8th Patras Workshop on Axions, WIMPs and WISPs

A Concept for a Dark Matter Detector Using Superfluid Helium-4

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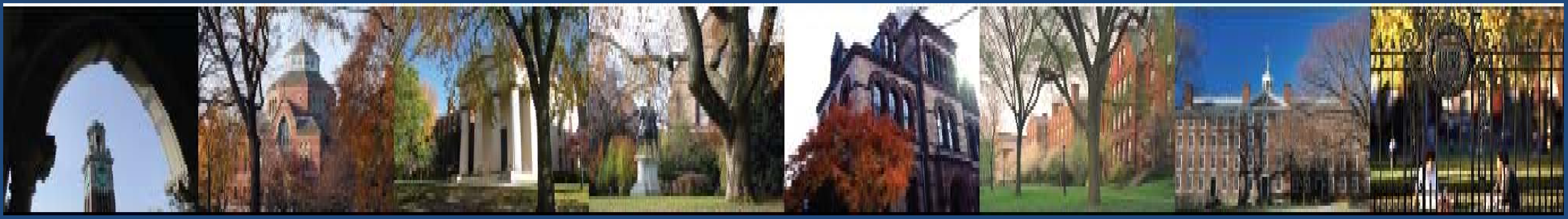


Outline

- Introduction
  - Basic properties of superfluid helium.

- Particle recoils in liquid helium
  - Nuclear recoils:
    - ✓ equilibrium charge states
    - ✓ ionization and excitation yields.
  - Event discrimination:
    - ✓ ratios of signals from different channels
    - ✓ Background rejection power

- Experimental setup schematics

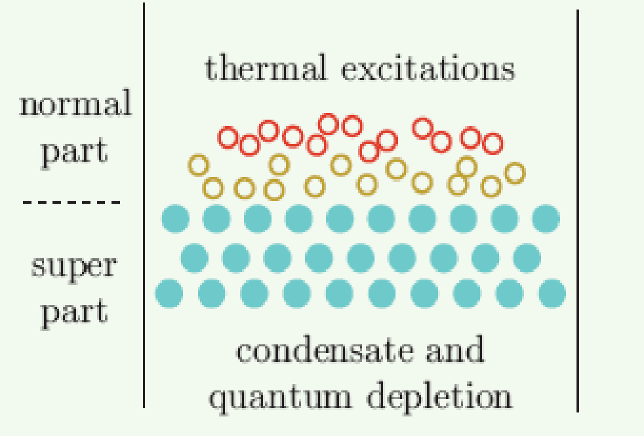
- Summary

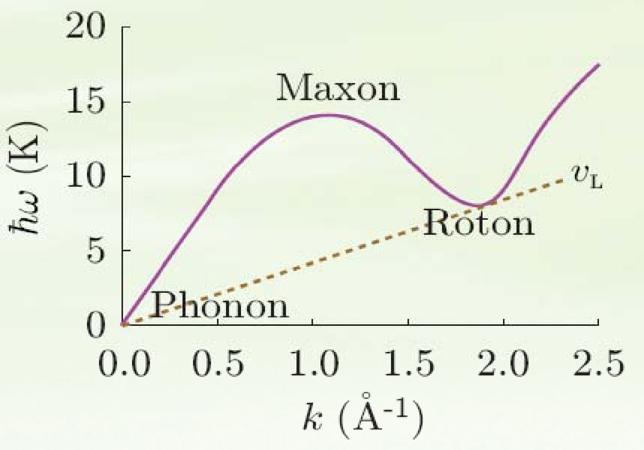
Introduction

- Superfluid helium: Two-fluid system

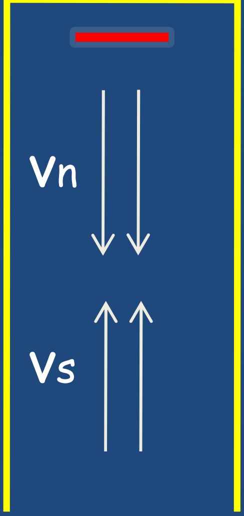
Liquid He4 becomes superfluid below ~2K
Two components:
Superfluid component (condensate)
Normal-fluid component (excitations)

$$\rho_s \to \rho \text{ as } T \to 0K$$
$$\rho_n \to \rho \text{ as } T \to T_c$$





The superfluid component flows with no viscosity!



Heat conduction:
thermal counterflow ➔ $v_n = \frac{w/A}{\rho S T}$ $v_s = \frac{\rho_n}{\rho_s} v_n$

- Why using liquid helium?

➔ Superfluid helium is of great interest as a detector material in particle and nuclear physics research:

Purity: all impurities freeze out ➔ extreme purity and negligible internal radioactive background.

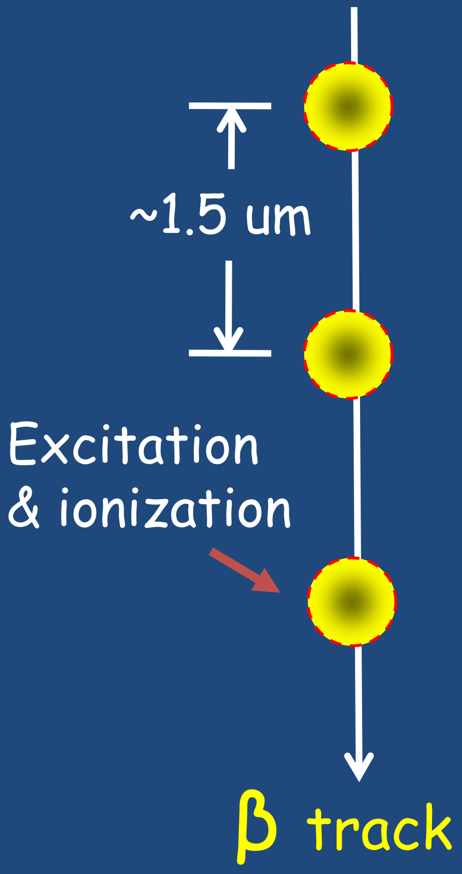
(1) UCN production; (2) nEDM; (3) solar neutrino detection; …

