Properties of Helium of Importance for Dark Matter Detection

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Some preliminary comments

I appreciate and am pleased to be invited to this workshop.

- primary focus of this talk is on the physics of helium important for the operation of a detector at a temperature above 1 K
- would have a different presentation for a helium detector operating below 100 mK
- will not discuss design of a detector, thresholds, sensitivity etc. but stick to the physics of the important atomic processes

Genesis of Research: Solar Neutrinos

PRL paper by Cabrera, Krauss and Wilcek (1985)

- silicon: $\Theta_D = 660$ K,
- $C = 1944\,(T/\,\Theta_D\,)^3$ J/ mole K
- at 1 mK an energy input of 1 keV in 10 tons
  produces $\delta T/T = 10^{-4}$

Problems

- impurities
- condensed matter
  $C \neq C_{Debye}$
- nuclear
  cosmogenically induced radioactivity

Lanou, Maris, Seidel, PRL (1987)

helium: $\Theta_D = 25$ K
separate energy input by
quantum evaporation

Results

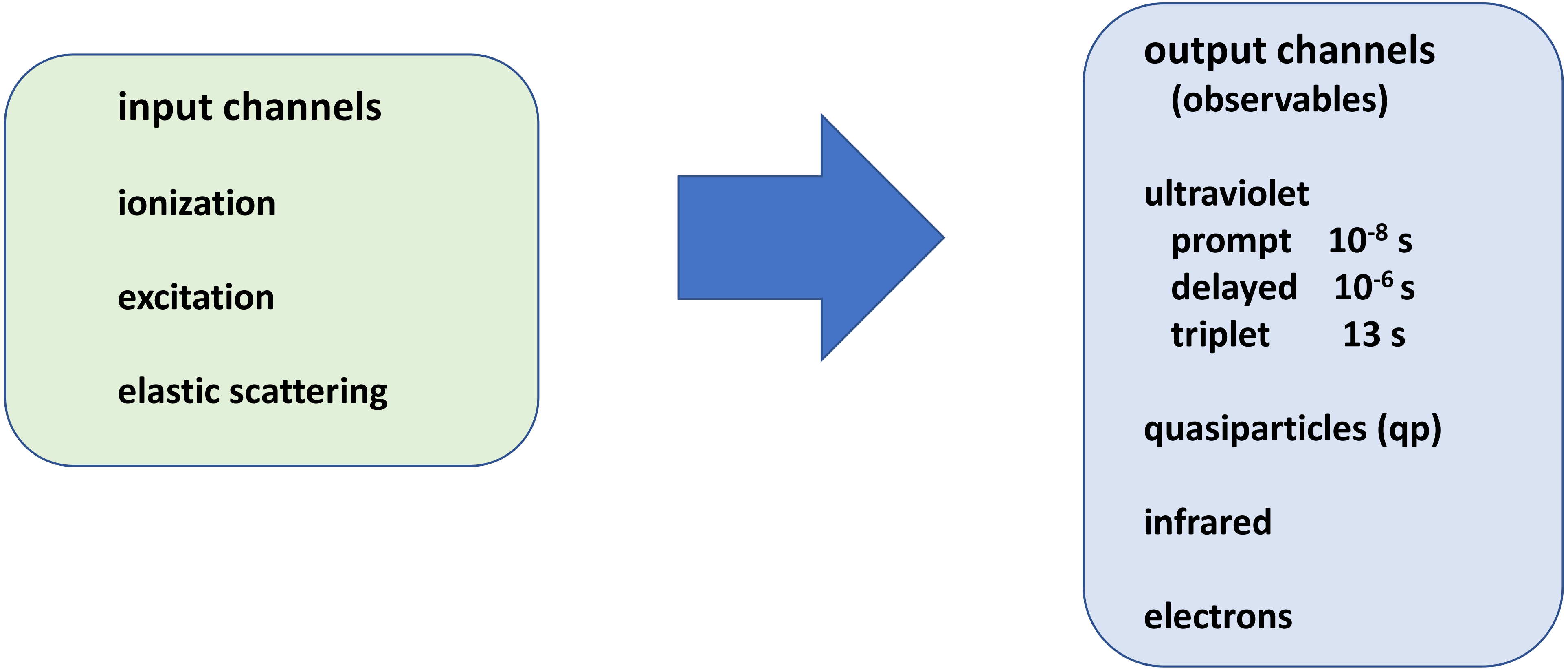
demonstrated feasibility (HERON)
Huang, etal Astropart. Phys. (2008)
applicable to dark matter detection
Lanou etal, Proc. Moriond Workshop(1988)

Problem

solar neutrino detection was no longer relevant

Outline

1. deposition of energy by a nuclear recoil and by electron scattering in liquid helium
2. processes in the liquid that affect energy distribution
3. energy distribution in various observable output channels



input channels

ionization

excitation

elastic scattering

output channels
(observables)

ultraviolet
prompt 10^{-8} s
delayed 10^{-6} s
triplet 13 s

quasiparticles (qp)

