Effects of Superconductor Electron Screening on Fusion Reactions

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Motivation

- An Alternate Approach to Fusion to Tokamak and inertial confinement fusion
  - Fusion cross sections are a function of their surroundings
  - Consider alternate means of modifying fusion cross sections (i.e., electron screening)
- Settle the disagreement on electron screening behavior in superconductors (possible large enhancements in fusion cross sections)

Outline

- □ - Discuss fusion cross sections and how electron screening changes them in materials (e.g., superconductor)
- □ - Show theoretical reaction rates and energy gains in a superconductor
- □ - Present design and analysis of experiment to determine effects of electron screening in superconductors on fusion reaction rates

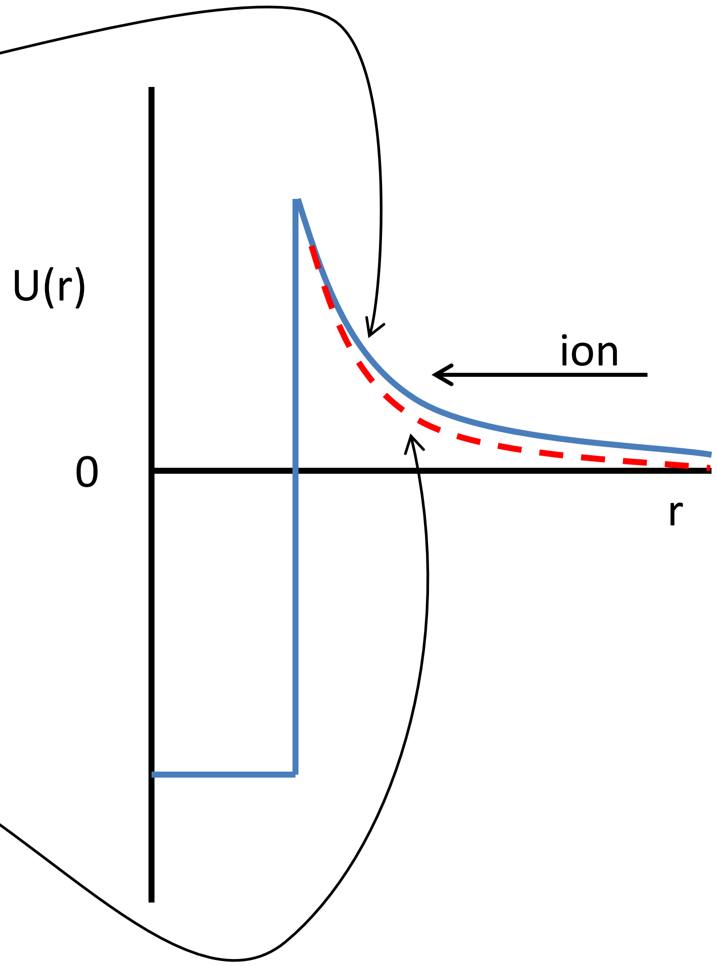
Cross Sections

- Classical Coulomb barrier
- Classical fusion cross section

$$\sigma_f \approx \frac{S(E)}{E} \cdot T(E) = \frac{S(E)}{E} \exp\left(-\sqrt{\frac{\epsilon_G}{E}}\right)$$

- Debye Length (λ)
  - Length of electric field influence
- Modified Coulomb barrier

$$U = U_o \exp(-r/\lambda)$$



Screening

- Screening energy (ϵ_s) from λ

$$\epsilon_s = \frac{Z_1 \cdot Z_2 \cdot e^2}{4\pi \cdot \varepsilon_o} \cdot \frac{1}{\lambda}$$