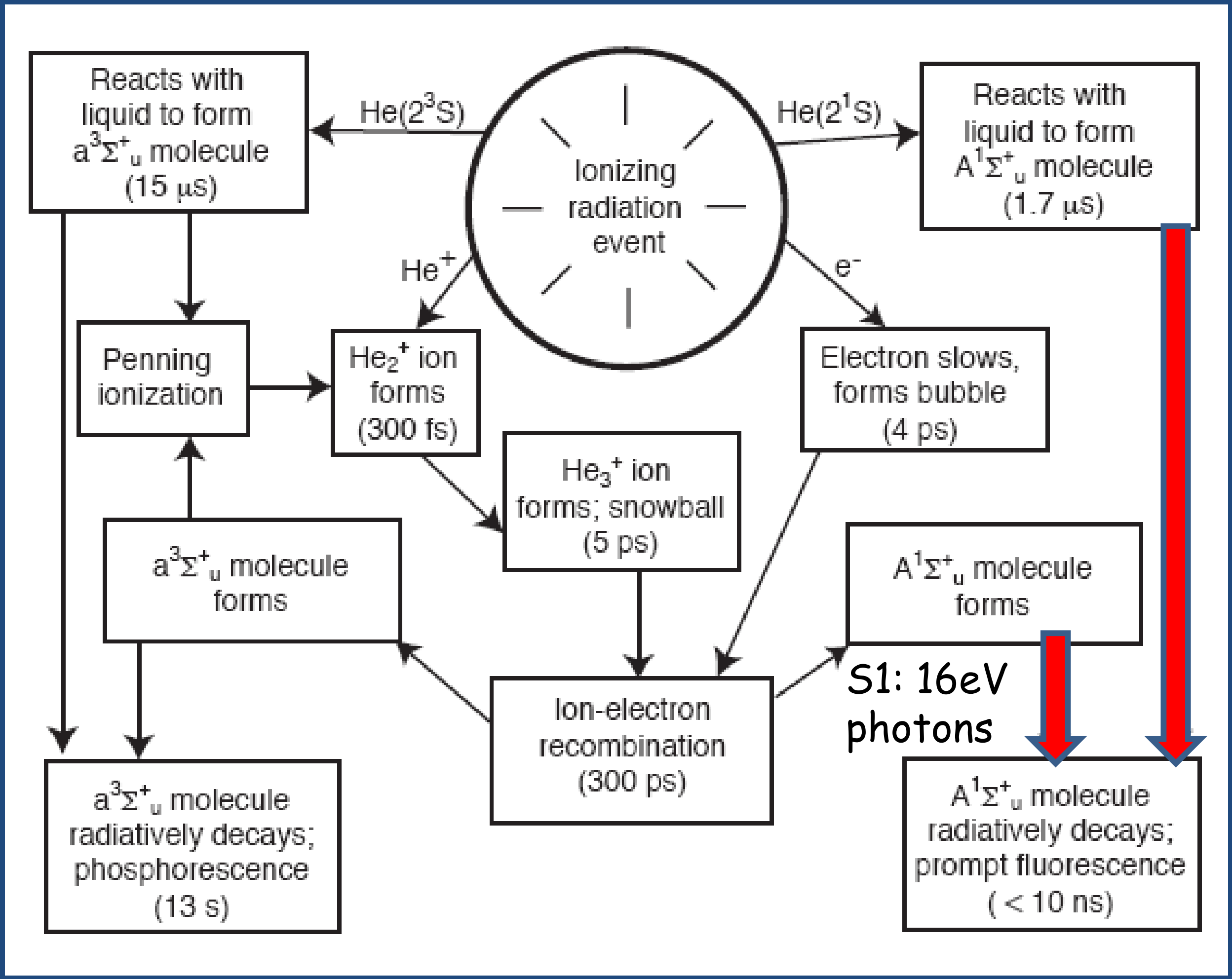
➔ Low mass WIMP (0.3~10GeV) detection

(energy threshold x nuclear mass) should be minimized to get the best sensitivity to low-mass WIMPs.

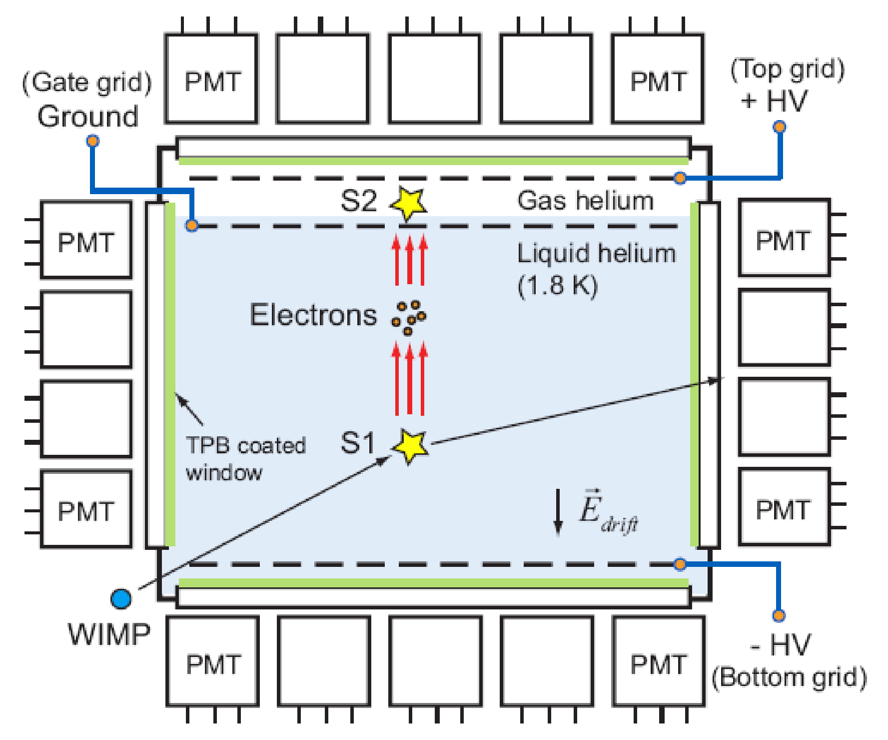
- Helium nuclei are light.
- Helium-based detector has excellent background rejection power and low energy-threshold, similar to Xenon.

- Energetic particles interacting with liquid helium





- Signals to be detected

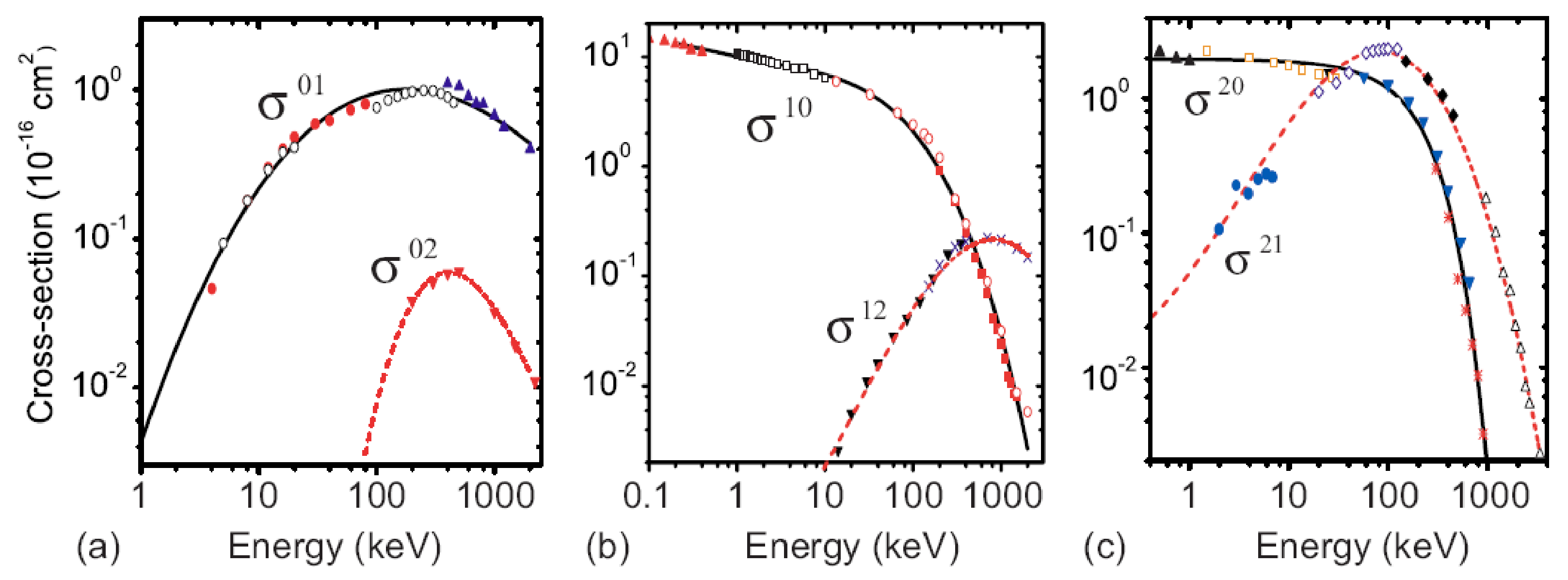


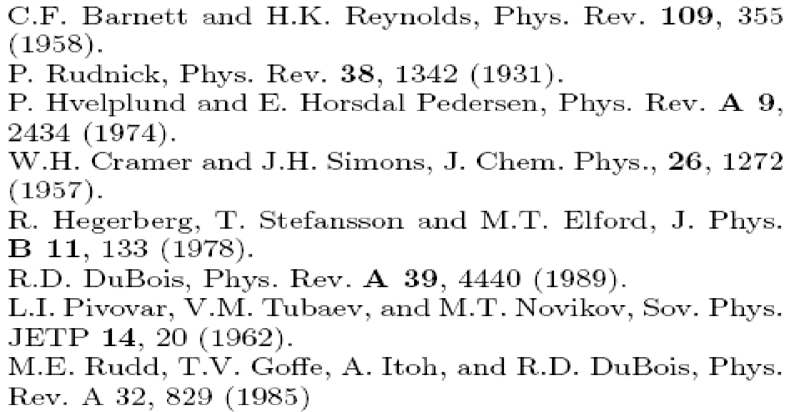
➢ Prompt scintillation (S1): due to the decay of singlet He2 molecules.
Charge signal (S2): electrons escaped recombination with ions in field.
Molecule signal (S3): triplet molecules that are long-lived.
Quasi-particles (S4): detectable at low temperatures.

