Electron Screening Constraints for the Cold Fusion

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Electron Screening in Nuclear Reactions I

\[ V(r) = \frac{Z_1 Z_2 e^2}{r} \exp\left(-\frac{r}{a}\right) \approx \frac{Z_1 Z_2 e^2}{r} - U_e \]

\[ U_e = \frac{Z_1 Z_2 e^2}{a} \]

screening energy

\[ P(E) = \sqrt{\frac{E_G}{E}} \exp\left(-\sqrt{\frac{E_G}{E}}\right) \]

s-wave penetration factor

\[ P(E) \rightarrow P(E + U_e) \]
Electron Screening in Nuclear Reactions II

cross section

\[ \sigma(E) = \frac{1}{E} S(E) \exp\left(-\sqrt{\frac{E_G}{E}}\right) = \frac{1}{\sqrt{EE_G}} S(E) P(E) \]

enhancement factor

\[ f = \frac{\sigma_{scr}}{\sigma_{bare}} \neq \frac{\sigma(E + U_e)}{\sigma(E)} = \frac{P(E + U_e)}{P(E)} \]

- \( E_G \) - Gamow energy
- \( S(E) \) - astrophysical S-factor
- \( P(E) \) - penetration factor
Experimental Results

\[ d + d \rightarrow \ ^3\text{He} + n \]
\[ d + d \rightarrow \ ^3\text{H} + p \]

**metal target**

Europhys. Lett. 54 (2001) 449

Similar results:

**gas target**

\[ U_e = 25 \pm 5 \text{ eV} \]

**Dielectric Function Theory**

\[ V(r) = \frac{e^2}{r} \Phi(r) = \frac{1}{(2\pi)^3} \int \frac{4\pi(e\varphi(q))^2}{\varepsilon_v(q) \varepsilon_c(q) q^2} \exp(iqr) \, d^3q \]

\[ \varepsilon = \varepsilon_v = \varepsilon_c = 1 \]

**self-consistent charge formfactor**

\[ \varphi(q) = 1 - z + \frac{zq^2}{(q^2 + k_{TF}^2)} \]

- \( z \): number of bound electrons
- \( k_{TF} \): Thomas-Fermi wave number

**valence-electron dielectric function**

\[ \varepsilon_v(q) = 1 - \frac{v(q)P(q)}{1 + v(q)G(q)P(q)} \]

- \( P(q) \): Lindhard RPA polarizability
- \( G(q) \): local field correction

**core-electron dielectric function**

\[ \varepsilon_c(q) \]

from f-sum rule
Cohesion Screening Contribution

Plasma: screening arising from interaction between positive ions
Solid: difference in binding energy of He atom and two deuterons in solid

universal screening potential ZBL

$$V(r) = \frac{Z_1 Z_2 e^2}{r} \Phi(x)$$

where

$$\Phi(x) = \sum_{i=1}^{4} A_i \exp(-B_i x)$$

with

$$x = \frac{r}{a}$$

$$a (\text{He+metal}) \neq a (\text{d+metal})$$

$$a = \frac{0.8854 \ a_o}{Z_1^{0.23} + Z_2^{0.23}}$$
Results: Screening Function & Screening Energy

PdD

\[ \phi(r) \]

Deuteron-Deuteron Distance \( (10^{-10} \text{m}) \)

- screening function with LFC
- exponential screening function
- screening function without LFC

U\text{eff}(eV)

Ed,CM (eV)

screening function with LFC
- exponential screening function
- screening function without LFC

high energy limit:

\[ U_e = \lim_{r \to 0} \left( \frac{e^2}{r} - \frac{e^2}{r} \Phi(r) \right) \]
Results: Screening Energy

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Screening Energy (eV)

Atomic Number
Results: Cross Section & Yield (PdD)

\[
\sigma_{scr}(E) \approx \frac{1}{\sqrt{U_0 E}} S_0 \exp \left( - \frac{E_G}{U_0} \right) \propto \frac{1}{\sqrt{E}}
\]

\[
Y_{scr}(E) = \int_{E_0}^{E} \frac{\sigma_{scr}(E)}{A \sqrt{E}} \, dE \propto \ln \frac{E}{E_0}
\]
Results: Reaction Rate (PdD)

\[ R_{scr}(E) = N \sigma_{scr}(E) v_{rel} = N \sigma_{scr}(E) \sqrt{\frac{4E}{M}} \approx \frac{2NS_0}{\sqrt{MU_0}} \exp\left(-\sqrt{\frac{E_G}{U_0}}\right) \]

low energy limit:

\[ U_0 = \lim_{E \to 0} U_{eff}(E) \]

\[ U_0 = 0.72 U_e \]
Hypothetic Resonance in $^4$He

resonance width $\Gamma_{sp} = 2 k P \gamma^2 \sim 10 \text{ MeV}$ for $P = 1$
$\sim 10 \text{ eV}$ for $P \ll 1$

resonance maximum $\sigma_{\text{max}} = \frac{4\pi}{k^2} \frac{\Gamma_i \Gamma_f}{\Gamma^2}$

resonance narrowing $\sigma_{\text{max}} \leftrightarrow 10^6$
Resonance Branching Ratios

resonance decay channels

\( ^4\text{He} + \text{e}^- \) internal conversion \( E_e \sim 24 \text{ MeV} \)

\( ^4\text{He} + \text{d} \) internal conversion \( E_\alpha \sim 8 \text{ MeV} \quad E_d \sim 16 \text{ MeV} \)

\( ^4\text{He} + \gamma \) \( \gamma \) decay \( E_\gamma \sim 24 \text{ MeV} \)

\( ^3\text{H} + \text{p} \) stripping reaction \( E_p \sim 3.6 \text{ MeV} \quad E_t \sim 1.2 \text{ MeV} \)

\( ^3\text{He} + \text{n} \) stripping reaction \( E_n \sim 2.4 \text{ MeV} \quad E_\tau \sim 0.8 \text{ MeV} \)

branching ratio

\[
\frac{\text{energy production}}{\text{neutron emission}} = \frac{\text{conversion}}{\text{stripping}} \approx 10^6
\]

\[
\Rightarrow \quad \frac{\gamma^2_d}{\gamma^2_n} \approx 10^8 \quad \text{quenching of neutron channel}
\]
Conclusions  (High Energy)

- observed target material dependence of the screening energy
  for heavier metals $U_e \rightarrow 300 \text{ eV}$
  for gas target $U_e = 25 \pm 5 \text{ eV}$

- theoretical screening energies (polarization of valence and core
  electrons + cohesion screening) smaller by a factor of 2
  dynamical effects ?

- effective screening energy approach $U_0 = 0.72 \; U_e$
Conclusions (Room Temperature)

- deuterons captured in the metallic lattice → theoretical reaction yields smaller by a factor of $10^{10}$ than the observed neutron emission

- quasi-free deuterons → neutron emission can be explained by means of the electron screening effect (enhancement by a factor of $10^{40}$)

- narrow resonance in $^4$He → additional enhancement by a factor $10^6$, possible explanation of the energy production and quenching of the neutron channel