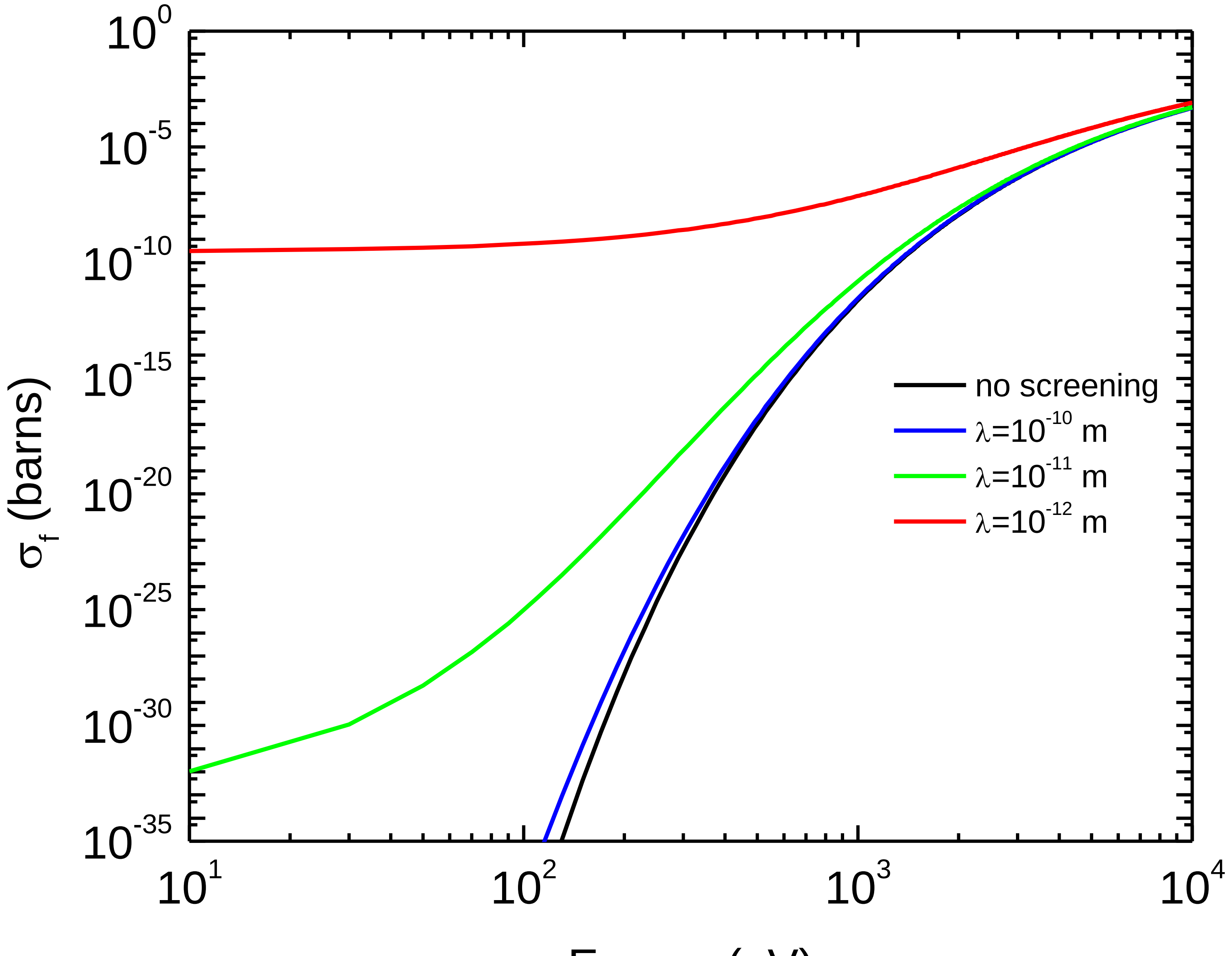
  – Insulator or gas*: $\lambda \approx 10^{-9} m$ and $\epsilon_s \approx 10 eV$
  – Metal*: $\lambda \approx 10^{-10} m$ and $\epsilon_s \approx 100 eV$