infrared

electrons

Properties of Liquid

density 0.145 g/cm^3

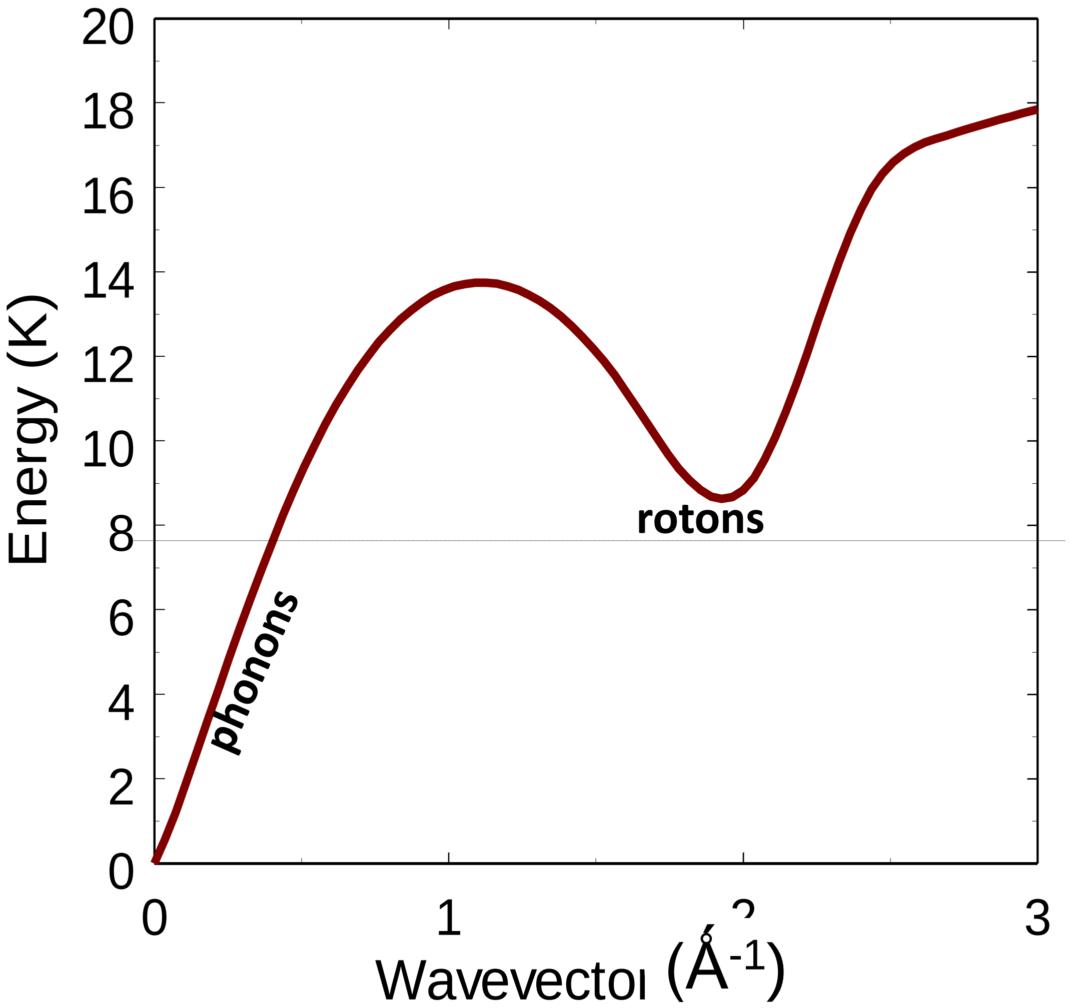
vapor pressure at low T
  gas density
  $n \approx 1.5\times10^{21}\,T^{1.5}\,e^{-7.2/T}$ #/cm^3

purity
  nothing soluble except ^{3}He
  no nuclear reactions

superfluidity below 2.17 K

electrons form bubbles r = 19 Å
positive ions form snowballs r = 7 Å

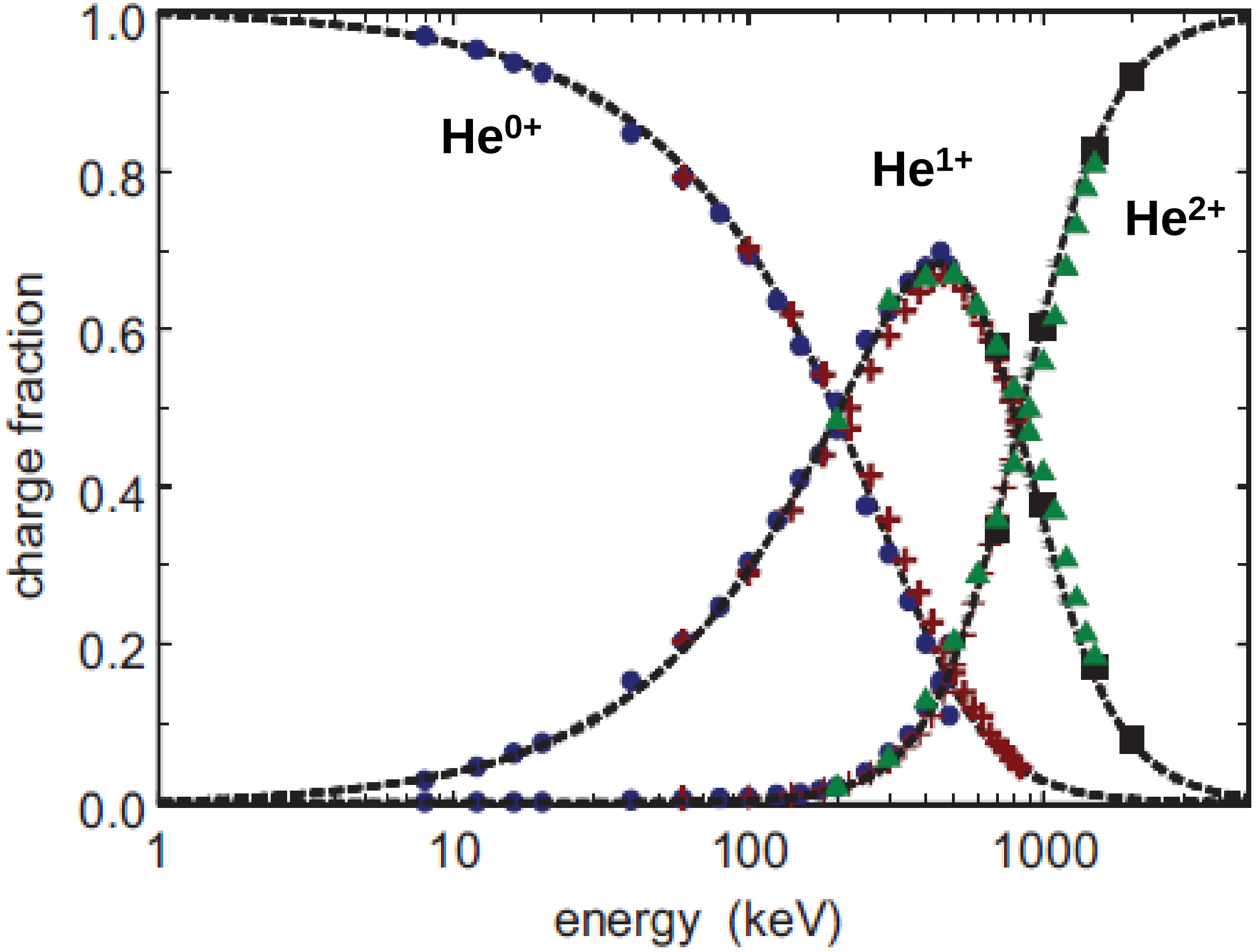
dispersion relation
  roton energy gap 8.65 K = .62 meV
  phonon velocity 238 m/s
  no anharmonic decay of rotons
  about minimum



