some properties of superfluid helium of relevance to dark matter detection

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Outline

historical introduction

properties of helium deduced from

- alphas and electrons stopped in liquid
- atomic scattering in gas
- interaction of quasiparticles with surfaces

calorimetry and conclusions

historical introduction

Cabrera, Krauss and Wilczek 1985

HERON 1987- 1999 (Lanou, Maris, Seidel)

Helium Roton Observation of Neutrinos

detect pp solar neutrinos with 40 keV threshold

10 ton He fiducial volume at 50 mK

record evaporated He atoms produced by rotons
and UV scintillation using coded aperture
array of calorimeter/wafers

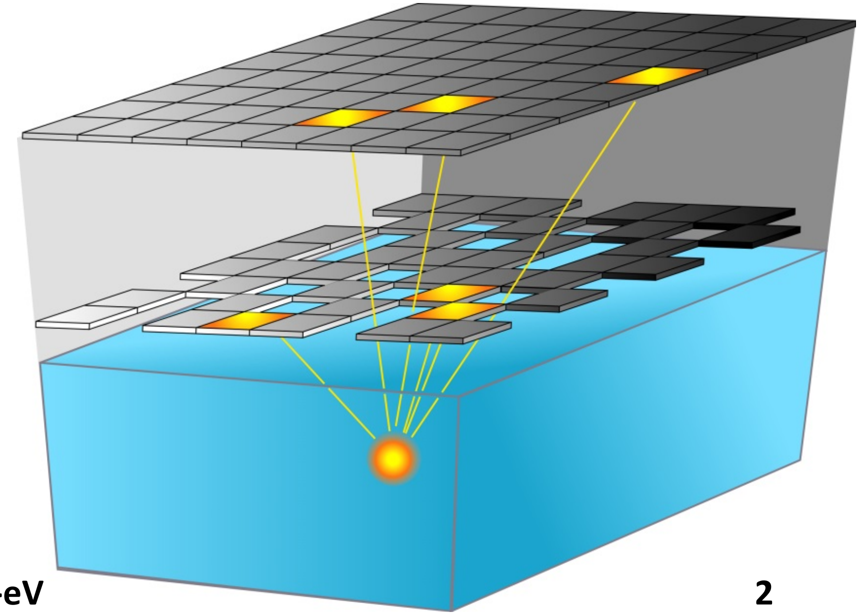
calorimeters film free -- thermal gain

demonstrated technical feasibility

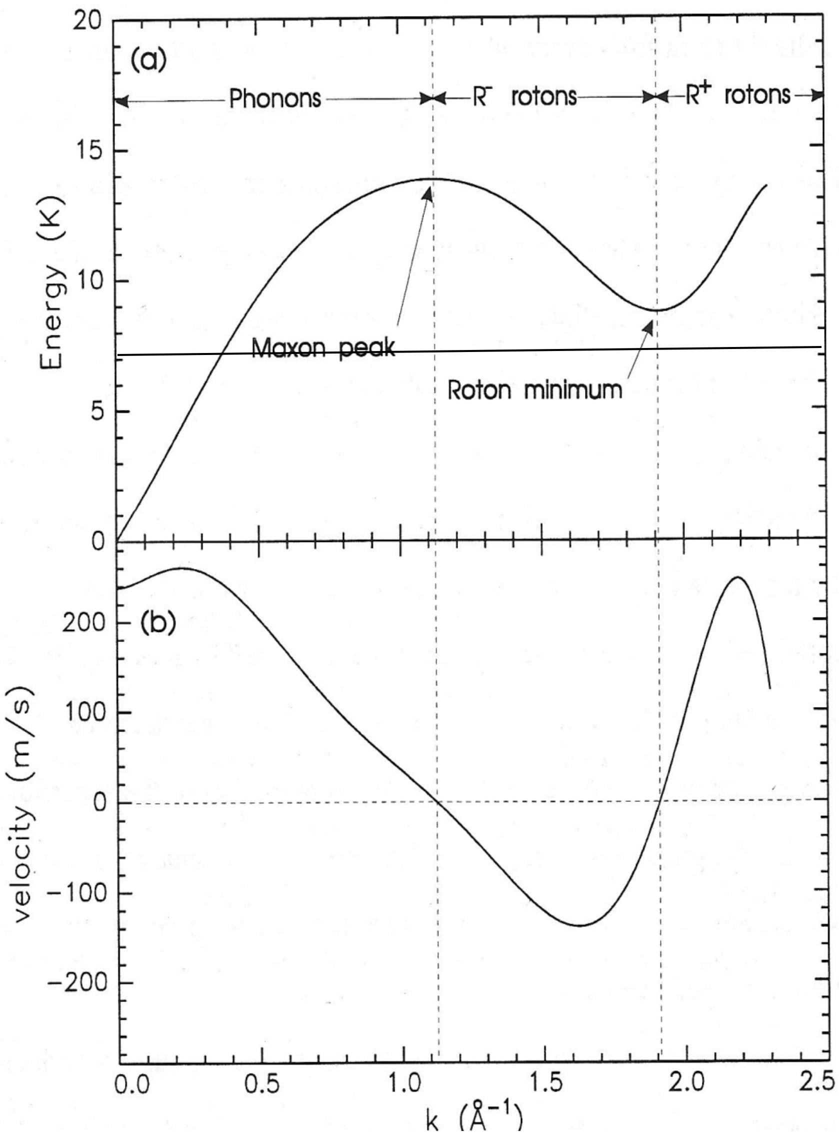
did not proceed to large scale detector
- age of principals
- physics no longer current

Huang et al, Astroparticle Physics 30,1 (2008).

HERON as a dark matter detector?
in “Dark Matter,Quantum Measurement”
ed Tran Thanh Van, Editions Frontieres,
Gif-sur-Yvette (1996)

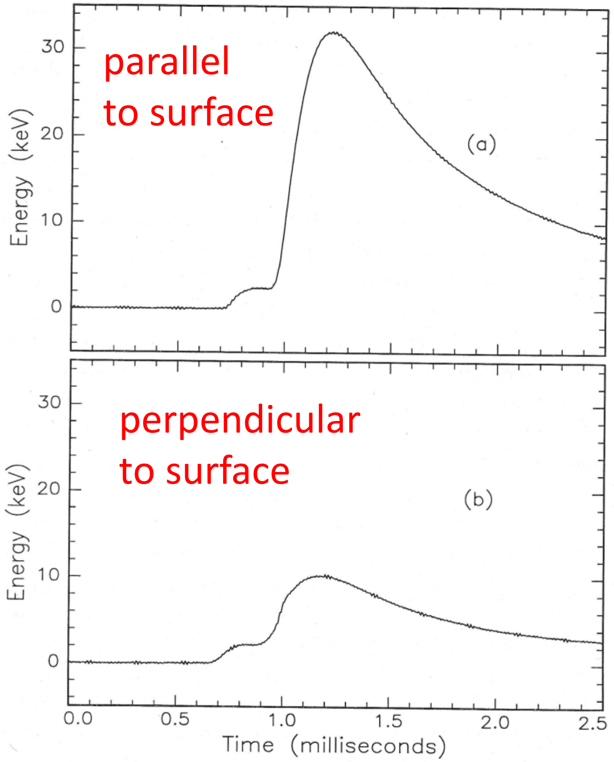


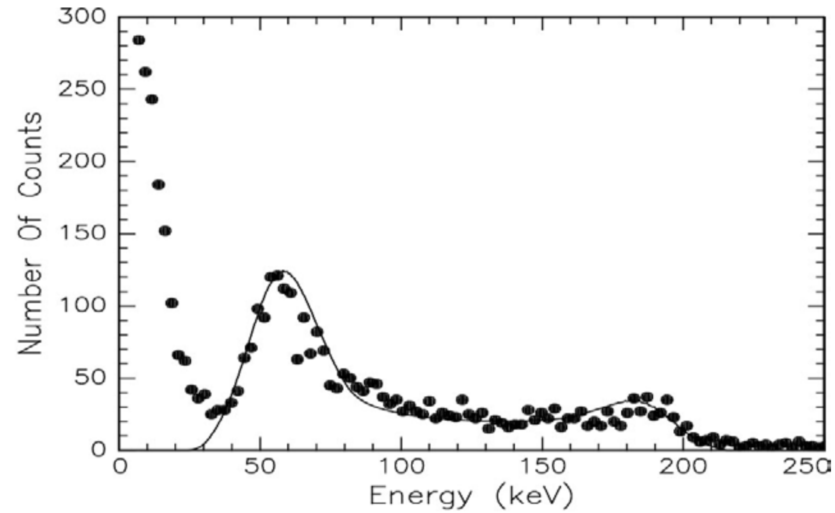
some properties of superfluid helium

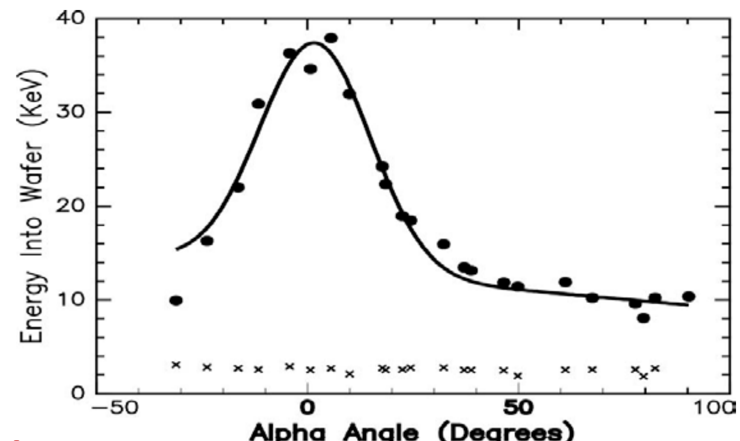


- gas/liquid energy difference 7.16 K (*.618* meV)
- vapor density: $1.5\times10^{21}\,T^{1.5}e^{-7.16/T}$ #/cm^3 at 100 mK $n\approx 4\times10^{-12}$ /cm^3
- roton energy minimum 8.65 K
- roton/roton scattering $\sim10^{-14}$ cm^2
- roton/^{3}He scattering $\sim10^{-15}$ cm^2
- ^{3}He has bound state on surface of ~2 K
- electron forms bubble 19 Å radius hydrodynamic mass $\sim250\ m_{He}$
- positive ion forms "snowball" mass $\sim40\ m_{He}$
- metastable triplet excimer forms bubble 7 Å radius