- Fusion cross section with added screening energy

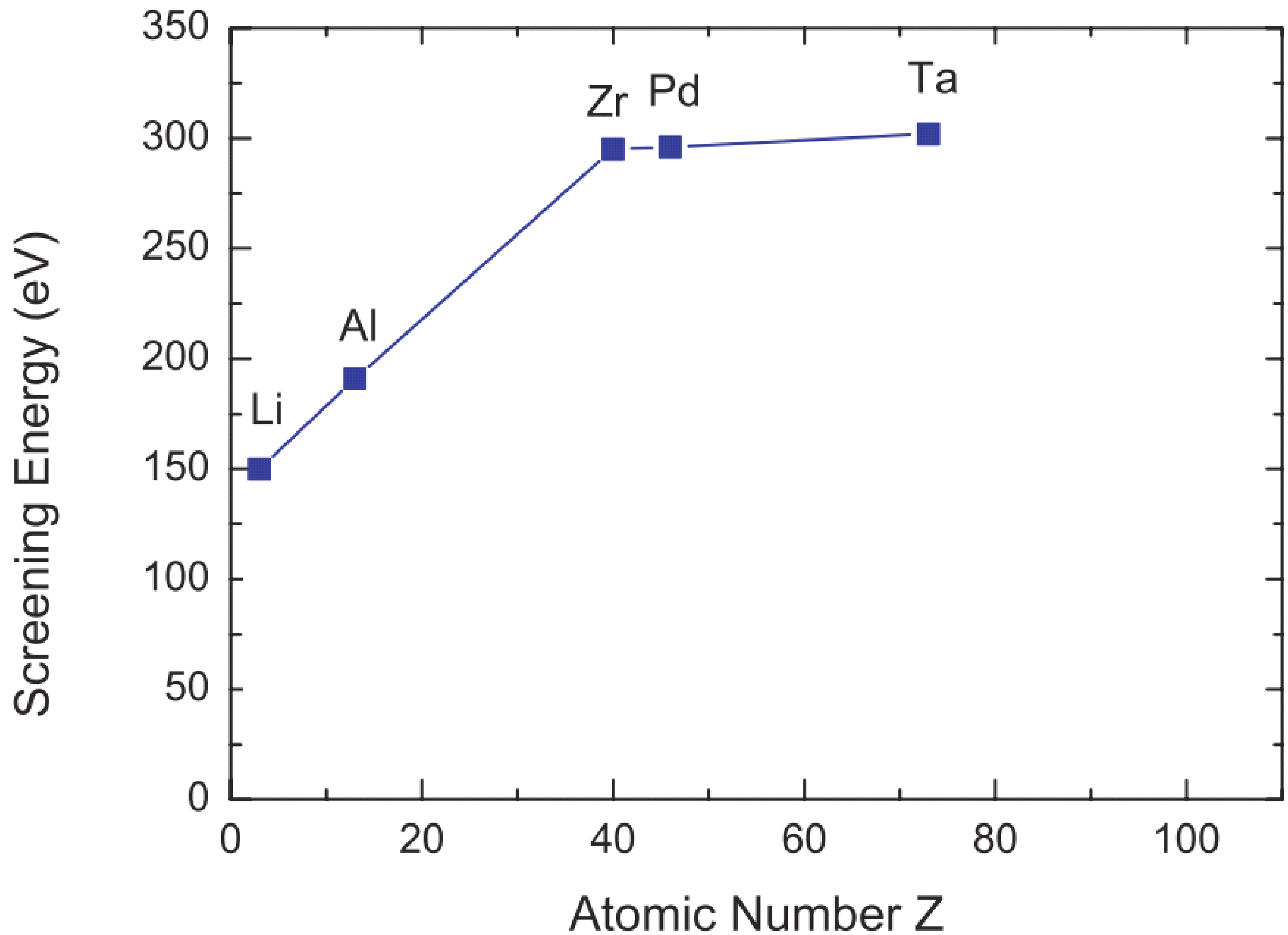
$$\sigma_f \approx \frac{S(E + \epsilon_s)}{E + \epsilon_s} \exp\left(-\sqrt{\frac{\epsilon_G}{E + \epsilon_s}}\right)$$

* Calculated for D-D fusion

D-D Fusion Cross Sections



Examples of Screening in Metals



Huke, A, et al. Enhancement of deuteron-fusion reactions in metals and experimental implications. Phys. Rev. C 78, 015803(2008).