➢ Q: Scintillation and charge yields? Does the ratio between signals from different channels allow good event-discrimination?

- Nuclear recoils in LHe

The recoil particles: He, or He+ , or He+2 ?





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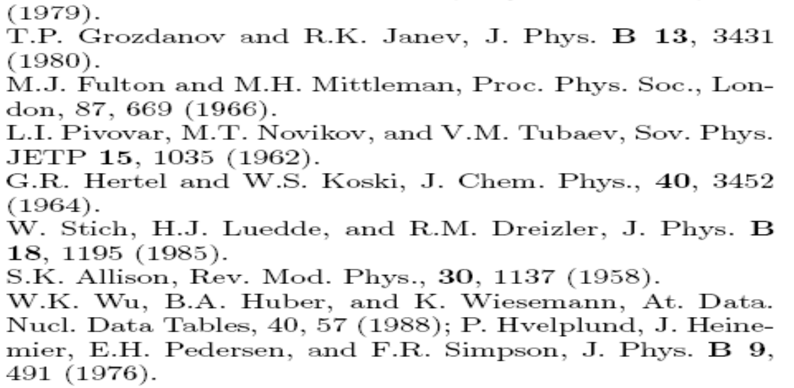

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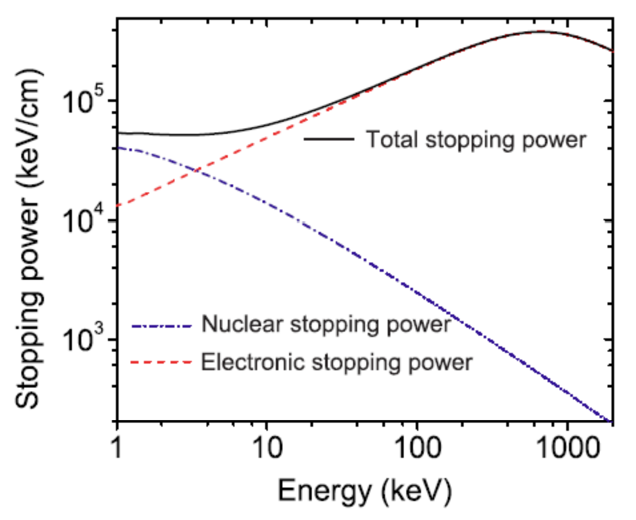
Large amount of experimental charge-exchange cross-section data are available for helium, which is unusual for other noble gas liquids !

- Equilibrium distribution of the charge states.

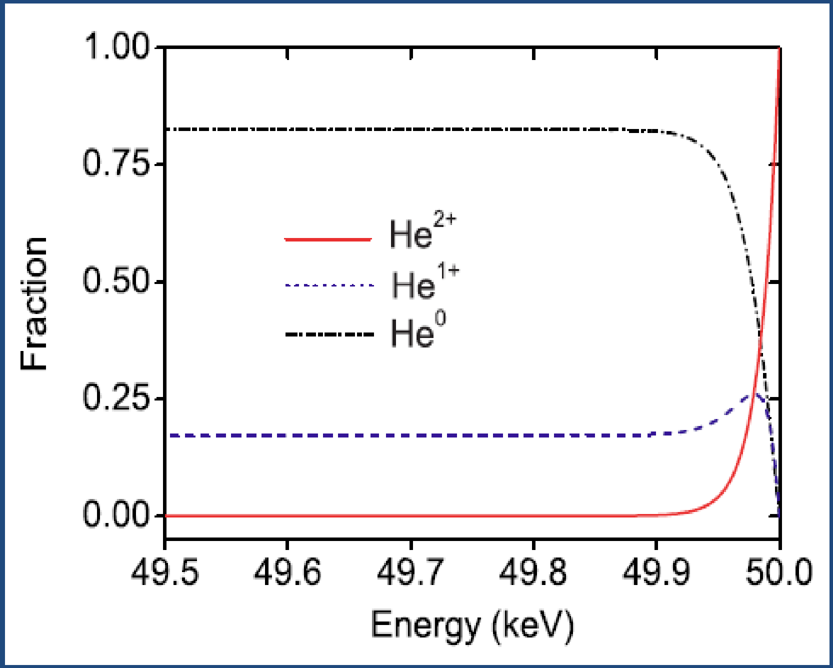


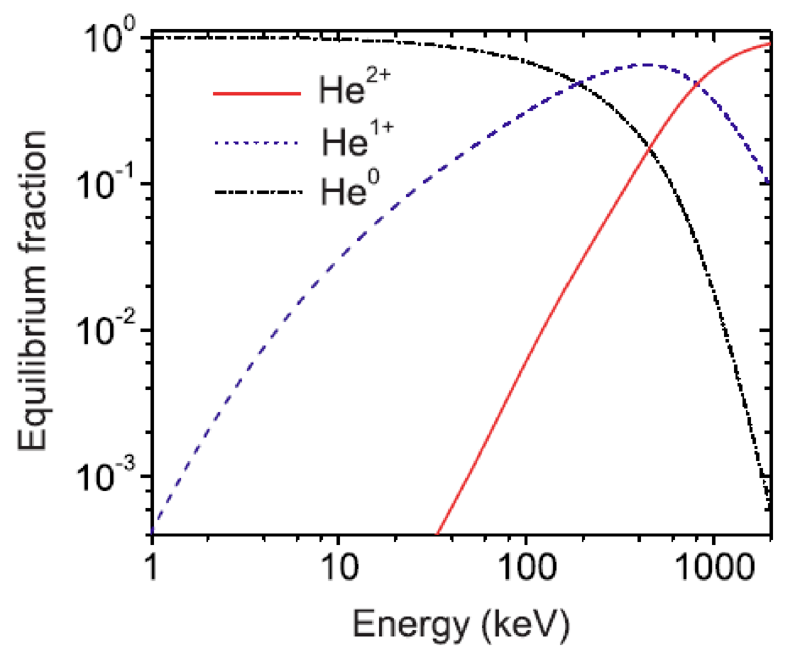
$$\frac{dF_0(E)}{dE} = \frac{N}{S(E)}\left[-F_0(\sigma^{01}+\sigma^{02}) + F_1\sigma^{10} + F_2\sigma^{20}\right]$$

$$\frac{dF_1(E)}{dE} = \frac{N}{S(E)}\left[-F_1(\sigma^{10}+\sigma^{12}) + F_0\sigma^{01} + F_2\sigma^{21}\right]$$