alpha signal with calorimeter







collimated α source

roton emission anisotropic

400 Å radius column heated to ~2 K

propagate into cold liquid from last scatter

UV energy less than expected (W value 43 eV)

quenching from Penning processes

$He_2^* + He_2^* \rightarrow He_2^+ + e^- + He + He$

Bandler, etal, Phys Rev Lett 74, 3169 (1995).

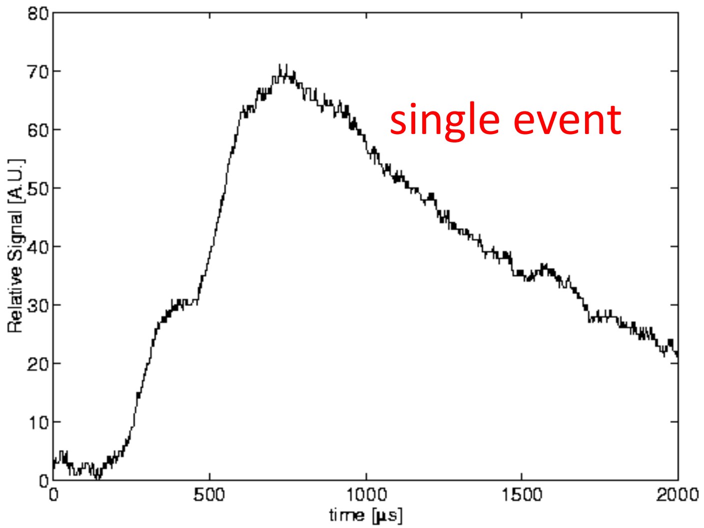
electron signal

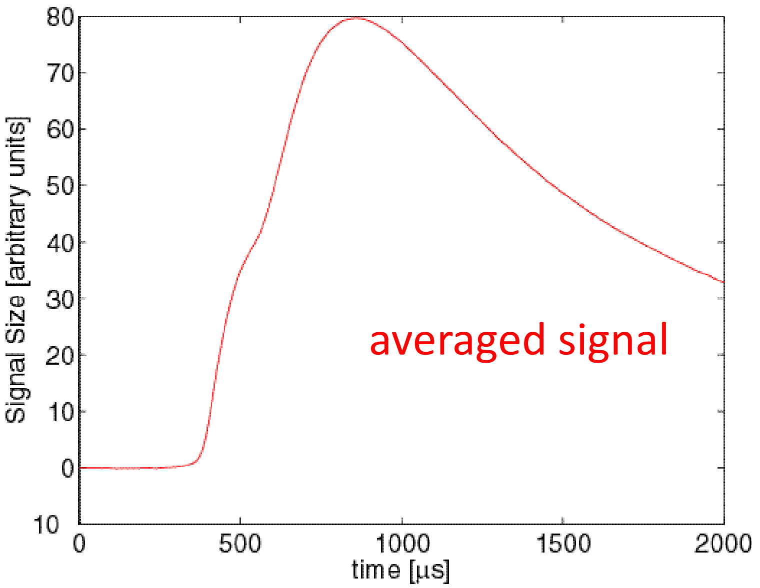
^{113}Sn source, monochromatic 364 keV

scintillation signal greater than predicted
assuming singlet to triplet ratio of 1 to 3

experimentally
ratio of singlet to triplets close to 1 to 1

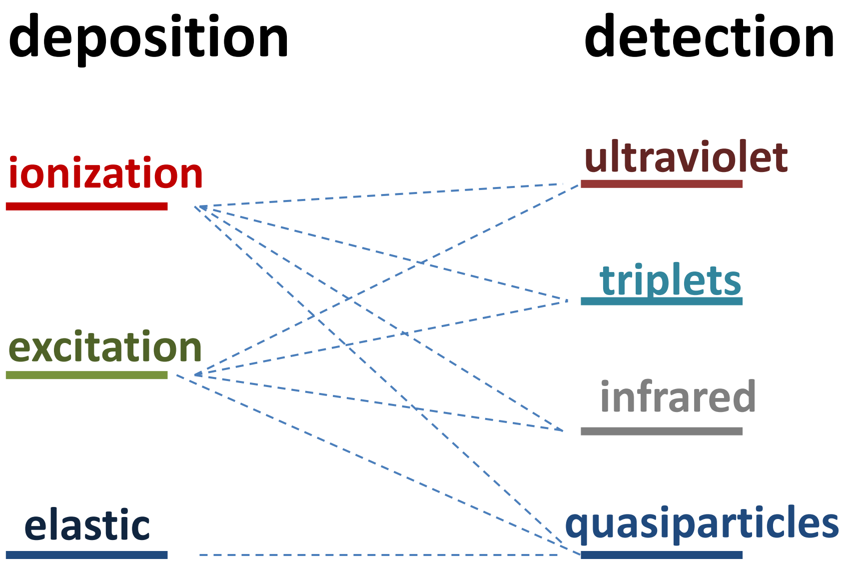
geminate recombination





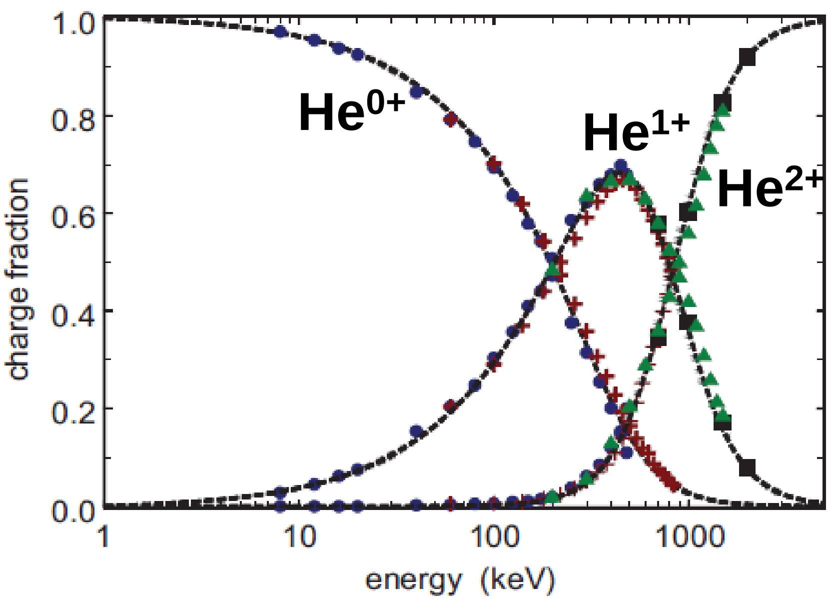
Adams, etal , J Low Temp Phys 113, 1121 (1998).
Adams, thesis, Brown University (2000).

energy partition

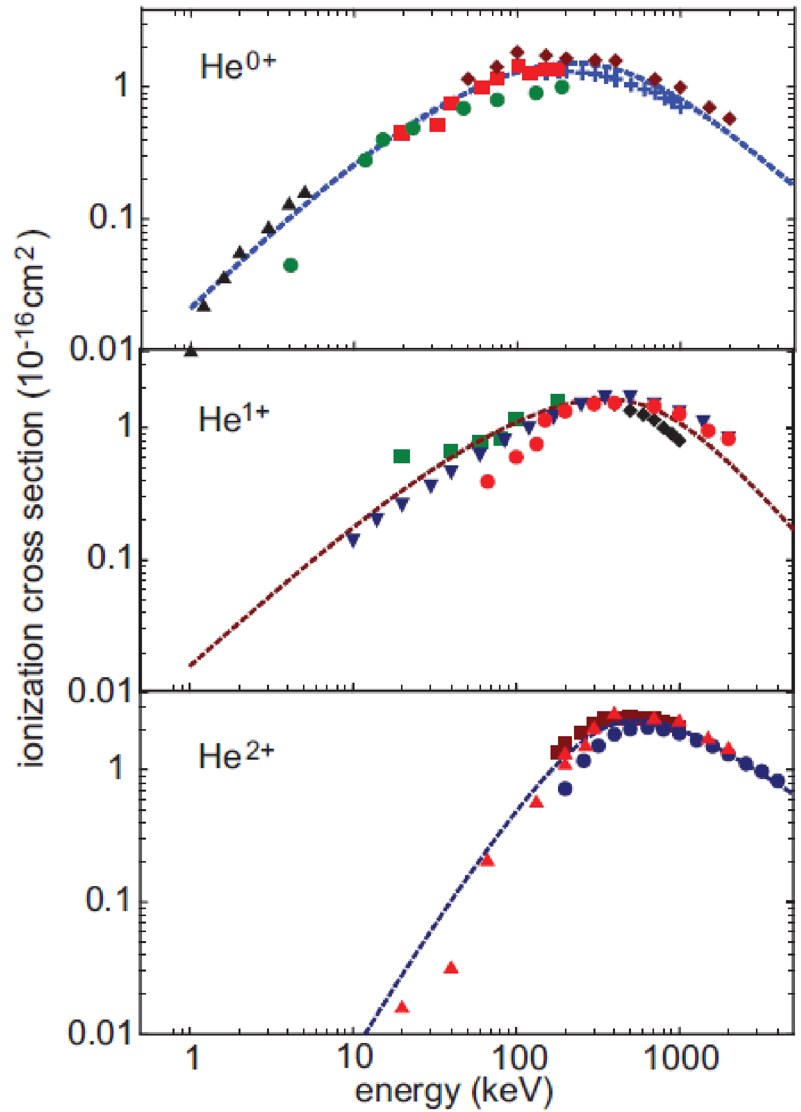


atomic He/He scattering data

charge state of He atom/ion
cross sections for ionizations and excitations
other processes
elastic scattering