Charge fraction

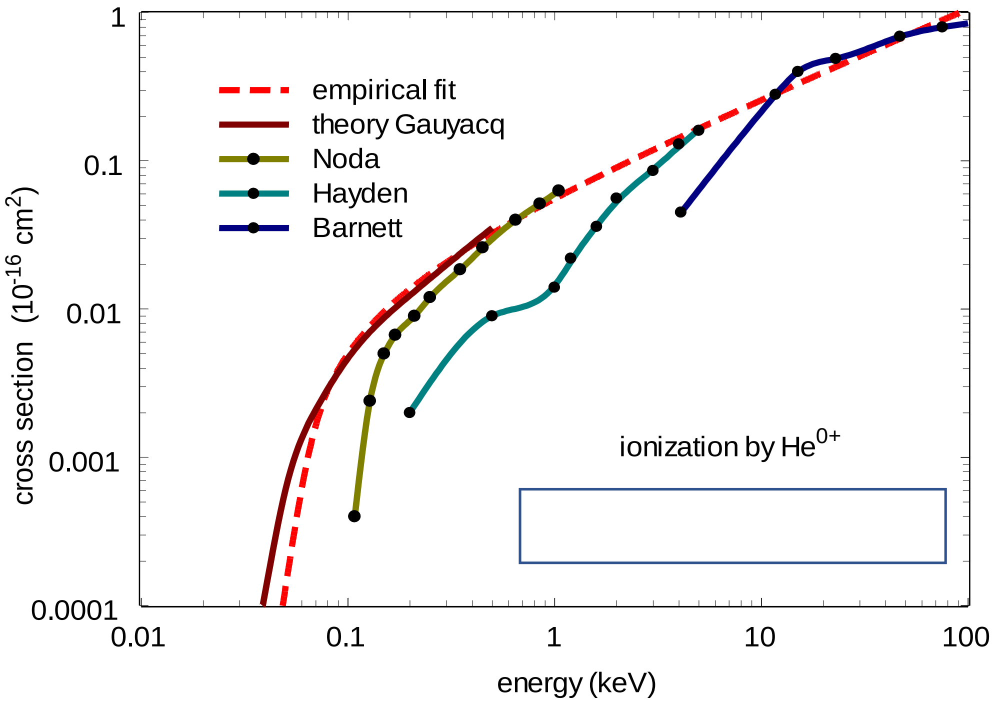
points: data from literature
lines: empirical fits

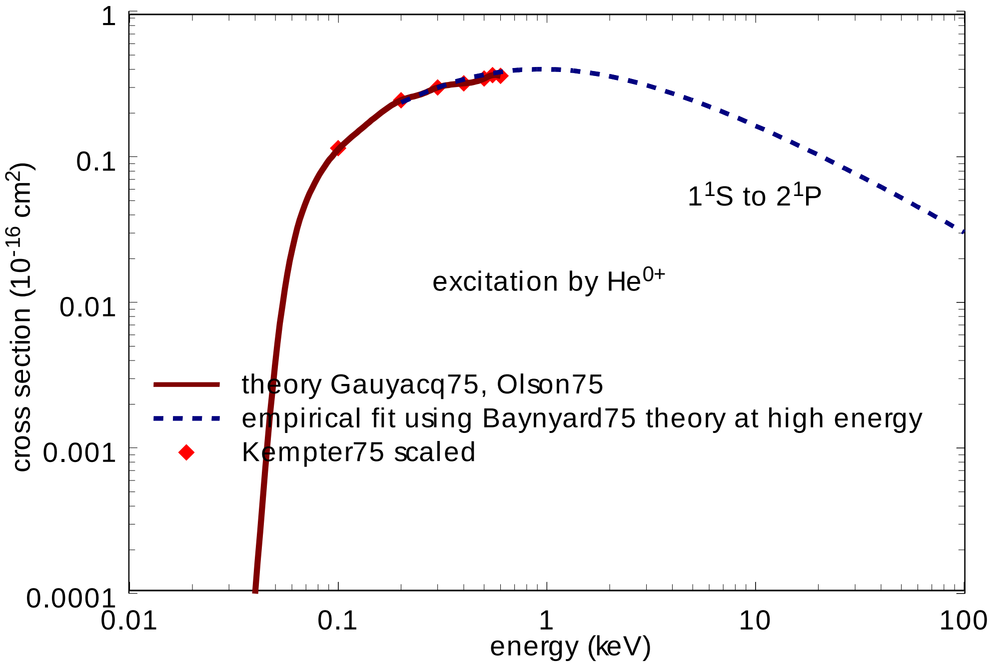
primarily interested in He^{0+}



Cross Sections for Ionization and Excitation

- plots of ionization and excitation cross sections as function of energy for He^{0+}; theory, experimental data and empirical fit
- obtain the same for He^{1+}
- excitation cross section only for 1^1S to 2^1P transition: to account for transitions to higher levels; multiply by factor of 1.4 for singlets by .14 for triplets