$$F_2(E) = 1 - F_0(E) - F_1(E)$$

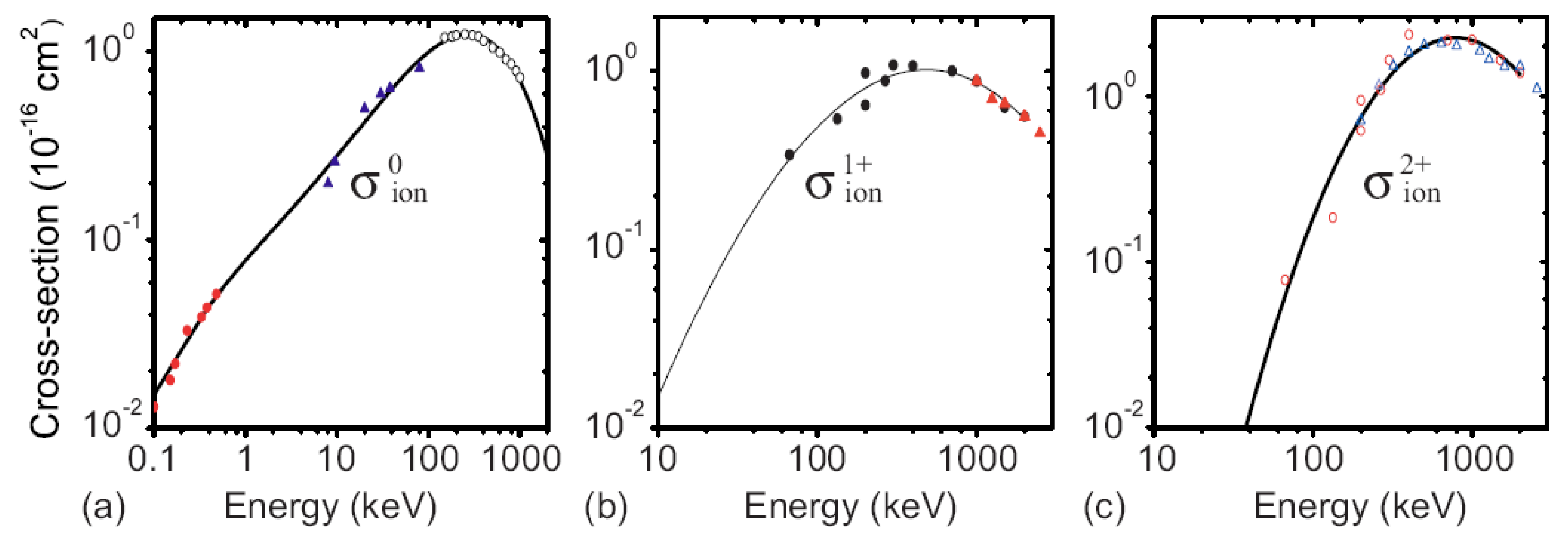
Charge exchange collisions lead to steady fractions in all three charge states !





For low energy recoils, the fraction of charge zero state dominates. The recoil particle is essentially an energetic neutral helium atom.

- Ionization and excitation yields.



The total number of electrons produced by the recoil helium ion is the sum of the ionizations due to direct ionization collisions, charge exchange processes, and ionizations due to secondary electrons.

$$
\begin{aligned}
N_{\texttt{el}} &= N_{\texttt{el}}^{\texttt{Dir}} + N_{\texttt{el}}^{\texttt{Exc}} + N_{\texttt{el}}^{\texttt{Sec}} \\
&= \int_0^E \frac{N\,dE'}{S(E')}\left[F_0^\infty(E')\sigma^0_{\texttt{ion}} + F_{1+}^\infty(E')\sigma^{1+}_{\texttt{ion}} + F_{2+}^\infty(E')\sigma^{2+}_{\texttt{ion}}\right] \\
&+ \int_0^E \frac{N\,dE'}{S(E')}\left[F_0^\infty(E')\left(\sigma^{01} + 2\sigma^{02}\right) + F_{1+}^\infty(E')\sigma^{12}\right] \\
&+ N_{\texttt{ion}}^{\texttt{Sec}}
\end{aligned}
$$

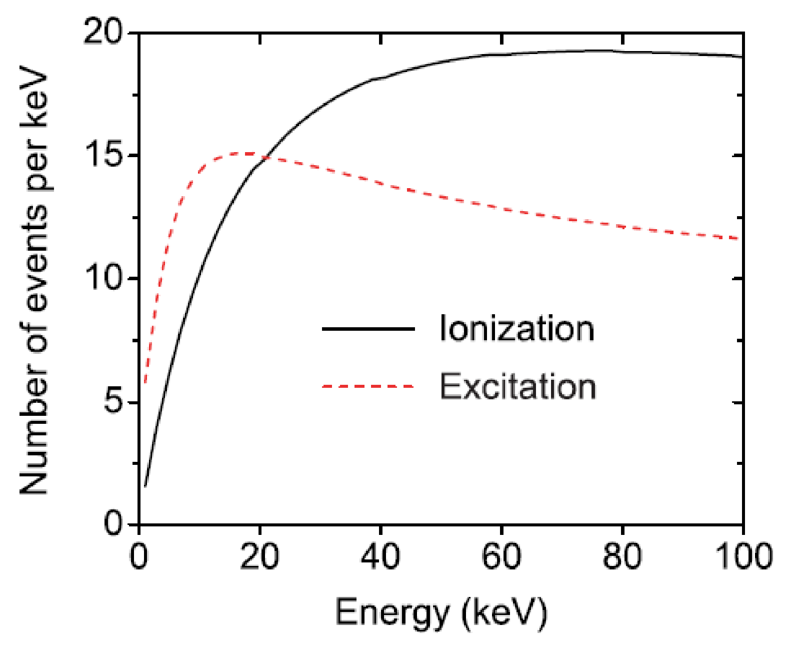
Ionization yield: $Y_{el} = N_{el} / E$

Excitation yield:

$$Y_{ex} = N_{ex} / E$$

$$N_{\text{ex}} = \int_0^E \frac{N dE'}{S(E')} [F_0^\infty(E')\sigma_{\text{ex}}^0 + F_1^\infty(E')\sigma_{\text{ex}}^{1+} + F_2^\infty(E')\sigma_{\text{ex}}^{2+}] + \tilde{N}_{\text{ex}}$$

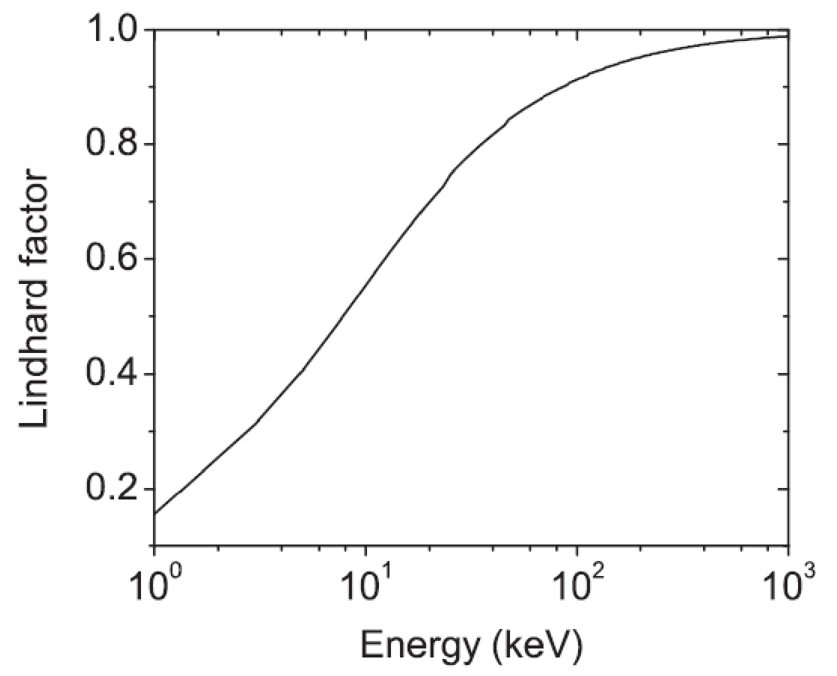
$$Y_{\text{ex}} \simeq \frac{L}{\bar{Q}_{\text{ex}}} - \frac{Q_{\text{He}}}{\bar{Q}_{\text{ex}}} Y_{\text{el}} - \frac{1}{E}\int_0^E \frac{N dE'}{S(E')} \frac{1}{\bar{Q}_{\text{ex}}} \cdot \{[F_0^\infty \sigma_{\text{ion}}^0 \bar{\varepsilon}_0 + F_1^\infty \sigma_{\text{ion}}^{1+} \bar{\varepsilon}_1 + F_2^\infty \sigma_{\text{ion}}^{2+} \bar{\varepsilon}_2] + [F_0^\infty(\sigma^{01} + 2\sigma^{02})\lambda E + F_1^\infty \sigma^{12} \lambda E]\}$$



For comparison:

$$Y_{el}^{(e)} = 22.7 \text{ keV}^{-1}$$

$$Y_{ex}^{(e)} = 10.2 \text{ keV}^{-1}$$



Lindhard factor:

$$L = \frac{1}{E}\int_0^E \frac{S_e(E')dE'}{S(E')}.$$

- Signals from different channels

  - Nuclear recoils:

    S1 (prompt scintillation): $N_{ex}\times\frac{2}{3}+N_{ex}\times\frac{1}{3}\times(1-q)+N_{el}\times(1-q)\times\frac{1}{2}$

    S2 (extracted electrons): $\left(N_{el}+N_{ex}\times\frac{1}{3}\right)\times q$

    S3 (triplet molecules): $N_{el}\times(1-q)\times\frac{1}{2}$

    (q: charge extraction coefficient under electric field ε)

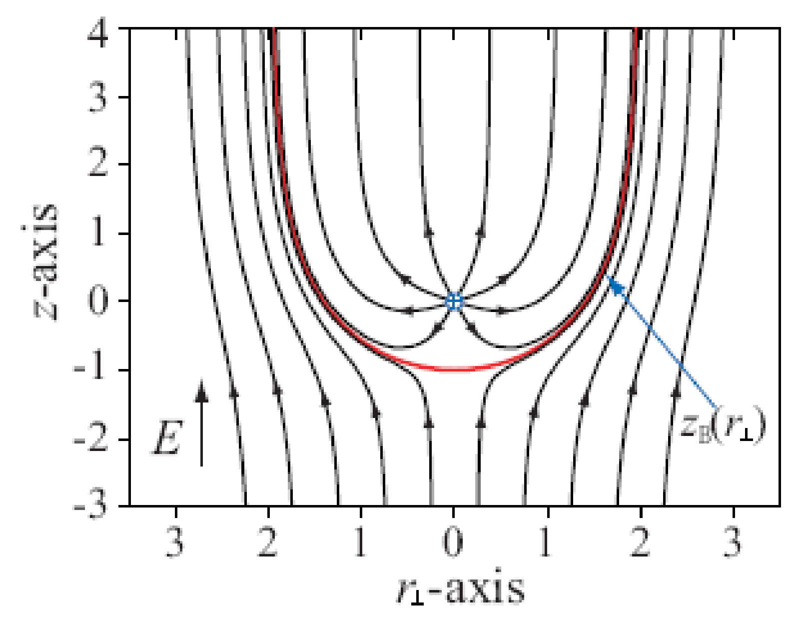
  - Electronic recoils:

    S1 : $N_{ex}^{(e)}\times 86\%\times\frac{2}{3}+N_{ex}^{(e)}\times 86\%\times\frac{1}{3}\times(1-q)+N_{el}^{(e)}\times(1-q)\times\frac{1}{2}$

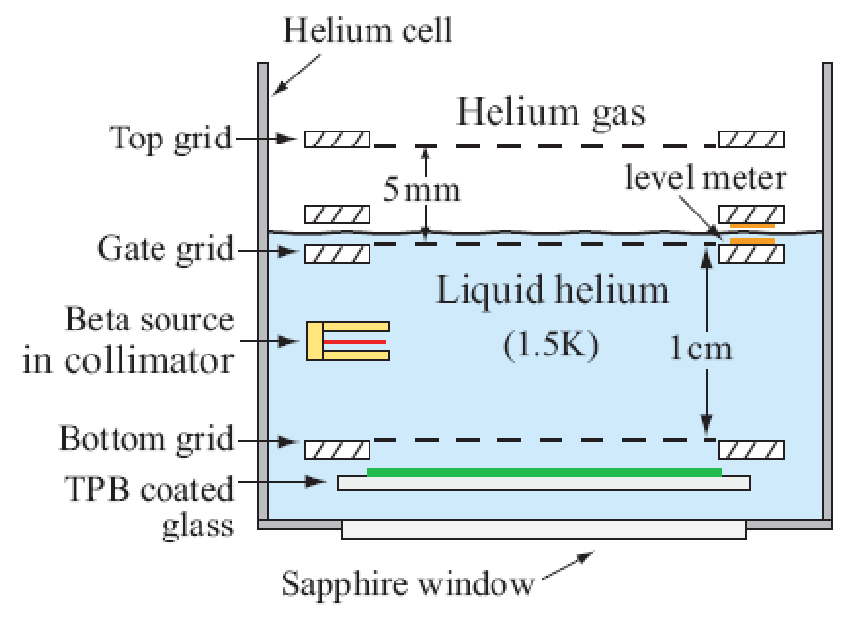
    S2 : $\left(N_{el}+N_{ex}\times\frac{1}{3}\right)\times q$

    S3 : $N_{el}^{(e)}\times(1-q)\times\frac{1}{2}+N_{ex}^{(e)}\times 14\%\times\frac{2}{3}+N_{ex}^{(e)}\times 14\%\times\frac{1}{3}\times(1-q)$

- Charge extraction coefficient q under electric field ε
  - Charge pairs due to electron recoils undergo germinate recombination. Ionized electrons move along field lines to escape or recombine with ions.

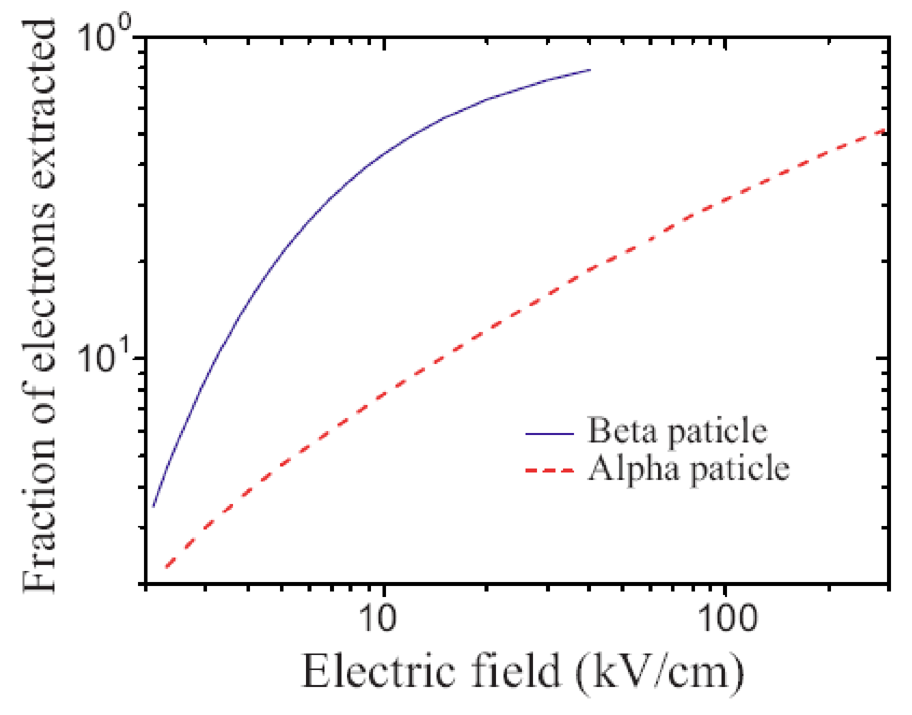


$$P_{escape} = 1 - \int_{-1}^{\infty} dz_B \int_0^{r_\perp(z_B)} 2\pi r_\perp dr_\perp \cdot \frac{8}{\pi^3 \xi'^3} \cdot \exp\left\{-\frac{4(z_B^2+r_\perp^2)}{\pi\xi'^2}\right\}.$$



W. Guo, *et. al.*, "Scintillation and Charge Yield from the Tracks of Energetic Electrons in Superfluid Helium-4", JINST 7, P01002 (2012).