Ito & Seidel, Phys Rev C 88, 025805 (2013).

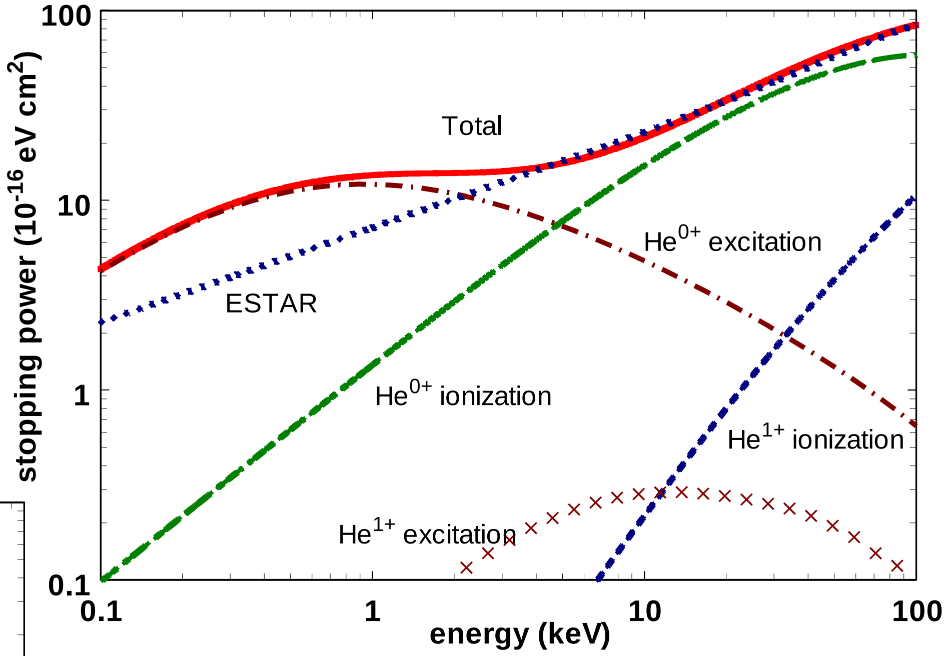


stopping power

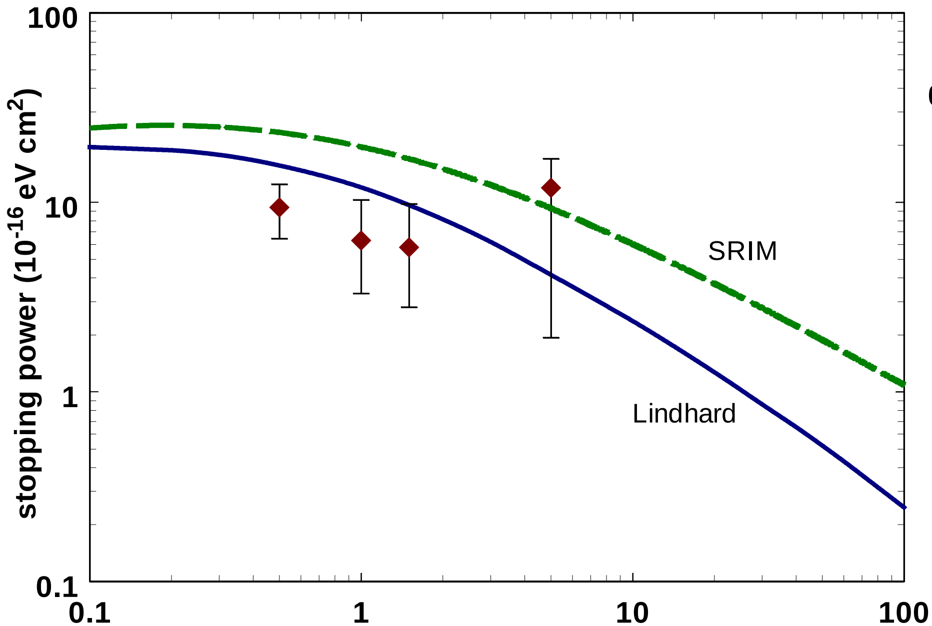
use stopping power as check
to determine is estimates
are consistent

$$SP = \sum_i \sum_j F_i \, \sigma_{i,j} \varepsilon_{i,j}$$

electronic stopping power

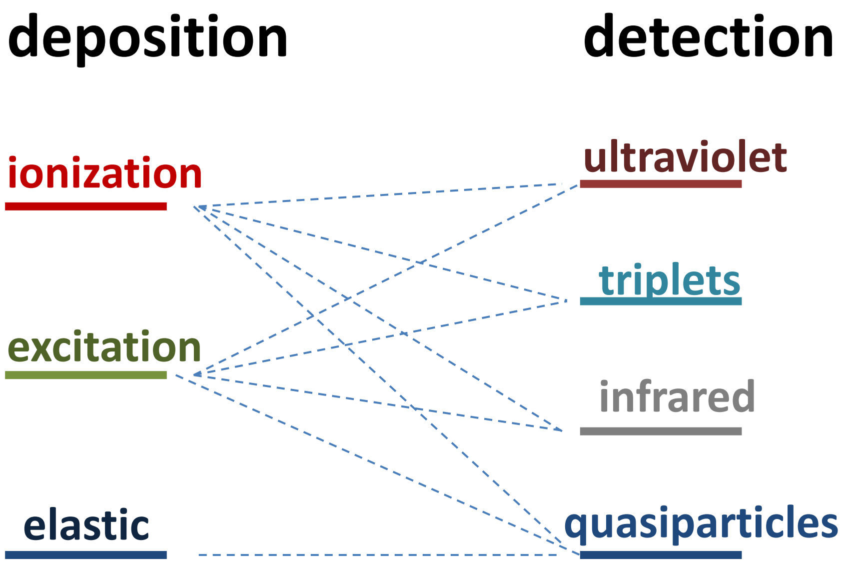


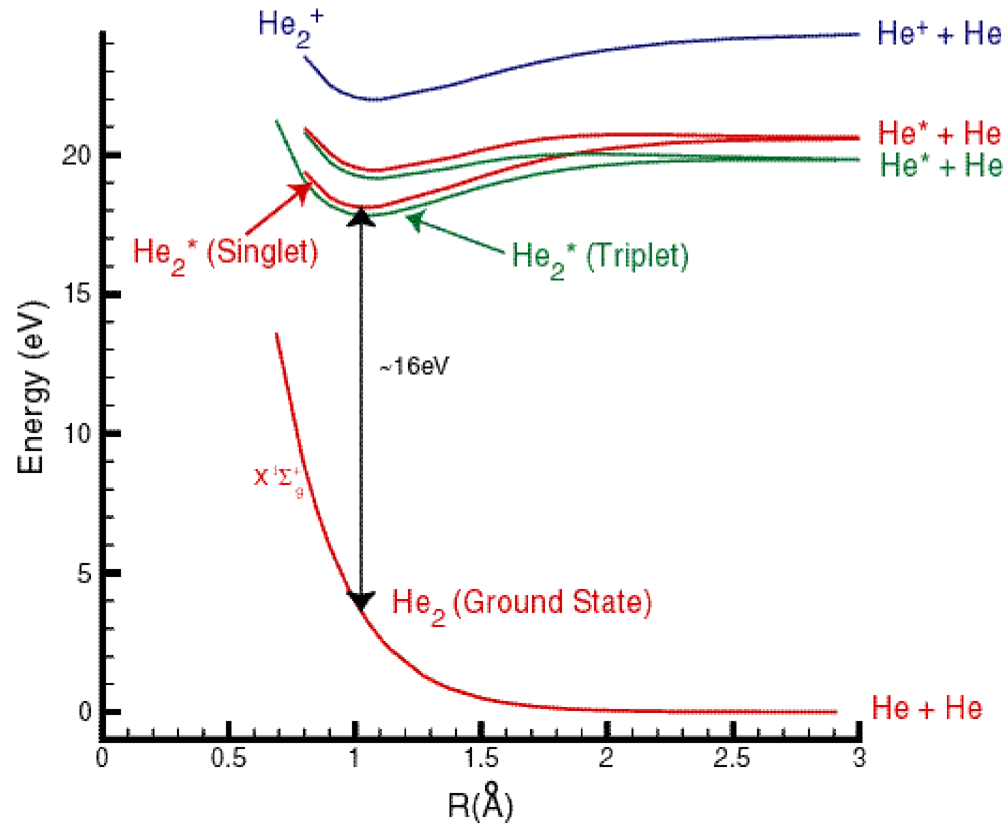
nuclear stopping power



Seidel, to be published.