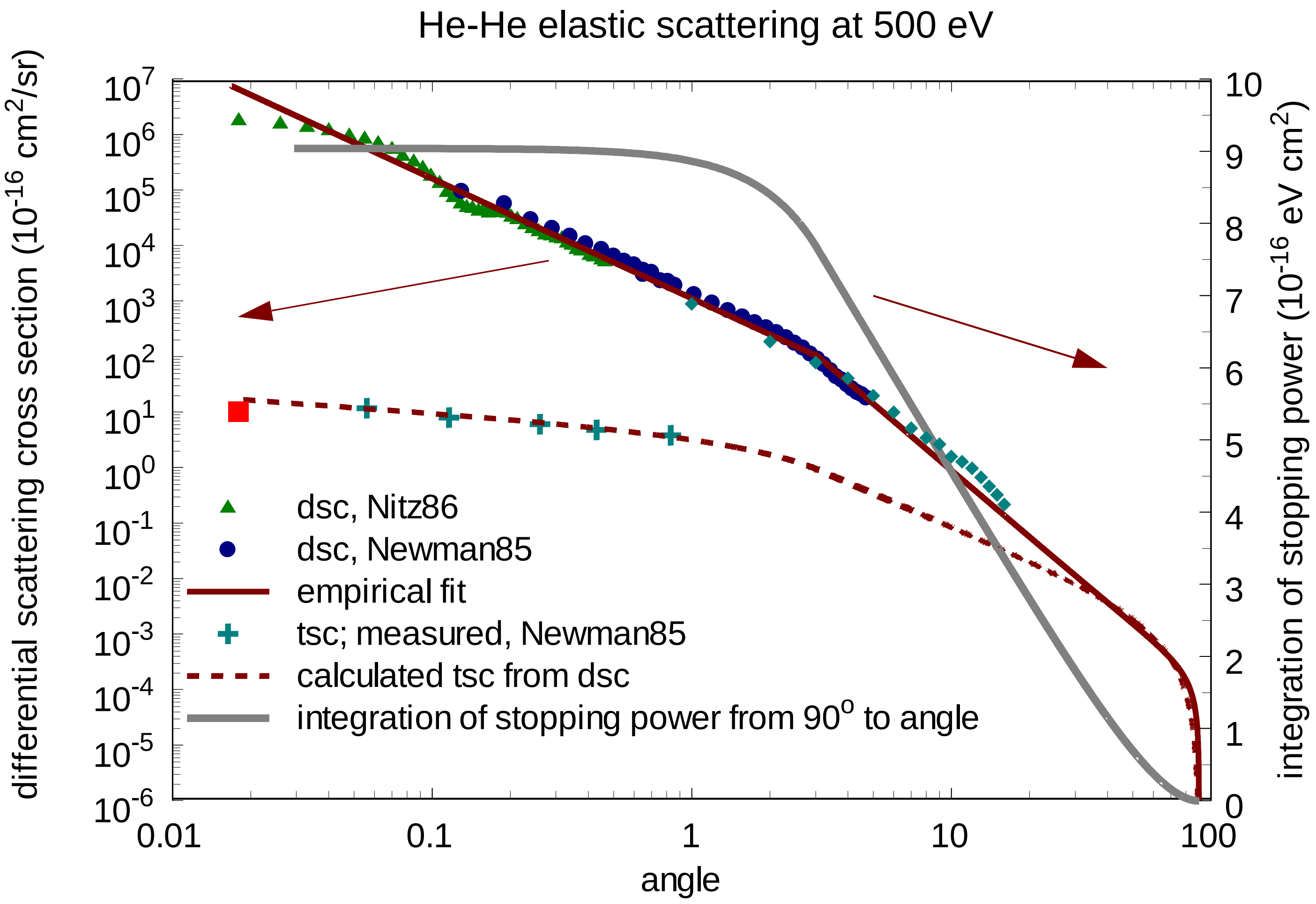
Cross Section for Elastic Scattering

differential scattering cross section with respect to angle, $d\sigma/d\Omega$

fit with function varying as $1/\sin^4(\theta)$;
1 adjustable parameter to match data

measurements at 4 different energies
integrate to obtain total scattering cross section from 90° to some lower angle

energy loss varies as $\sin^2(\theta)$



Nuclear Stopping Power

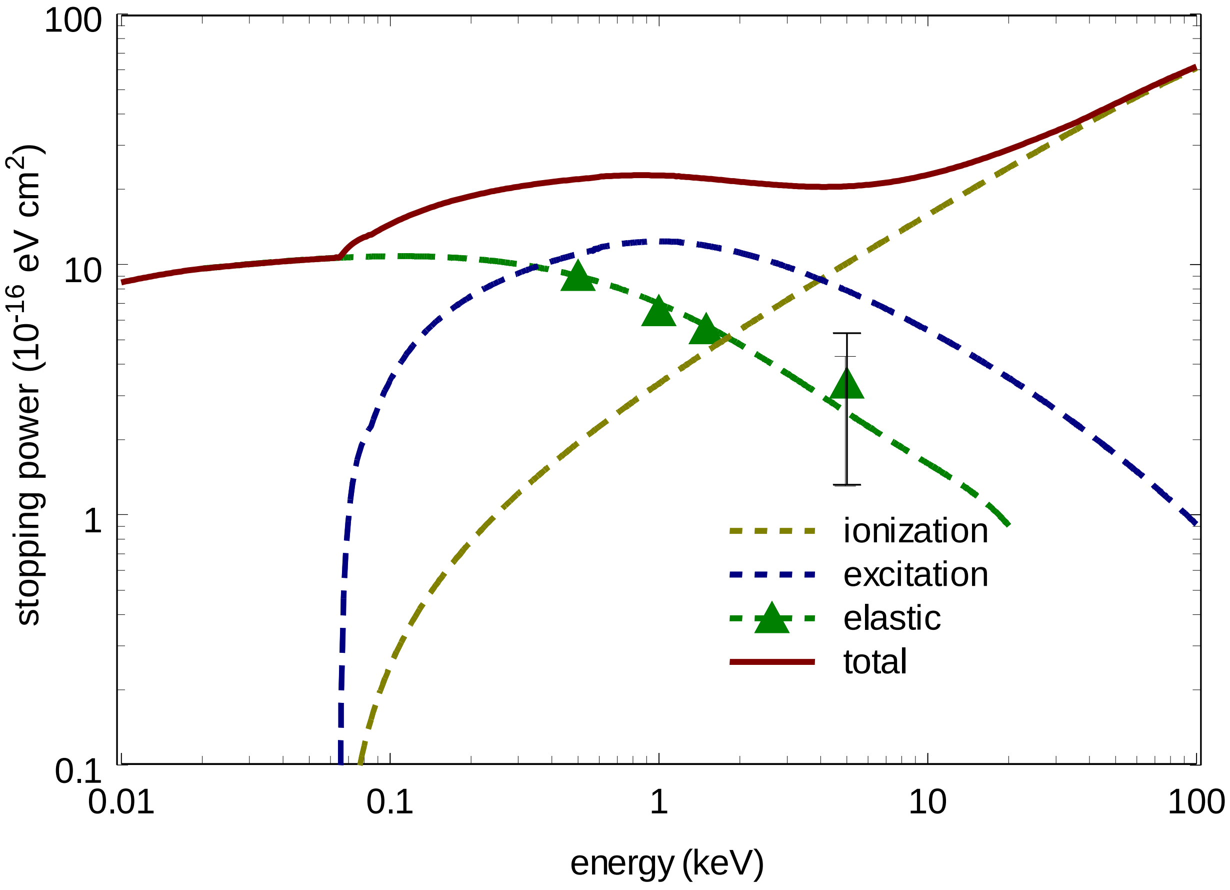
$$SP = \Sigma_{ij} F_i \sigma_{ij} \varepsilon_j$$

i: sum over charge states He^{0+} and He^{1+}
j: sum over channels; ionization excitation and elastic scattering