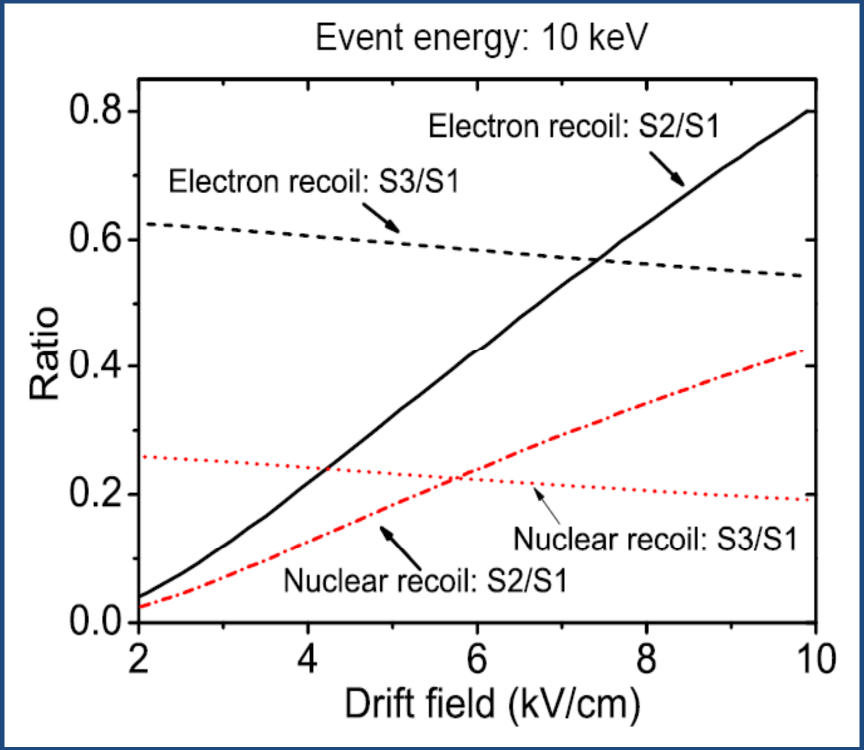
- Ionized electrons along alpha track are attracted by all nearby ions. Charge recombination is described by Jaffe's columnar theory.

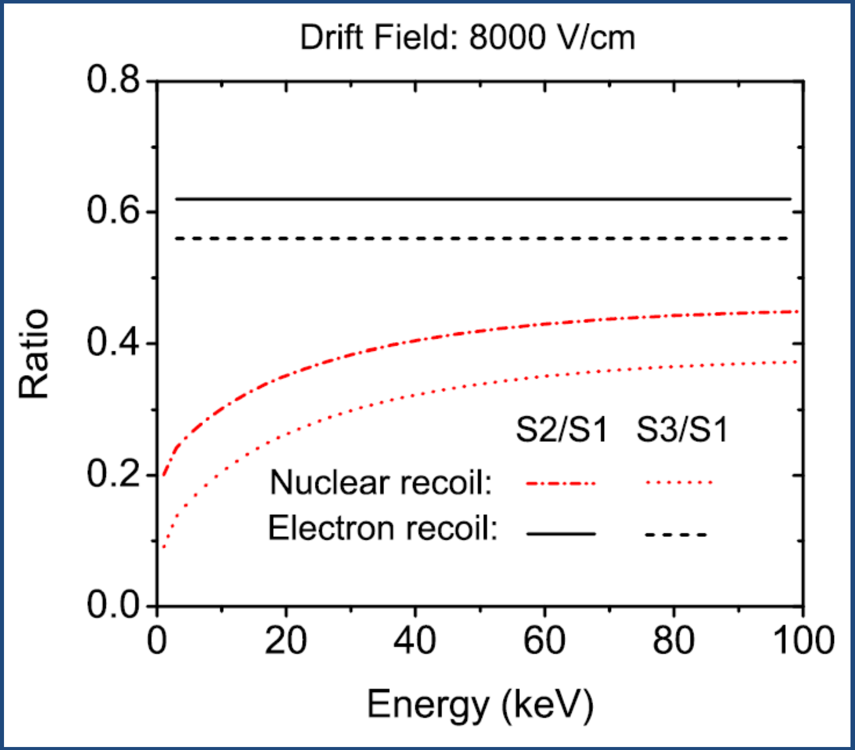


alpha: PRA 85, 042718 (2012)
beta: JINST 7, P01002 (2012)

- Ionization density along low energy recoil helium ion/atom is low. Charge extraction should be similar to that of electron recoils.

- Ratio of signals from different channels



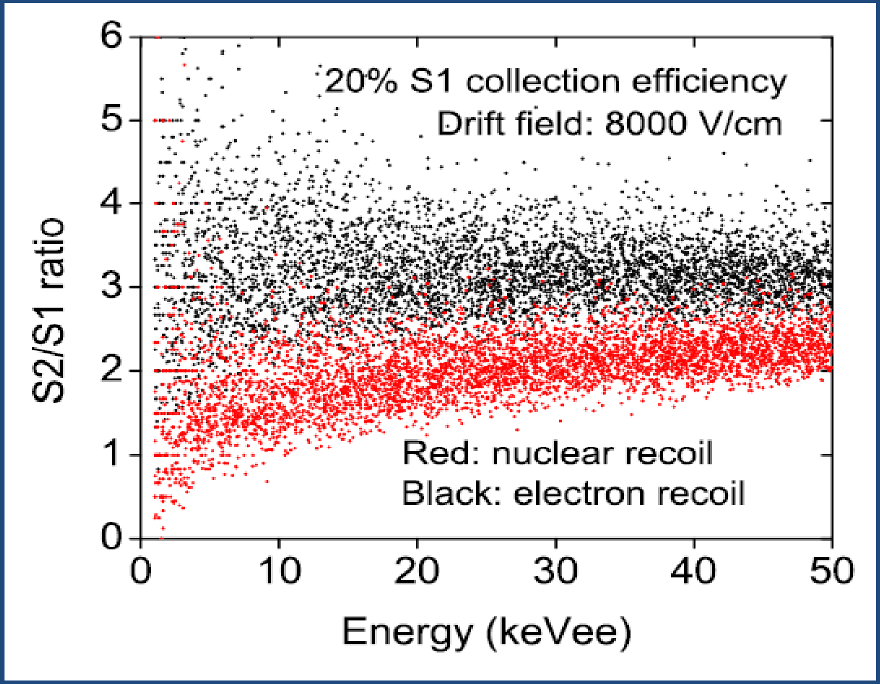


* The difference in S2/S1 ratio becomes larger at higher field.

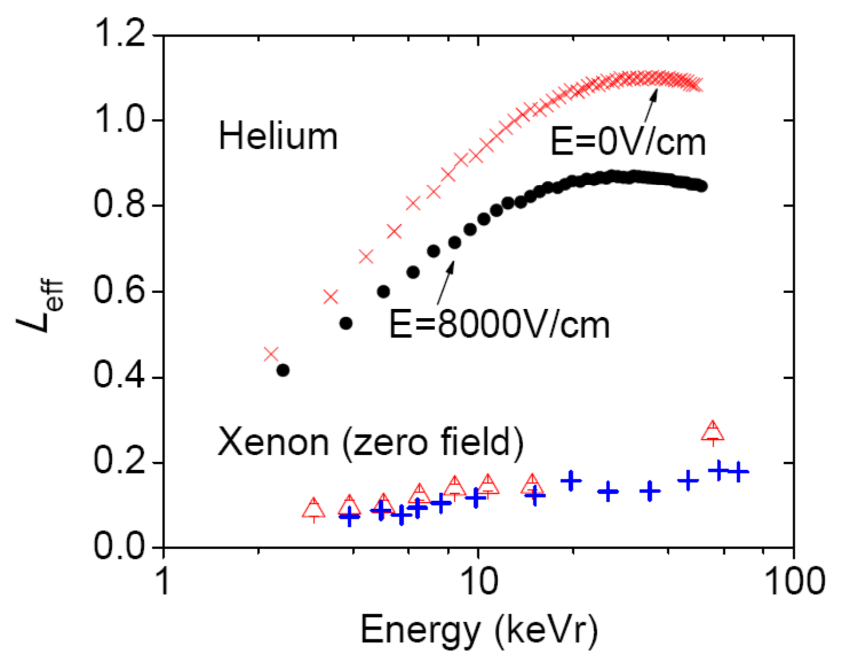
* At low energies, the nuclear recoil curves bends away from the electron recoil ones. This leads to good event discrimination at low E.

In real experiment, S1, S2, S3 all fluctuate from event to event. Monte Carlo simulation that takes into account the number uncertainty is needed.

- Background rejection



* Monte Carlo simulation, assuming Poisson distribution of S1 and S2.



* Scintillation efficiency and quenching factor. (Triangle: G. Plante, *et, al.*, arxiv: 1104.2587v1; Cross: A. Manzur, *et, al.*, Phys. Rev. C 81, 025808 (2010).)