energy partition



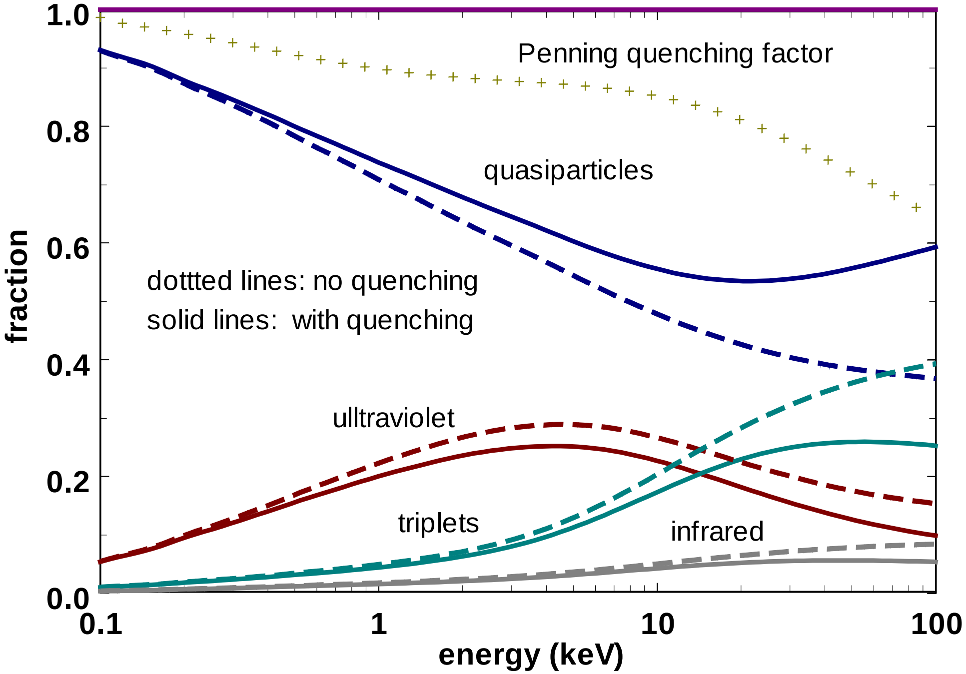


for ionization

dimer formation
ground state dissociation
secondary electrons
radiative transitions in IR
metastable triplets
non radiative quenching (Penning)

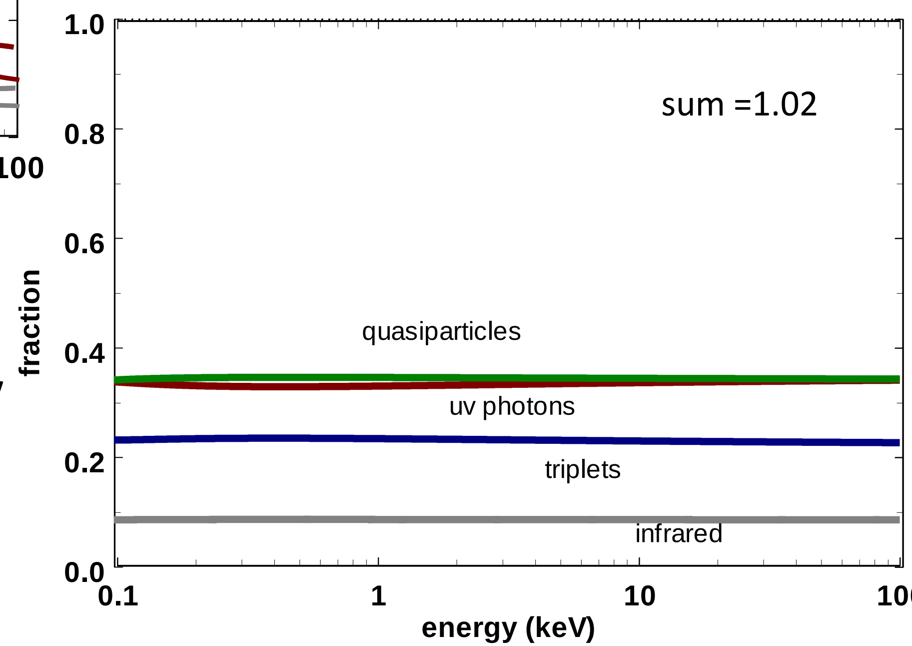
energy partition

nuclear recoil



fraction of energy

electron recoil



for electrons have at least one ionization or excitation down to 20eV energy loss in elastic scattering event is very small

evaporation

kinematic conditions

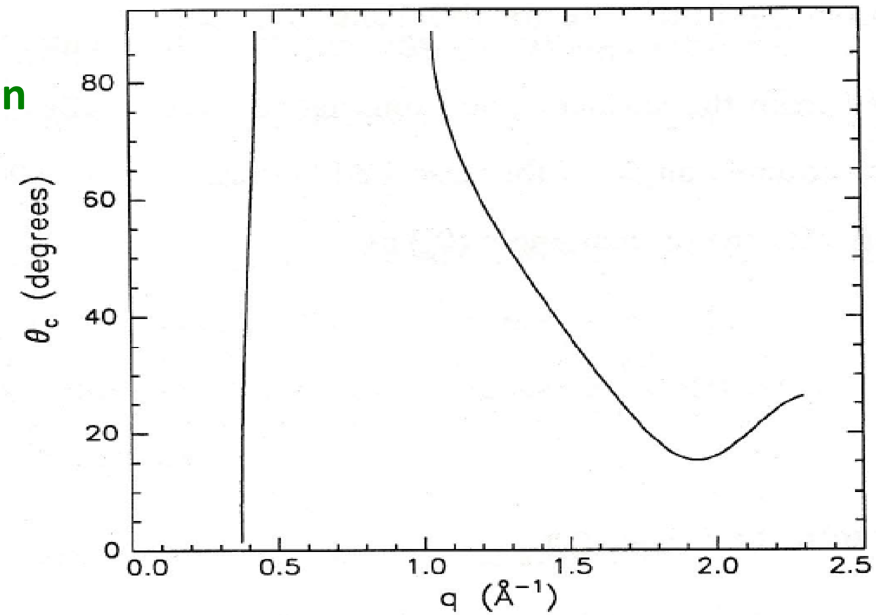
$p_{||}$ conserved; $\varepsilon_r = \Phi + p^2/2m_4$

for $\theta > \theta_{critical}$, have total internal reflection

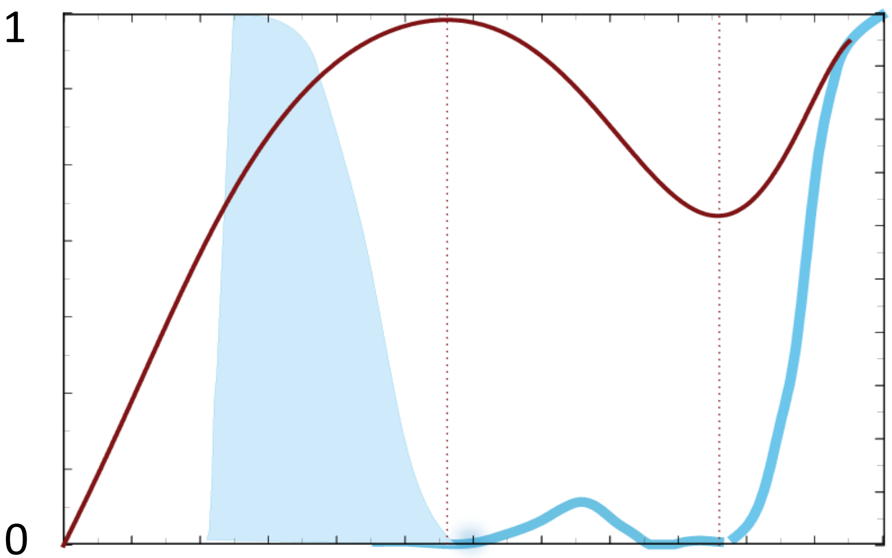
$\theta_{critical} \approx 25^o$ for excitations of importance