Improve Electron Screening

- Metal screening energies are the highest known, but are still relatively low
- Is it possible to increase ϵ_s to make low energy fusion reaction rates more substantial?
- Theories exist (Stoppini & Shibata) claiming large ϵ_s enhancements with superconductors
- However, superconductor electron screening has been contentious

Superconductivity

- Superconductivity exists below a superconductor's critical temperature (T_c)
  - Fraction of conduction electrons travel in pairs (Cooper pairs) with less resistance
  - When sufficiently below T_c most conduction electrons are in Cooper pairs
  - Electrons in pairs are separated by coherence length (ξ), which is 10-100s of lattice constants
- PdD (T_c=11°K) consists of D-D fusion reactants
- Stoppini & Shibata theories consider that both electrons in a Cooper pair participate in screening

Reaction Rates

- Lattice vibration induced fusion reaction rates

Reactant density & nearest neighbors

$$\mathrm{RR} = \frac{\omega_D}{2\pi} \cdot \frac{N \cdot N_n \cdot S}{k_B T + \epsilon_s(T)} \cdot \frac{1}{4\pi a^2} \exp\left(- \sqrt{\frac{\epsilon_G}{k_B T + \epsilon_s(T)}} \right) \cdot f_1 \cdot f_2$$

Vibration frequency — Vibrational directions — Mobility reduction factors

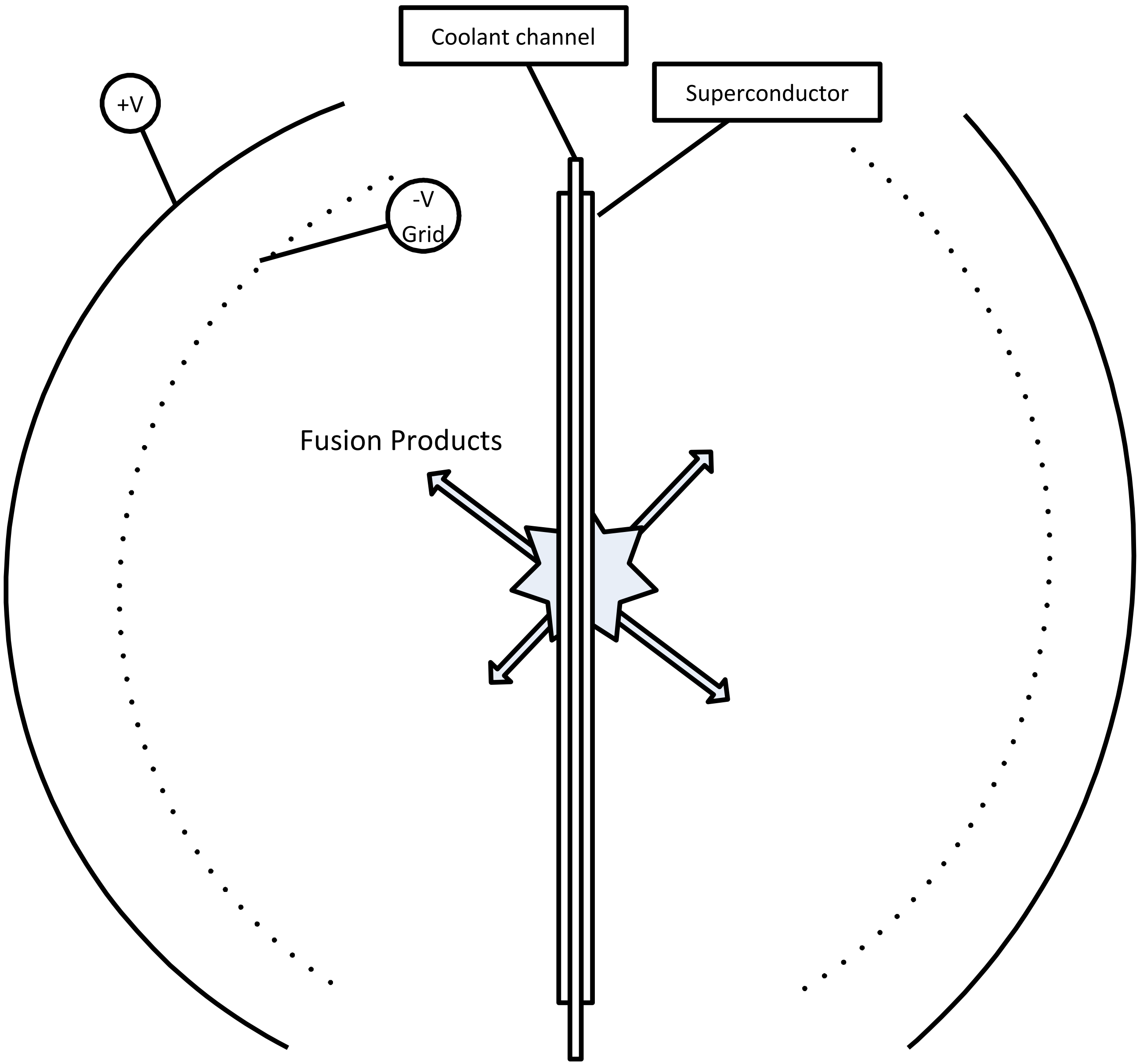
- Consider vibration induced reaction rates in palladium deuteride (PdD)
  - Metal (293°K): ~ 10^{-5} m^{-3}-s^{-1}
  - Superconductor (10°K): ~0 m^{-3}-s^{-1}
  - Superconductor* (266°K): ~10^{18} m^{-3}-s^{-1}