* The conversion between keVee energy and nuclear recoil energy keVr is given by

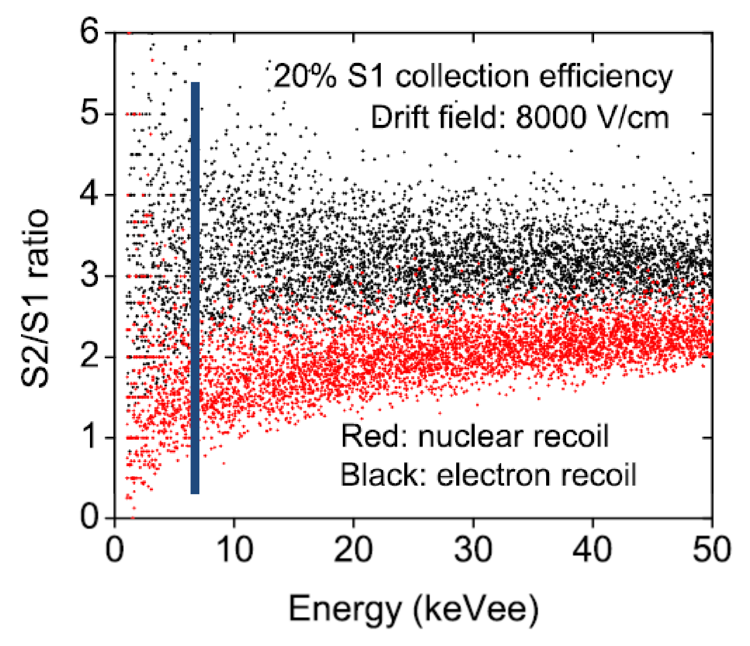
$$E_r = E_e / L_{eff}$$

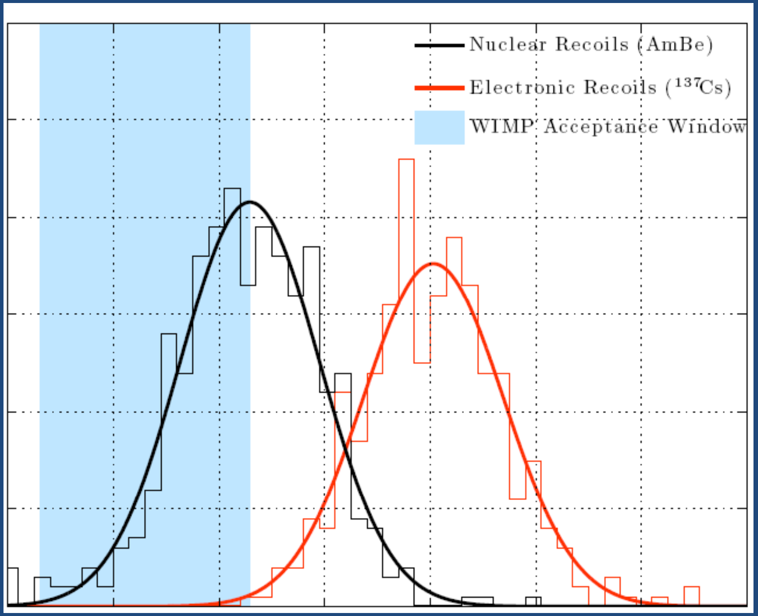
L_{eff} for He decreases to about 0.4 at low energies, due to Lindhard effect, but is not equal to the Lindhard factor !

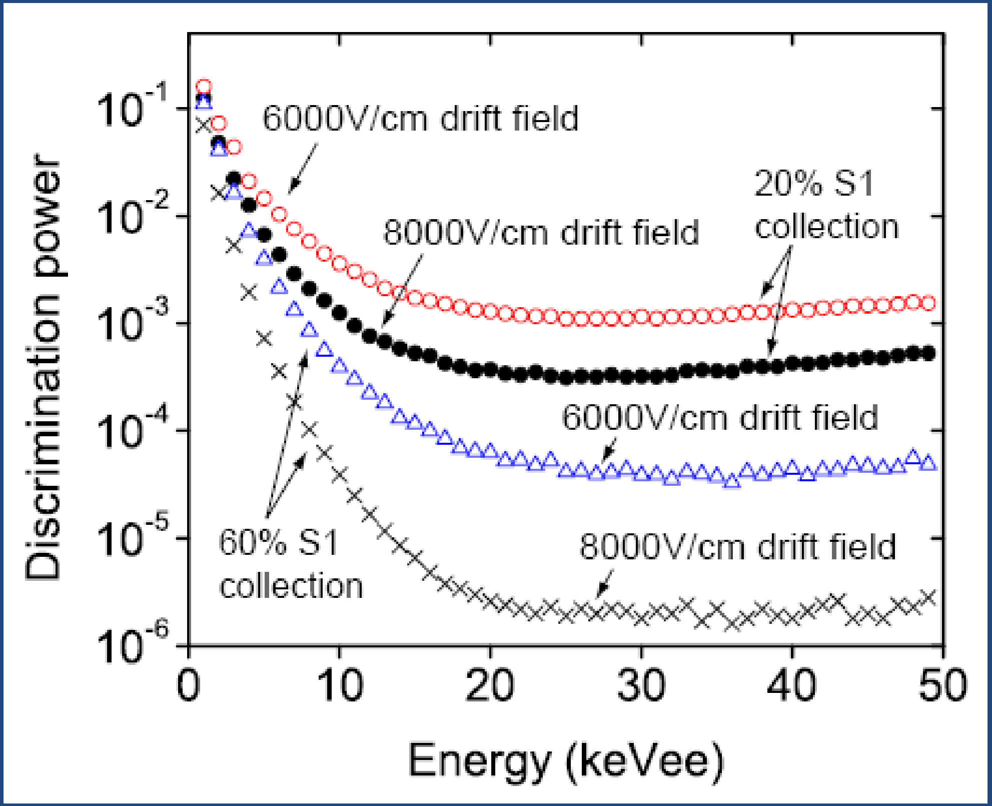
* For Xenon, L_{eff} has been measured to be less than 0.1 below 5 keVr.

* Higher L_{eff} means lower energy threshold for nuclear recoils!