surface waves (ripplons) not significant

critical angle



evaporation probability



probability high for R^+ rotons away from minimum but critical angle is small

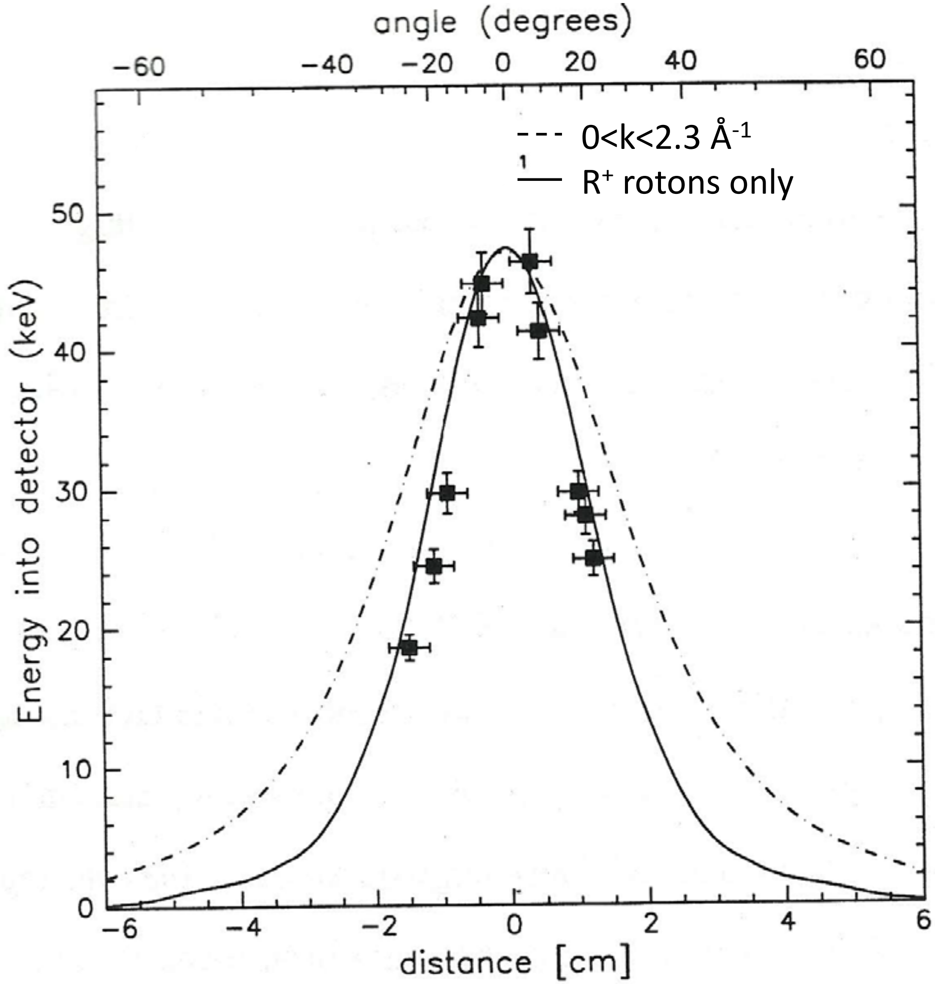
probability low for R^- rotons

probability for phonons depends on angle of incidence

far fewer phonons generated than R^+ rotons

evaporation

angular dependence



measurement of evaporation signal as function of position of source

measurements fit by R^+ rotons only
no need to invoke phonons

25° cone contains 4.8% of solid angle

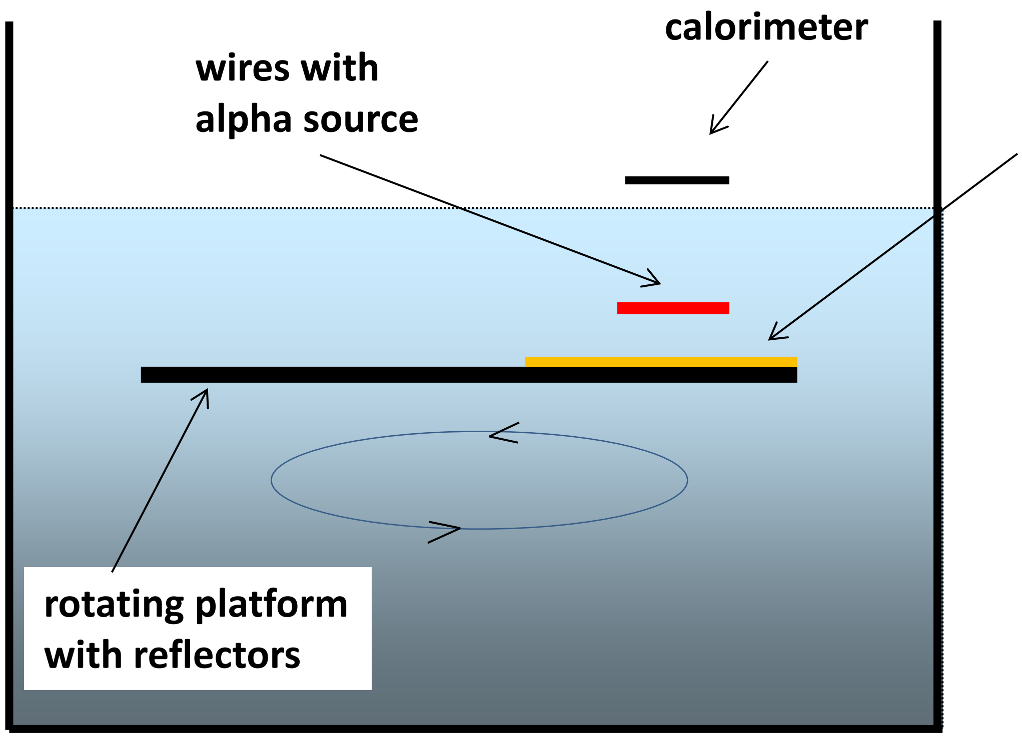
heater results identical

R^+ rotons only excitations of consequence

Enss, etal, Physica B 194, 515(1994).

very rough estimate
50% probability of evaporation

roton reflection from solid surface



in separate experiment reflection determined to be diffuse

30% reflection as rotons

rotons do not contribute to heat transfer

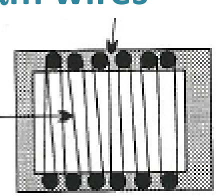
Andreev reflection

R^+ roton reflected

as R^- roton

overhead view of α source evaporated on underside of 5 and 10 μm wires

wires wrapped around pins in holder
~1000 μm spacing



Bandler, thesis, Brown University (1996).

calorimeters

detection of single UV photons and triplet excimers by calorimeters immersed in liquid helium below 100 mK should be possible (certainly true for metallic magnetic calorimeters)

roton detection requires the use of evaporation

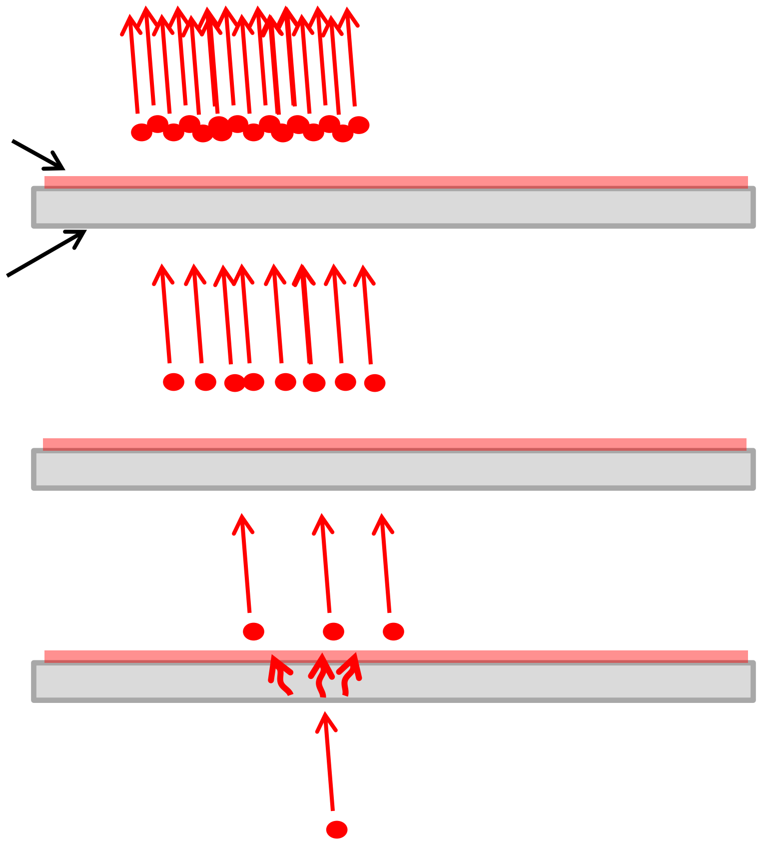
development of very low-energy threshold, large-area calorimeters is the principal need for a successful helium-based dark matter detector (alternatively, smaller area with multiplexing)

the energy threshold of calorimeters will determine the limit of low dark mass detection