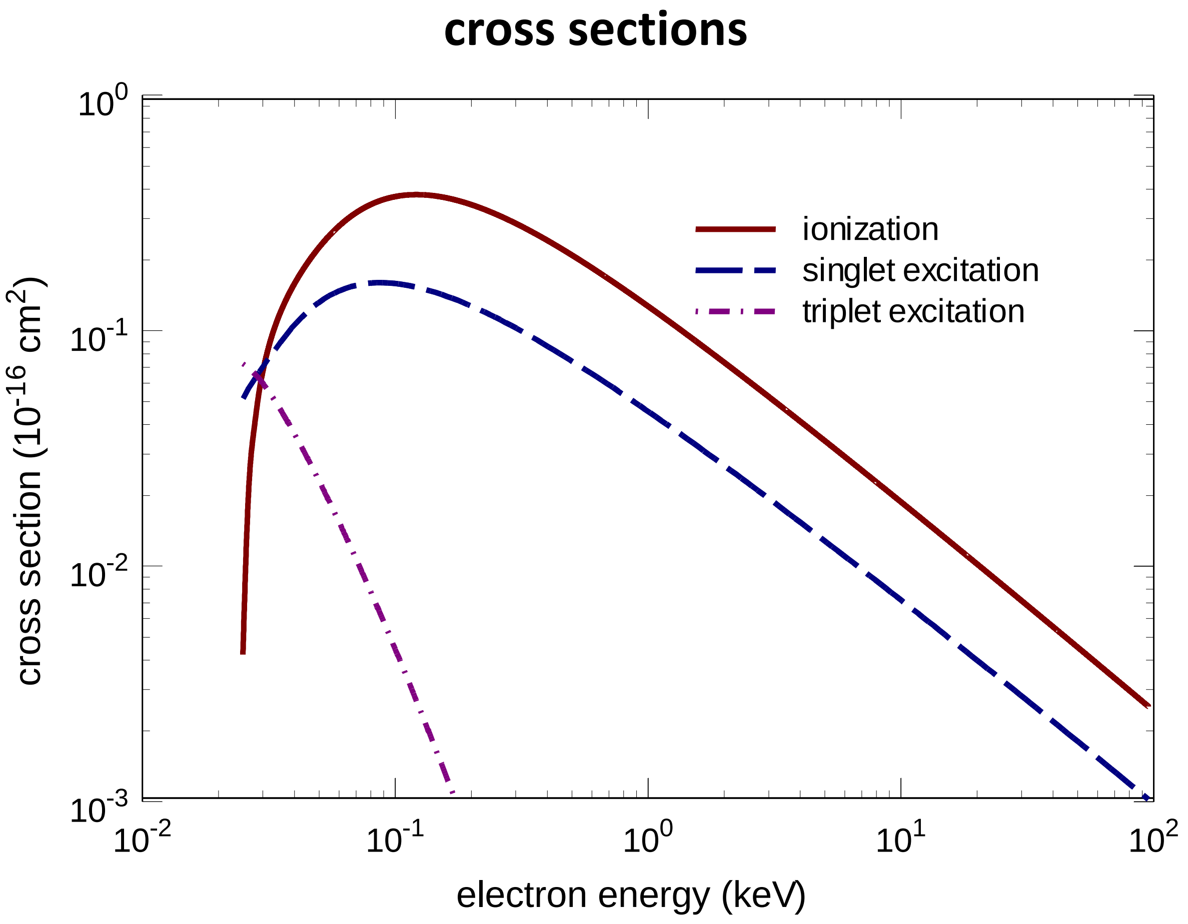
ε_{ion} = IP + KE of electron recoil
electron KE calculated from Rudd (RMP85) for protons on He, scaled; depends on energy of He projectile.

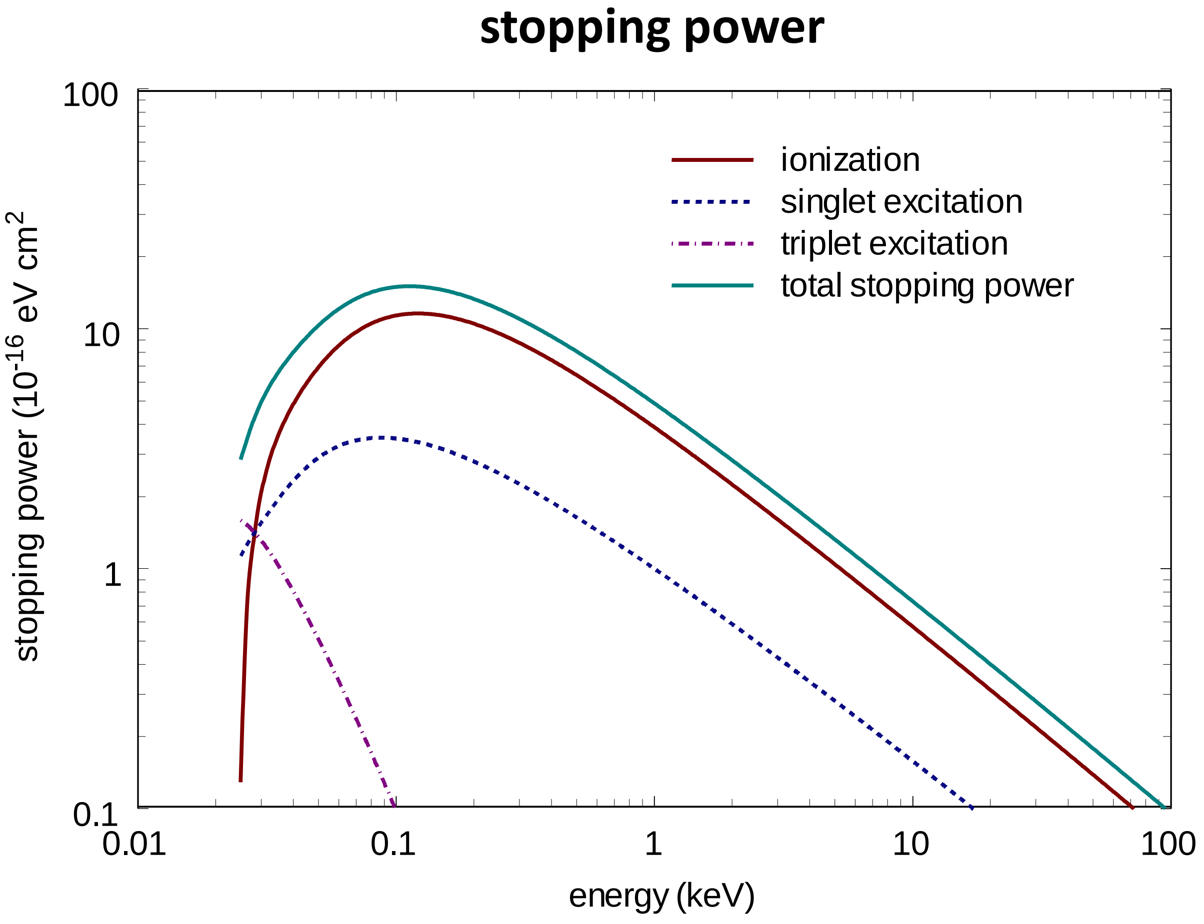
$$\varepsilon_{exc} = E_{2P\ state} + .4(IP - E_{2P})/2 + .14(IP - 2)$$

