Schools (ENNAS), a network made by the four European schools on nuclear astrophysics and related areas (the Santa Tecla, the Sinaia, the Russbach schools), having the common effort of preparing and educating young physicists in nuclear physics, astrophysics and their mutual relationship in the nuclear astrophysics field.