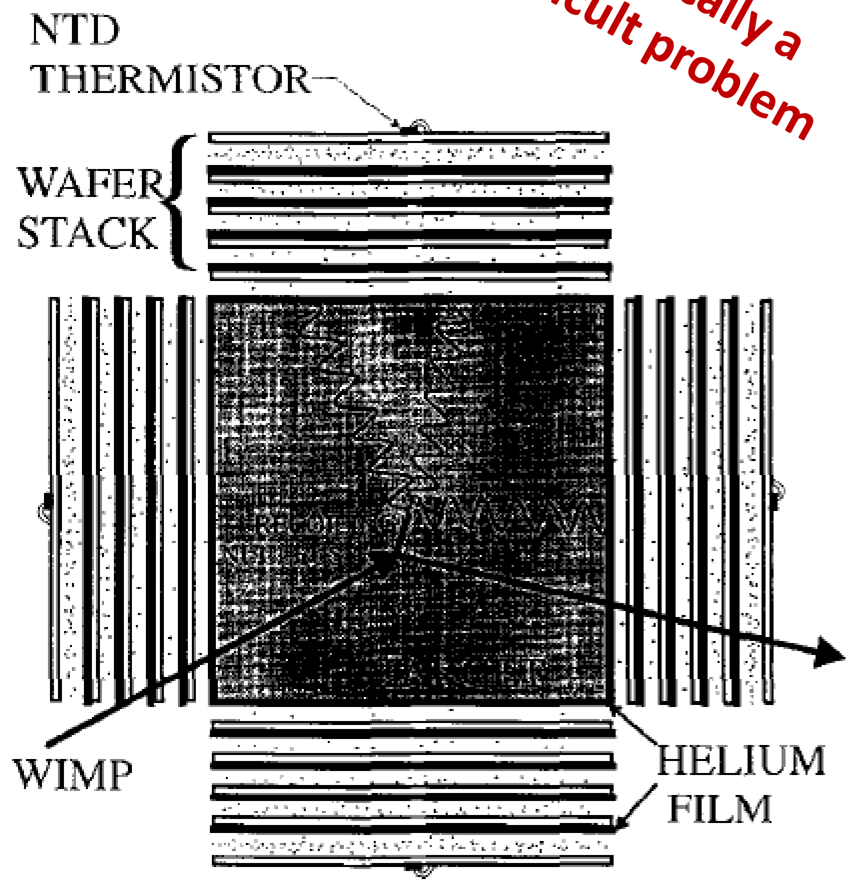
thermal amplification

topologically a difficult problem

strong binding substrate on one side weak binding on the other



bare silicon on one side
He film on other – gain of .2



More, etal, NIM A 370, 147 (1996).
Phys. Rev. B 54, 535 (1996).

other considerations

single electron sensitivity

can move electron to free surface,
extract it from liquid with assistance of vortex ring,
accelerate it in vacuum,
detect it calorimetrically

difficulty:
separating electron from positive ion
electron diffuses only ~ 400 Å before forming bubble
high field required to separate charges

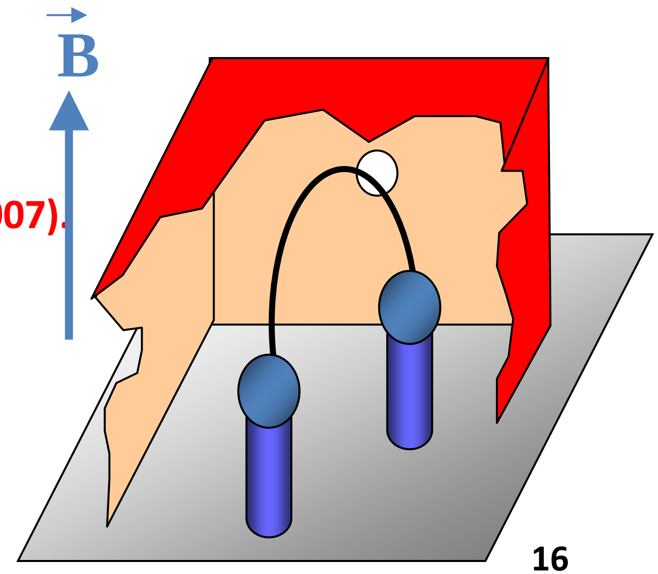
Sethumadhavan, etal, NIM A 520,142 (2004).

Seidel, etal, Phys. Rev. C 89, 025808 (2014).

quasiparticle detection using a nanomechanical device

example of superfluid ^{3}He; vibrating wire,
1 keV threshold

Winkelmann etal, NIM A 574, 264 (2007).



nothing apparent at present that surpasses calorimetry

comments and conclusions

- better quantitative measurements of properties of helium would be helpful in designing a dark matter detector

- discrimination between nuclear and electron scattering is, in principle, possible with recoil energies down to 20 eV

- quasiparticle detection via evaporation is limited to R^+ rotons

- event location can be determined from evaporation pattern on calorimeter array

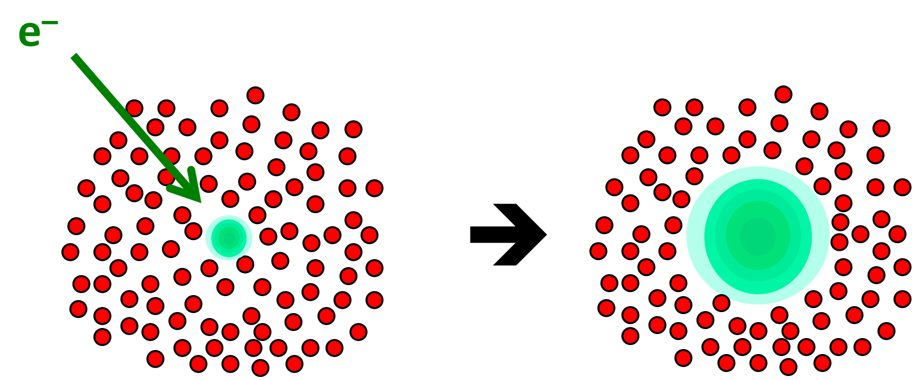
- use of quasiparticles reflected from container surfaces may be possible but is problematic

- low eV dark matter detection needs the development of low threshold energy calorimetric detection using large area wafers

back up

charges in liquid helium

electron forms a bubble in liquid helium
energy ~ 1 eV below conduction band
bubble formation not fully understood



$$E = \frac{h^2}{8mR^2} + 4\pi R^2\sigma + \frac{4\pi}{3}R^3 P$$

for $P = 0$

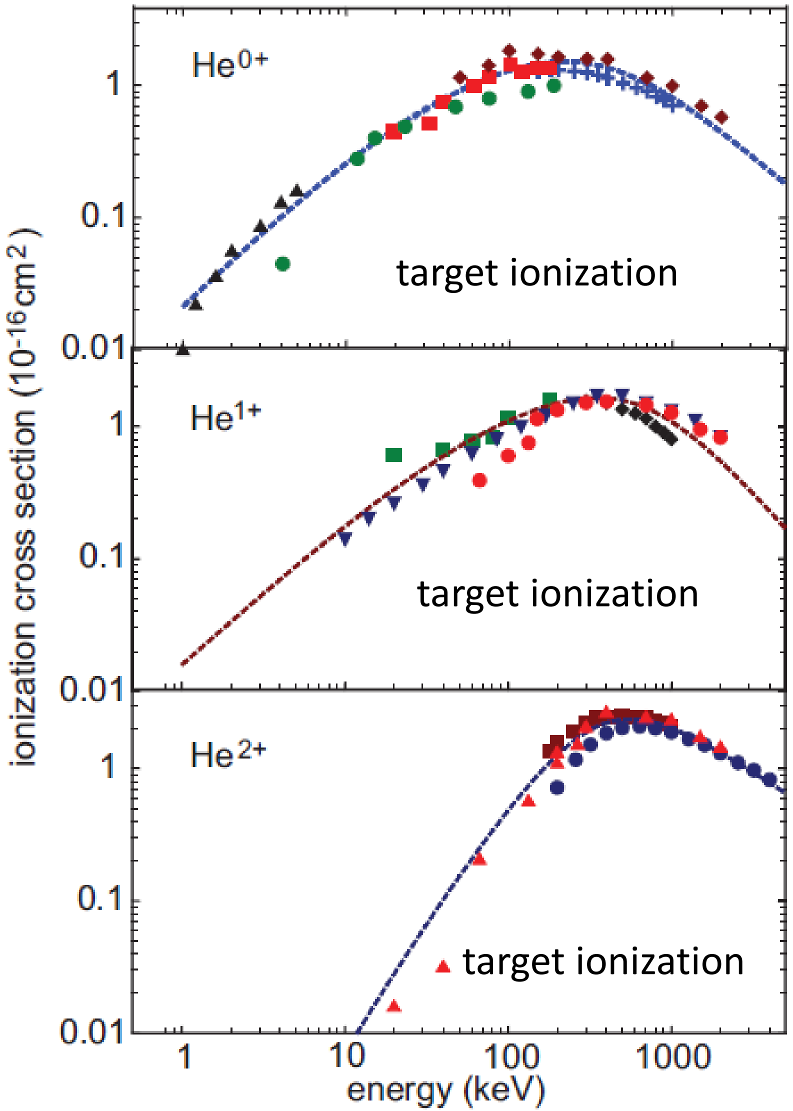
$$R = \left(\frac{h^2}{32\pi m\sigma}\right)^{1/4}$$

1s ground state, R = 19 Å displaces ~ 590 He atoms
hydrodynamic mass ~ 250 m_{He}