$$\varepsilon_{elastic} = 2\pi \int (\sin(\theta)\, d\sigma/d\Omega)\, E \sin^2(\theta)\, d\theta$$



Electron Cross Section and Stopping Power

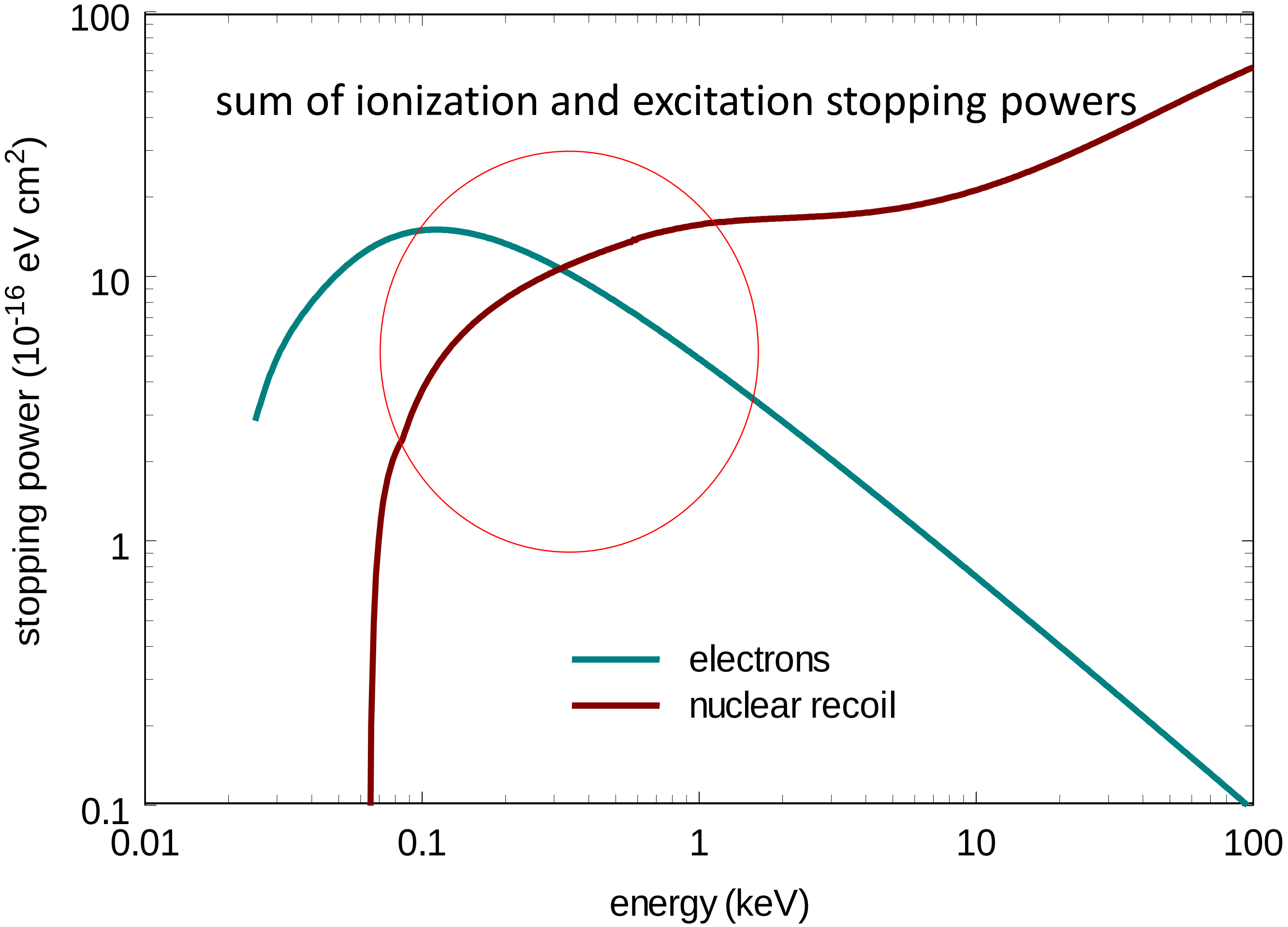




Comparison of Stopping Powers

at low energies an electron is a highly ionizing particle.