* Tripodi published observations of near-room temperature superconductivity in PdD

Potential Application

- If superconductor screening could provide sufficient fusion reaction rates due to lattice vibrations, could energy be extracted from these reactions?
- Analysis considers losses from energy conversion and superconductor cooling requirements

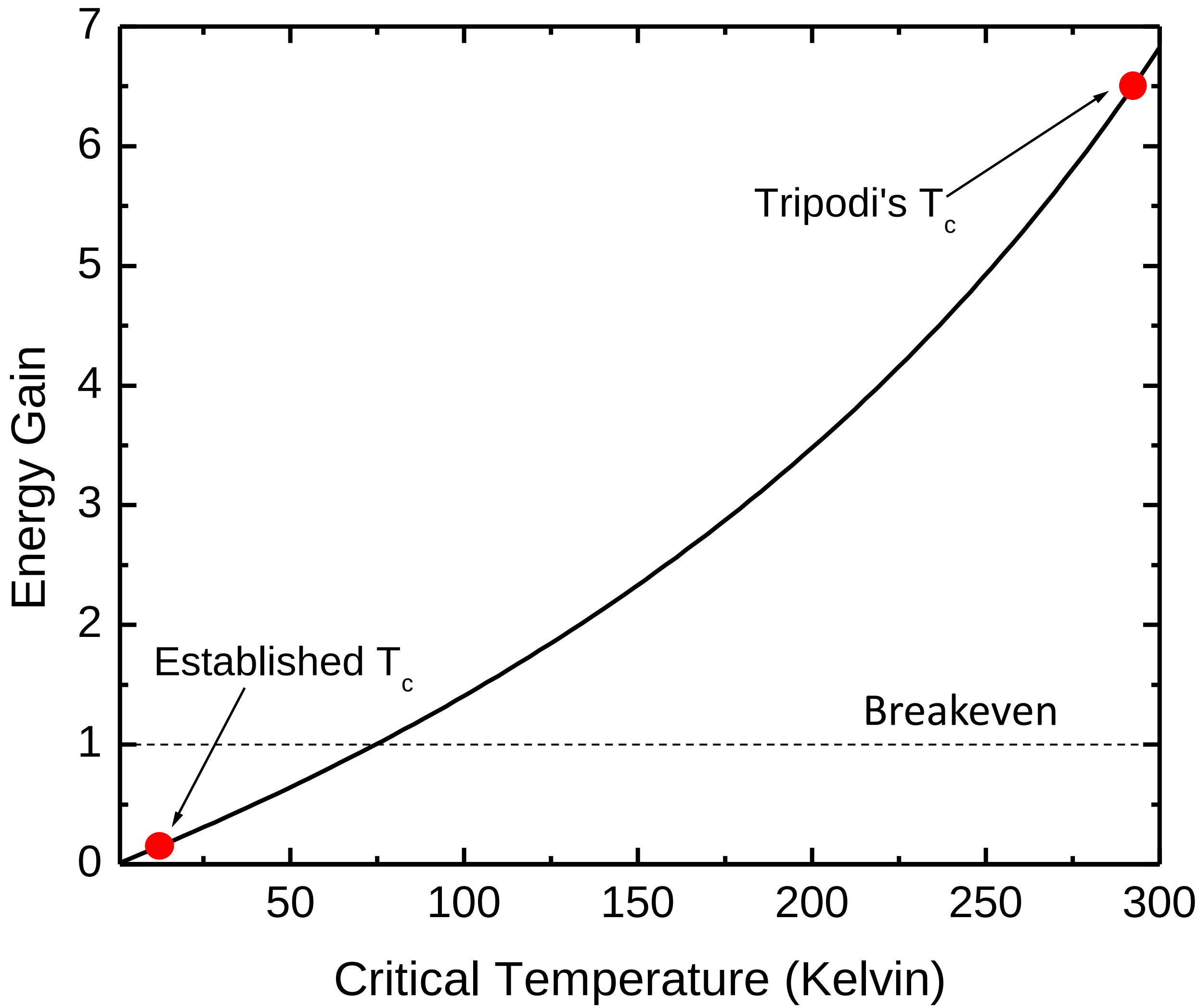
Simplified Model



Calculation Assumptions

- PdD superconductor held at $T_c/2$ for sufficient Cooper pair density