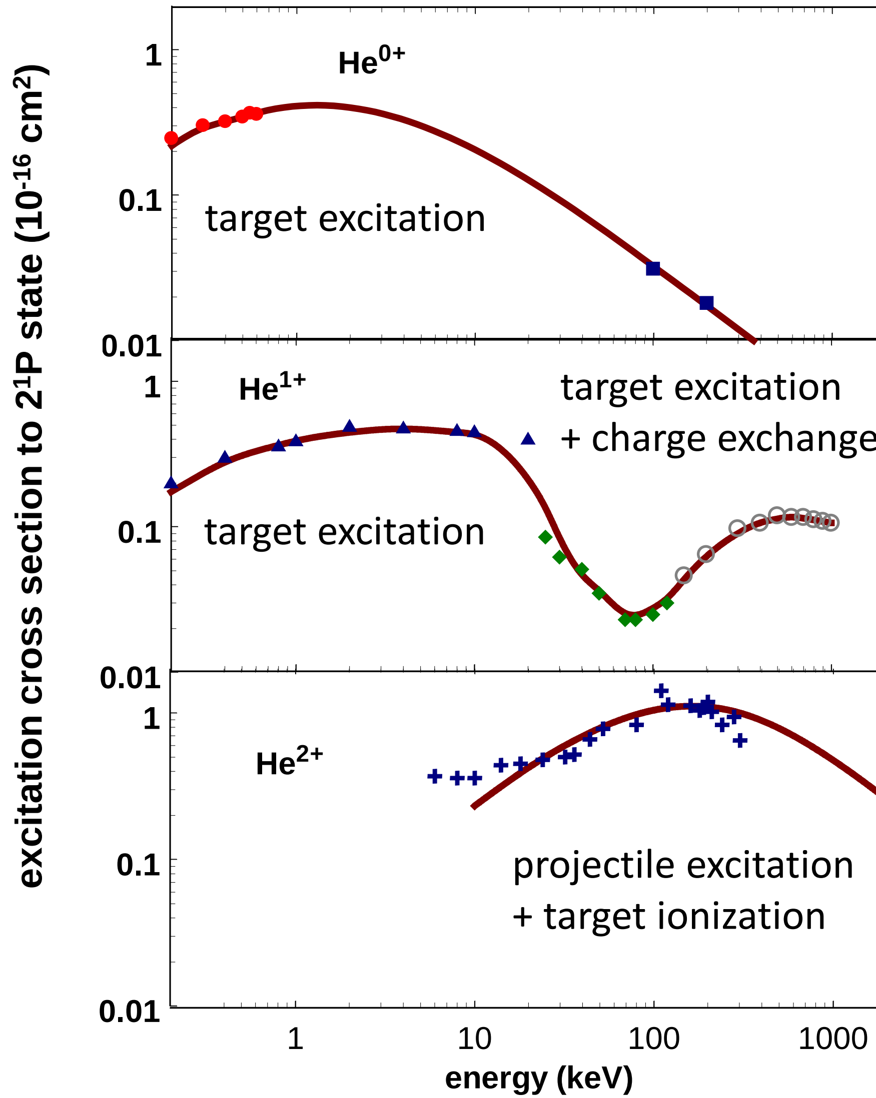
a positive ion is not He_2^+ ;
forms a snowball because of electrostriction
R ≈ 7 Å $m_{snowball} \approx 40\ m_{He}$

$He_2^*(a^3\Sigma)$ dimer
forms a bubble,
R ≈ 7 Å

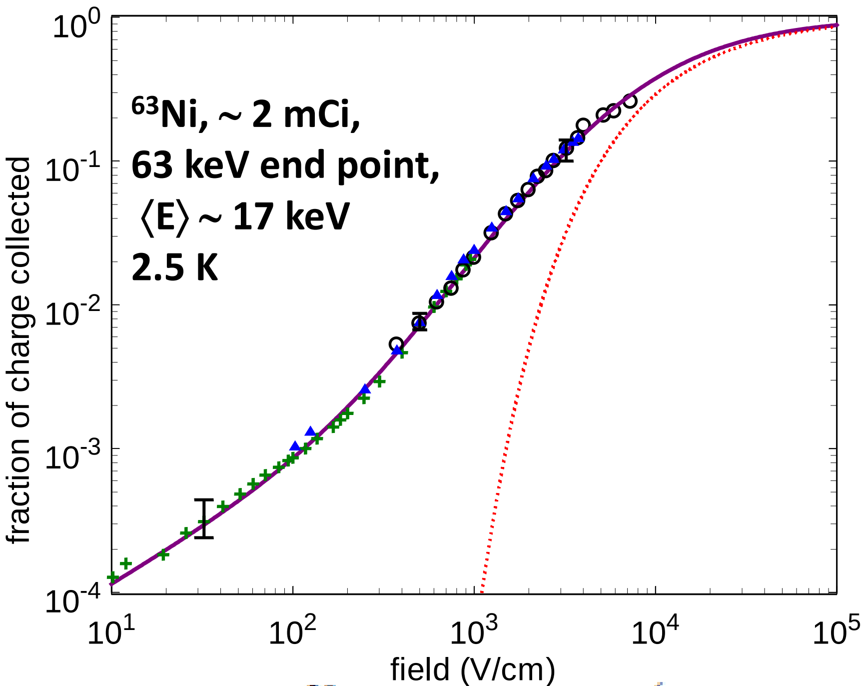
ionization cross section



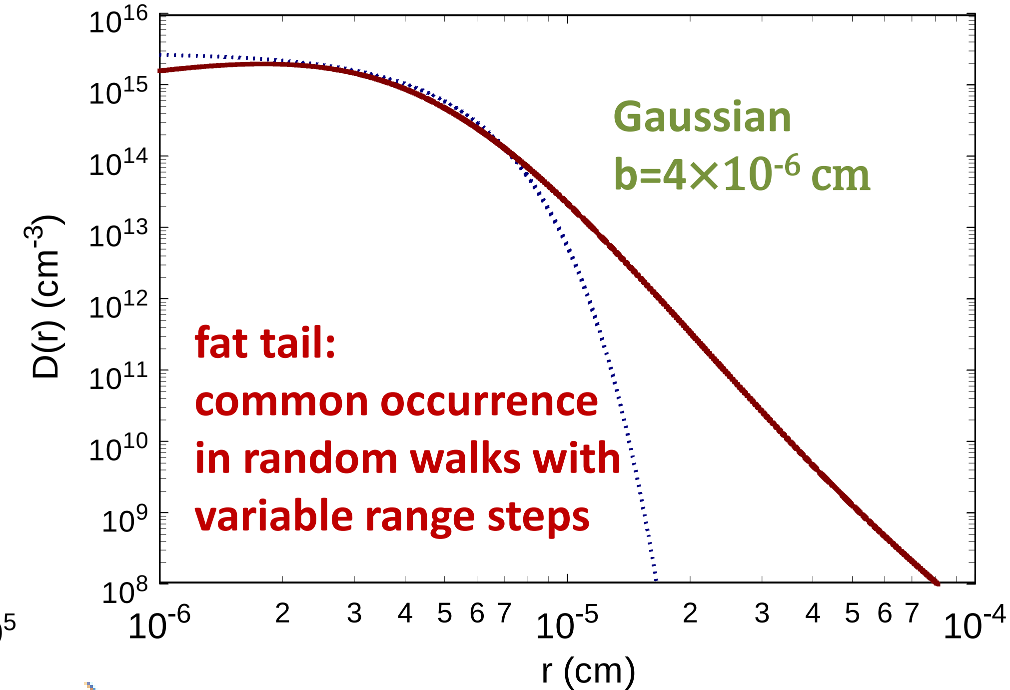
excitation cross section



current vs field



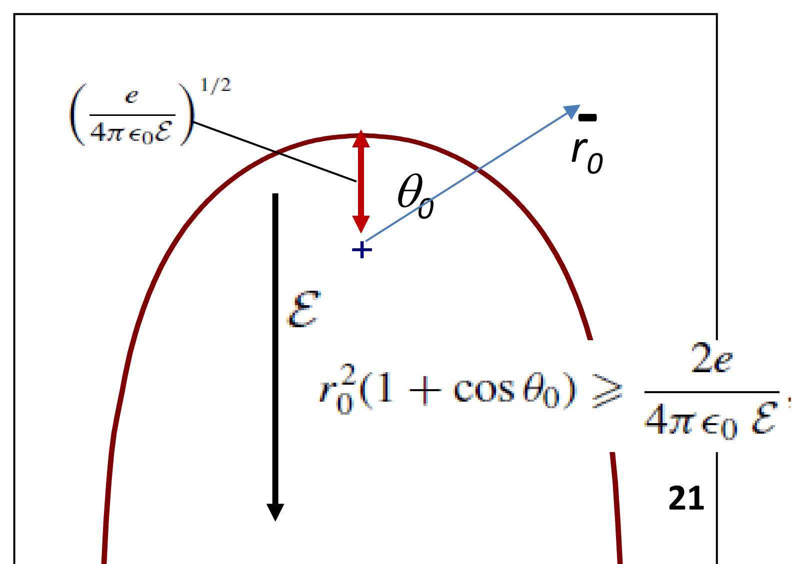
density vs distance



$$i(\mathcal{E}) = 4\pi \int_{\left(\frac{e}{4\pi\epsilon_0\mathcal{E}}\right)^{1/2}}^{\infty} D(r) r^2 dr \left(1 - \frac{e}{4\pi\epsilon_0\mathcal{E}r^2}\right)$$

$$D(r) = \frac{4\pi^{1/2}\epsilon_0^{3/2}\mathcal{E}^{5/2}}{e^{3/2}} \frac{d}{d\mathcal{E}} \left(i + \mathcal{E}\frac{di}{d\mathcal{E}}\right)$$

where $r = (e/4\pi\epsilon_0\mathcal{E})^{1/2}$



Seidel, et al, Phys. Rev. C 89, 025808 (2014)

elastic scattering of electrons

based on random walk and known cross section for elastic scattering of low energy electrons
expect secondary electrons have Gaussian distribution with half width of ~2000 Å rather than 400 Å as measured

physics of how an electron forms a bubble is not well understood

very different electron distribution than for Ar or Xe determine particle density along track