nuclear recoil primarily excitations
electrons primarily ionizations



From Energy Input to Output

input channels

ionization

excitation

elastic scattering

processes in liquid

monomolecular	bimolecular
electron thermalization	
dimerization	Penning processes
cascade	
ground state dissociation	

output channels
(observables)

ultraviolet

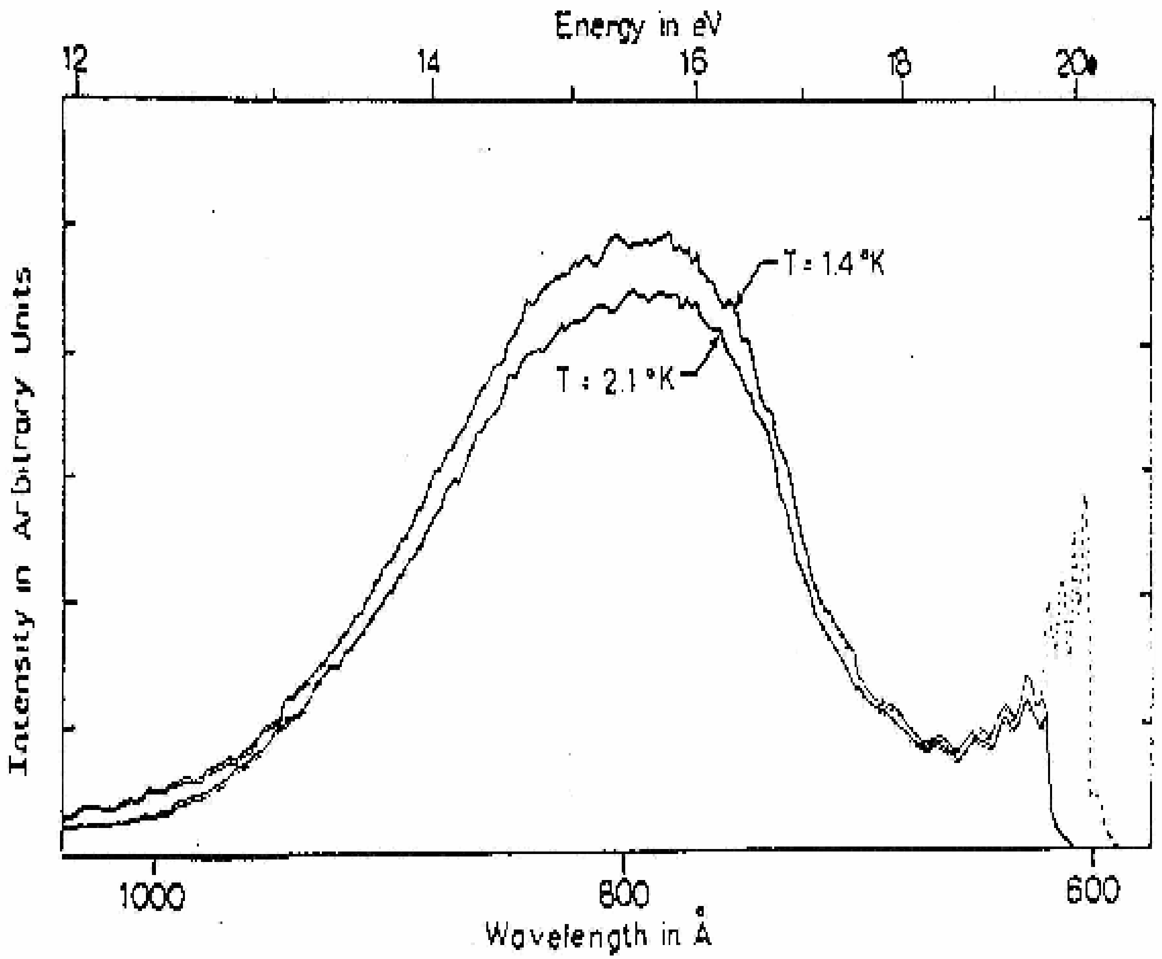
prompt	10^{-8} s
delayed	10^{-6} s
triplet	13 s