- Sample thickness at limit of superconductivity (ξ)
  - Minimize fusion product energy loss in superconductor
- Carnot refrigeration efficiency for cooling
- Maintain direct energy conversion system near room temperature

Result

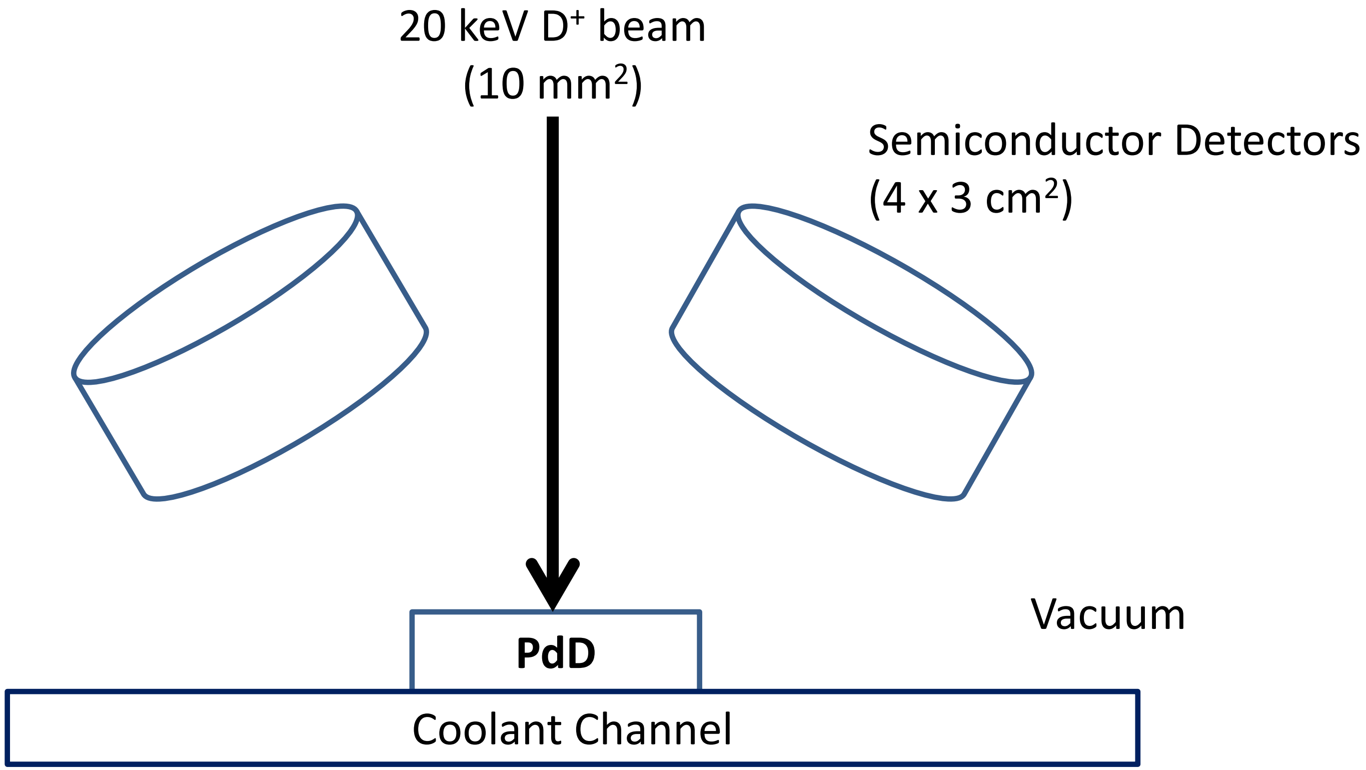


- No net energy gain when the T_c for the superconductor (i.e., PdD) is <75°K
- Possible energy gain with Tripodi's PdD_x ($x \gg 1$)
- Reaction rates will determine if auxiliary systems (e.g., vacuum) can be supported for net energy gain