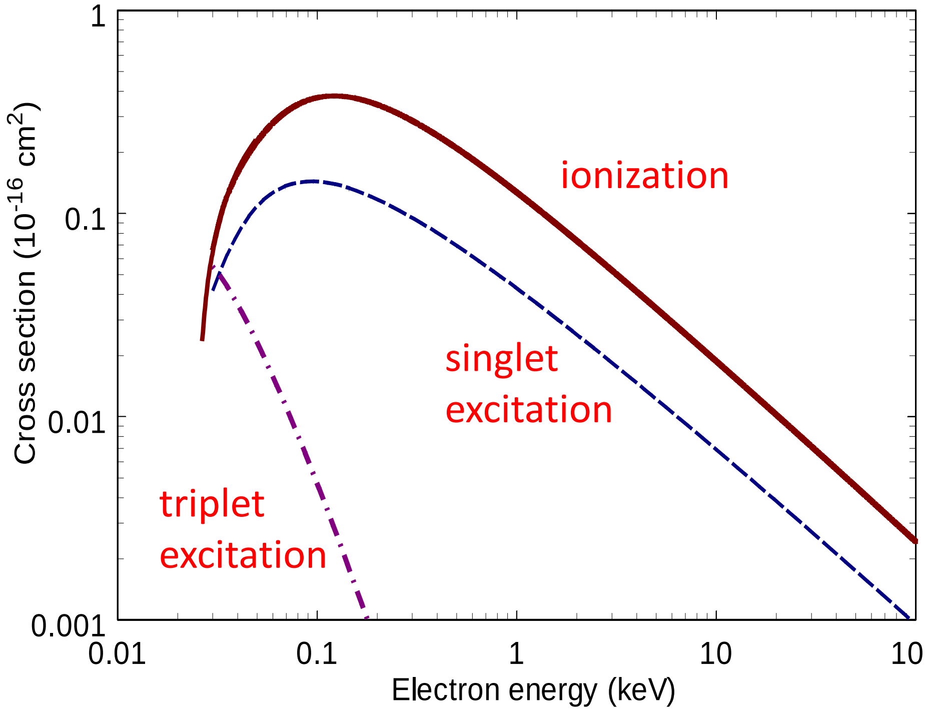
compute quenching from Penning process

assume density is uniform in cylinder, neglect diffusion

$$\frac{dn}{dt} = -\gamma n^2 - \frac{r\,n}{\tau}$$

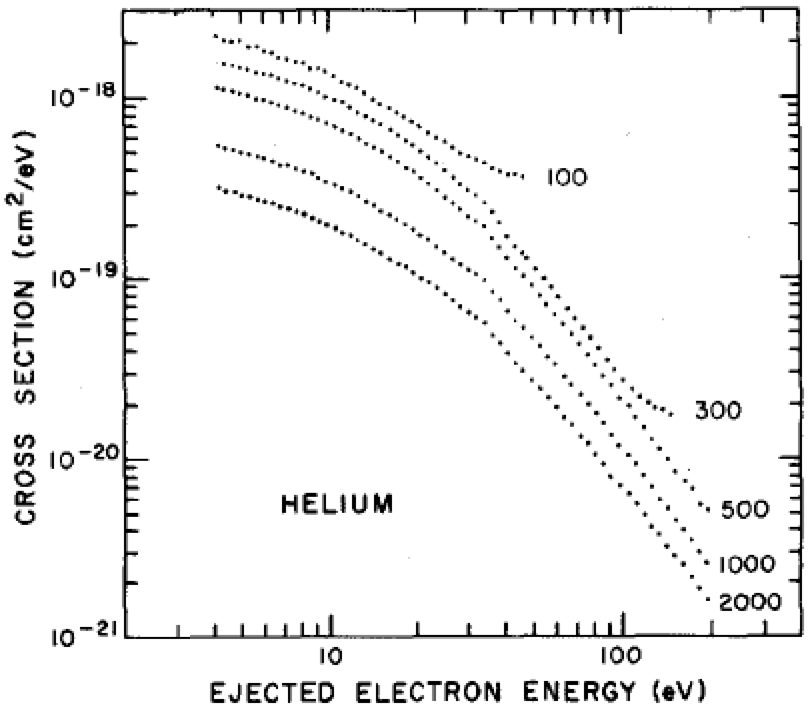
$$\xi = \quad n_0$$

cross sections for electron scattering on helium



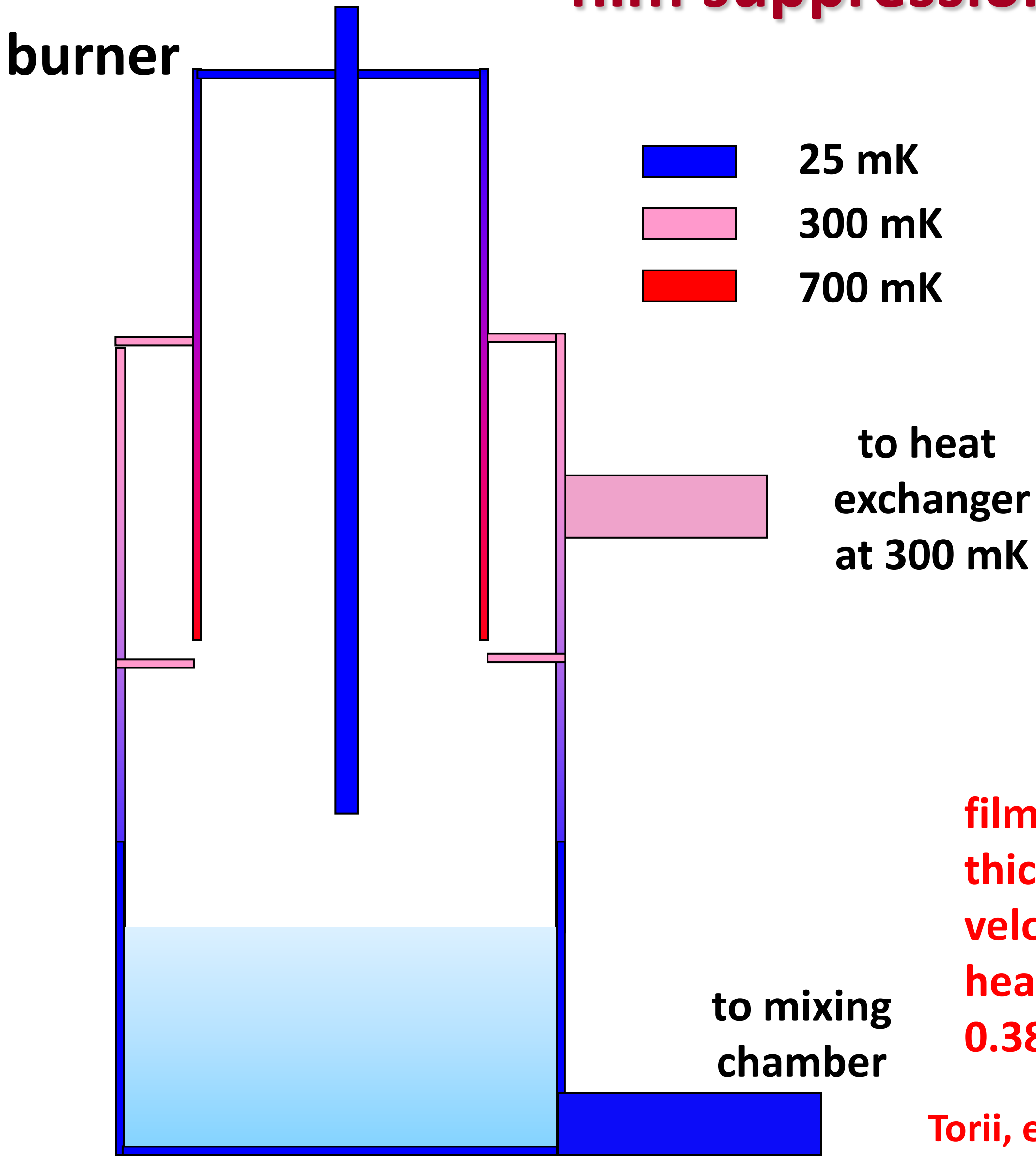
Ralchenko, etal, At. Data & Nucl. Data Tables 94, 603 (2008).

energy distribution electron recoils

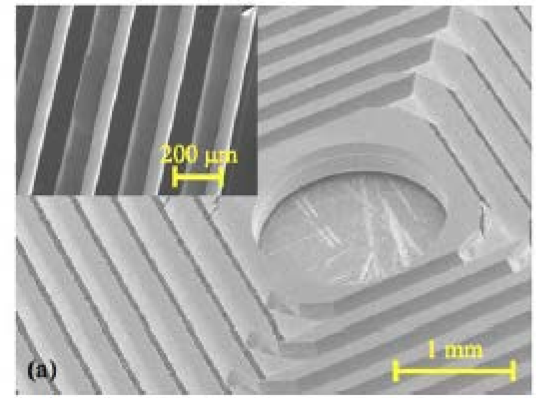


C. B. Opal, etal, At. Data 4, 209 (1972).

film suppression



knife edge suppressor



sharp on an atomic scale; removal of last monolayer more difficult

film
thickness 200 Å
velocity 50 cm/s
heat to evaporate
0.38 mW/cm

Torii, etal, Rev Sci Instrum, 63, 230 (1992).