• Discrimination power





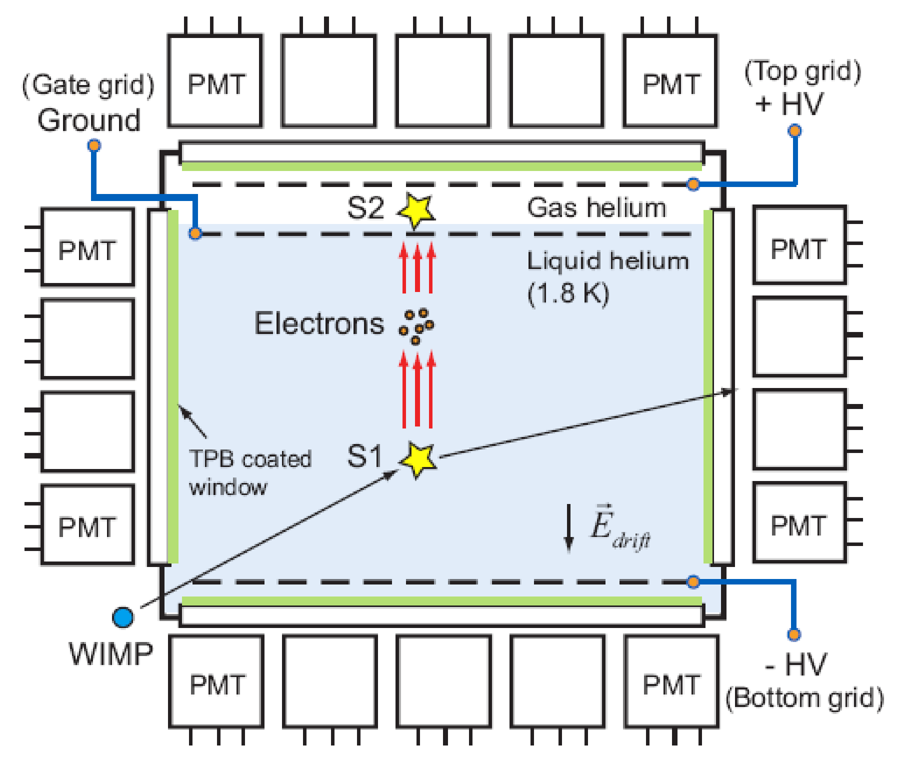


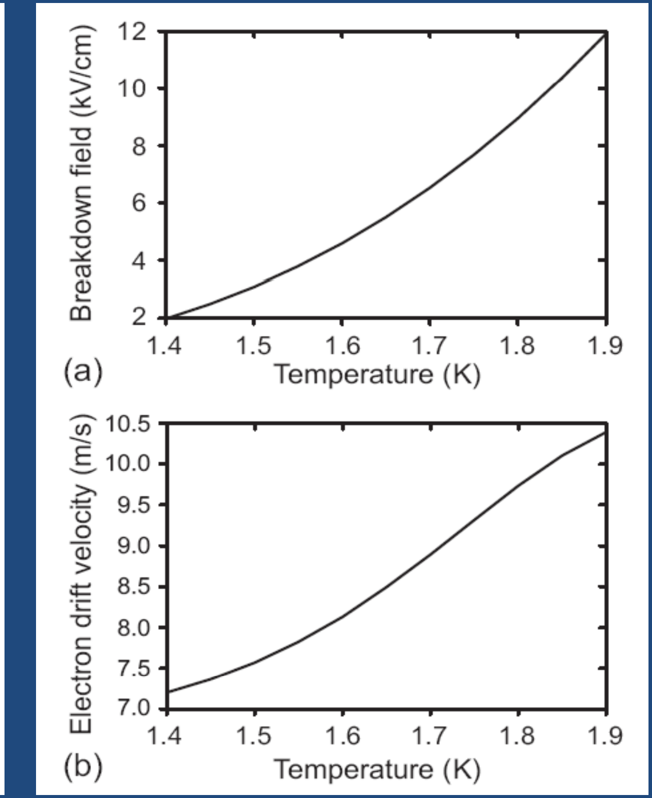
(To be submitted to PRD.)

- The two bands are divided in energy slices and fitted with a Gaussian distribution. Based on both Gaussians the rejection is found as the fraction of ER events below the NR centroid.
- Depending on field and S1 collection, higher than 99% rejection can be achieved for event energy as low as 5 keVee.

➢ Experimental setup schematics

- Using PMT arrays or GEMs for signal detection (operated at ~1.8 K)





✓ Breakdown in He gas is not an issue. High drift field can be achieved.

✓ Electron bubbles drift at 10m/s. Event overlap should not be an issue.

✓ Existing detection techniques: PMT (Meyer 2010), GEMs (Breskin 2011). Other possible ways: electrode luminescence in liquid; bolometers at low T, etc.

Summary

(1) We studied the excitation and ionization yield for low energy nuclear recoils in liquid helium.

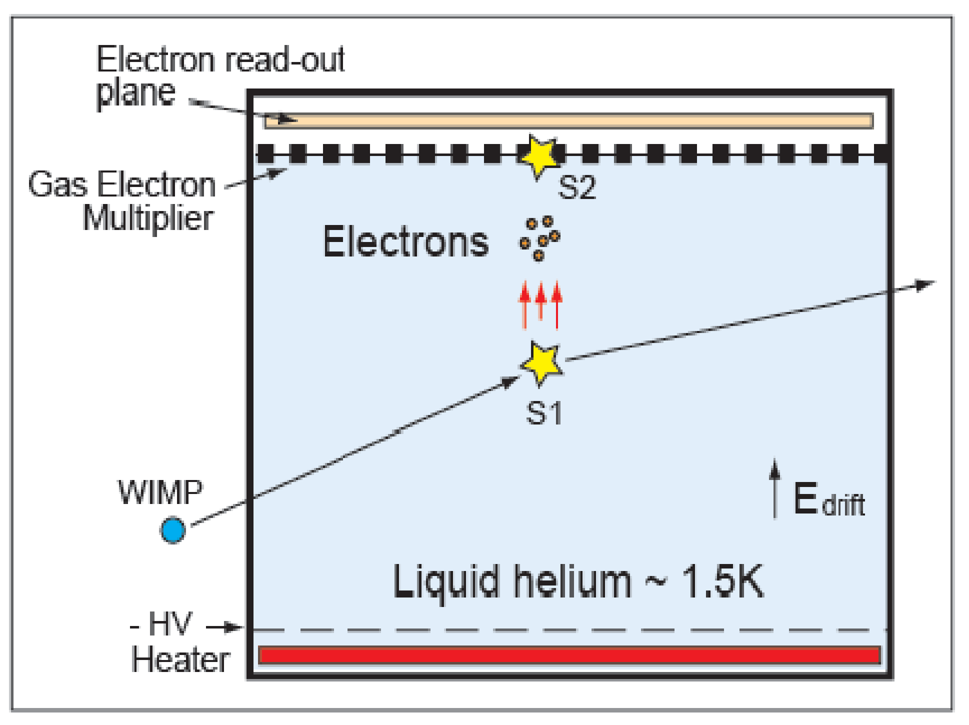
(2) Monte Carlo simulation is performed to derive the background rejection power of LHe-based detector.

(3) Schematic of possible helium-based detector is presented.

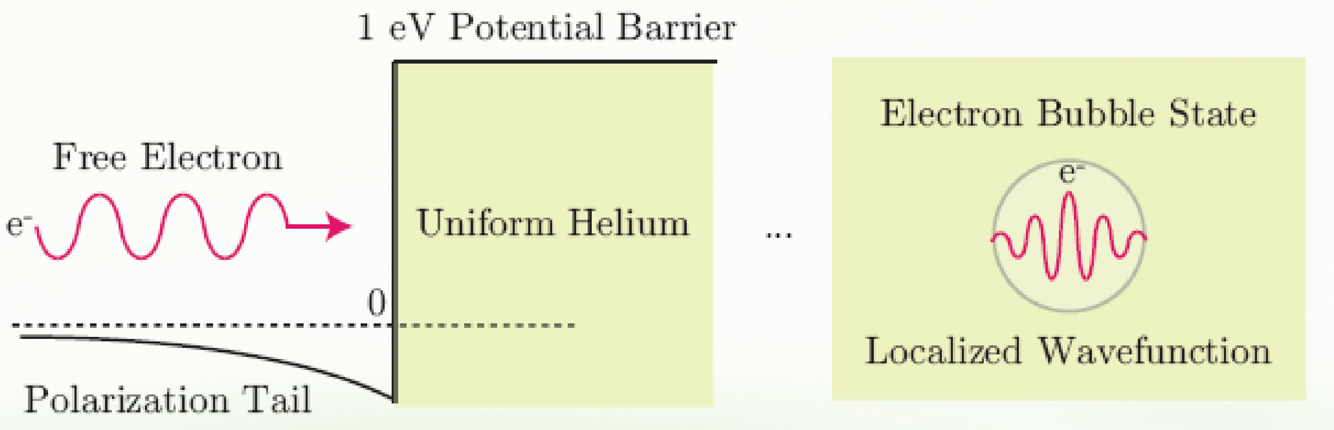
Thank you!

Dark matter detection with He

- G/L two phase detector → looks for prompt scintillation (S1) and charge signal (S2).
- Gas electron multiplier coated with CsI provides gain for both S1 and S2.
- He2 triplet molecules quenching on CsI may be a third signal .



- Electrons in liquid helium



$$E_{total} = E_{electron} + \alpha\int dA + P\int dV$$

ELECTRON CONFINING ENERGY

SURFACE ENERGY

VOLUME ENERGY

For a spherical bubble in the ground state:

$$E_{\text{bubble}} = \frac{h^2}{8mR^2} + 4\pi R^2\alpha + \frac{4\pi}{3}R^3P$$

At zero pressure, the stable bubble has a radius:

$$R_0 = \left(\frac{h^2}{32m\pi\alpha}\right)^{1/4} \approx 19\ \text{Å}$$