Superconductor Screening Experiment Design

- Experimental design is warranted due to debated Cooper pair screening effect and possibility of fusion energy extraction
- PdD experiment designed and analyzed expected result uncertainties
- Protocol:
  - Test PdD above and below T_c to extract Cooper pair contribution to electron screening
  - Bombard low energy deuteron ions (~20 keV D^+ or lower) to allow screening energy to be resolved
  - Limit D^+ loading to prevent radiation damage and changes in T_c

Experimental Setup



Contributors to Uncertainty

PdD_x

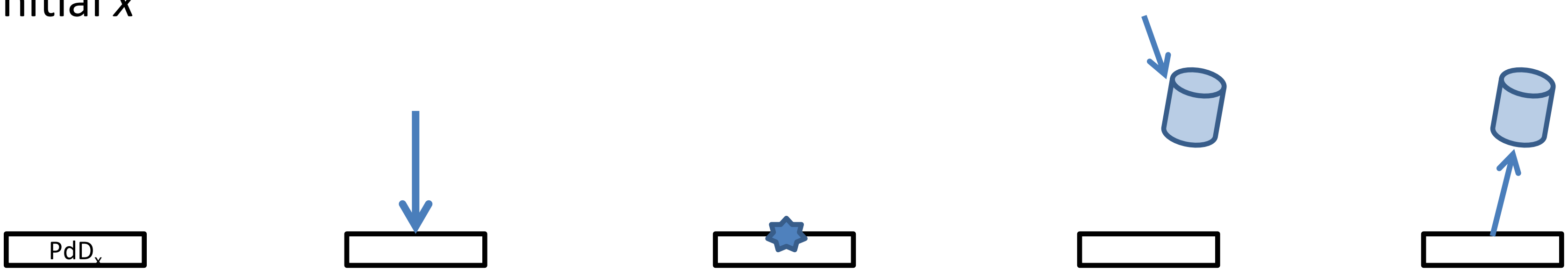
initial x

Incident D^+

Fusion reactions per D^+ ion $(\sigma_i N_D)$

Background radiation

Fusion product counting statistics



Error Analysis

- Fusion events per ion error

$$\sigma\_(\sigma_i N_D)_{\text{exp}} = \sqrt{\eta_{\text{det}} \cdot D_{limit} \cdot \sigma_i N_D} \left(\frac{1}{\eta_{\text{det}}} \cdot \frac{1}{D_{limit}} \right)$$

- Screening energy interpolation error

$$\sigma\_\epsilon_{s\_\text{int}} = \left(\epsilon_{s\_high} - \epsilon_{s\_low}\right) \cdot \sqrt{\frac{\left[\sigma\_(\sigma_i N_D)_{\text{exp}}\right]^2 + \left[\sigma\_(\sigma_i N_D)_{hl}\right]^2}{\left[(\sigma_i N_D)_{high} - (\sigma_i N_D)_{low}\right]^2} + \left(\frac{\left[(\sigma_i N_D)_{\text{exp}} - (\sigma_i N_D)_{low}\right]^2 2(\sigma\_(\sigma_i N_D)_{hl})^2}{\left[(\sigma_i N_D)_{high} - (\sigma_i N_D)_{low}\right]^4} \right)}$$

- Analyzed errors prior to experiment
  - 38% error with 95% confidence on sample PdD with $\epsilon_s = 400\ eV$
  - Able to differentiate screening between theorized higher superconducting ϵ_s and lower metal ϵ_s

Conclusion

- No net energy gain from a superconductor (PdD) with T_c<75°K
  - Even with a T_c>75°K reaction rates appear too low to support auxiliary systems (e.g., vacuum)
- Experiment designed would clarify effects of electron screening in superconductors
  - Consider MgB_2 superconductor experiment with incident protons to understand screening with a reactant with inner orbital electrons

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