quasiparticles

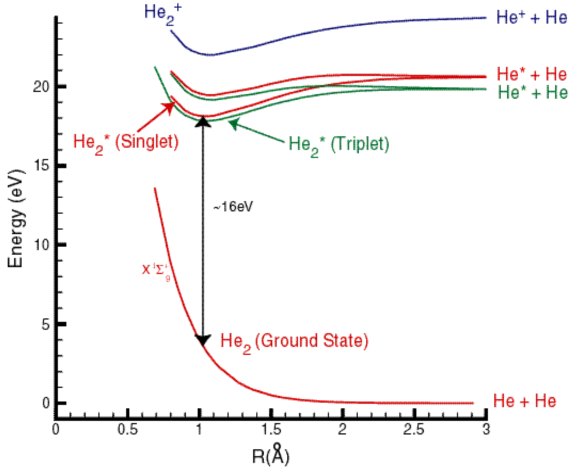
infrared

electrons

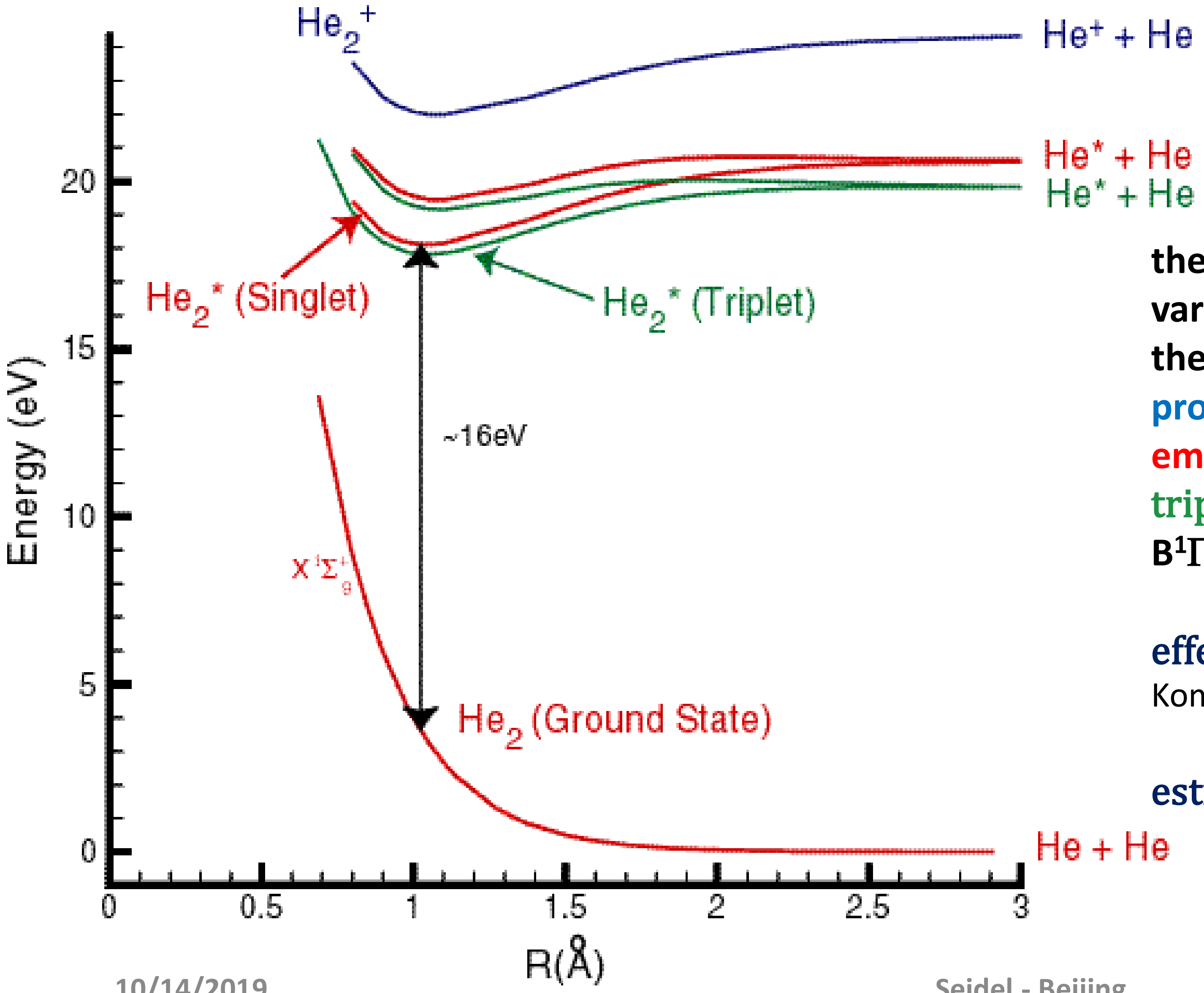
Scintillation in Liquid



Stockton, Keto, and Fitzsimmons, Phys. Rev. A (1972)



Energy Levels of Atom and Excimers



the problem with estimating the energies in the various uv channels is we do not know with certainty the upper states corresponding to those channels

prompt ($\tau < 10^{-8}$ s) emission: $A^1\Sigma_u^+$

emission with $\tau = 1.6 \times 10^{-6}$ s: 2^1S

triplet $\tau = 13$ s: $a^3\Sigma_u^+$

$B^1\Pi_g$? , 2^3S ?

effect of vibrational states?

Komasa, Molecular Phys.**104** (2006)

estimate of ratio of 10^{-8} to 10^{-6} s problematic

Energy Distribution: Input to Output

ionization

secondary electron energy (primarily) converted to qp
recombination yields ¼ singlets and ¾ triplets
formation of dimers He_2^* , 2eV to qp
cascade by ir emission to $A^1\Sigma_u^+$ or $a^3\Sigma_u^+$ states; 4 eV to ir
(uv emission followed by re adsorption much less likely)
singlets end up in $A^1\Sigma_u^+$ state
triplets end up in $a^3\Sigma_u^+$ state
radiatively decay to ground state 16 eV uv and 4 ev qp

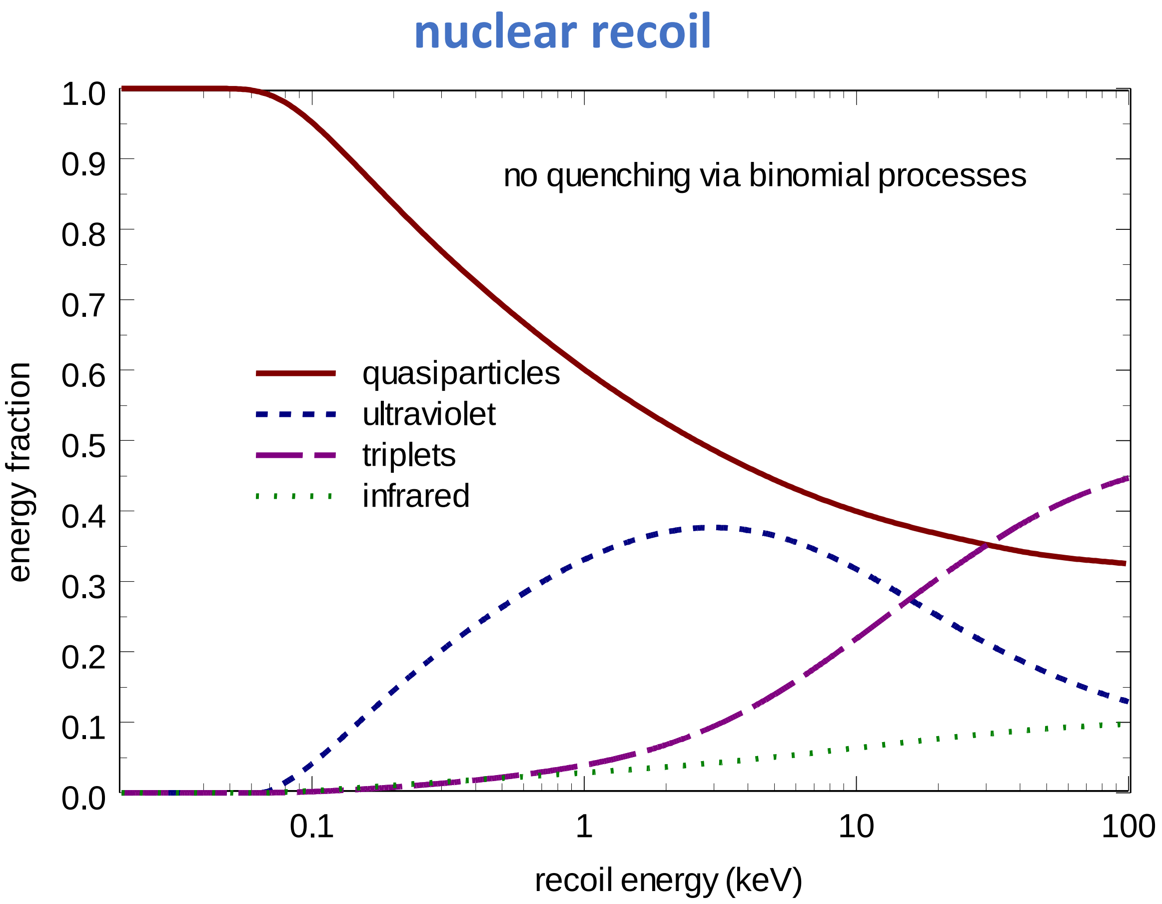
excitation

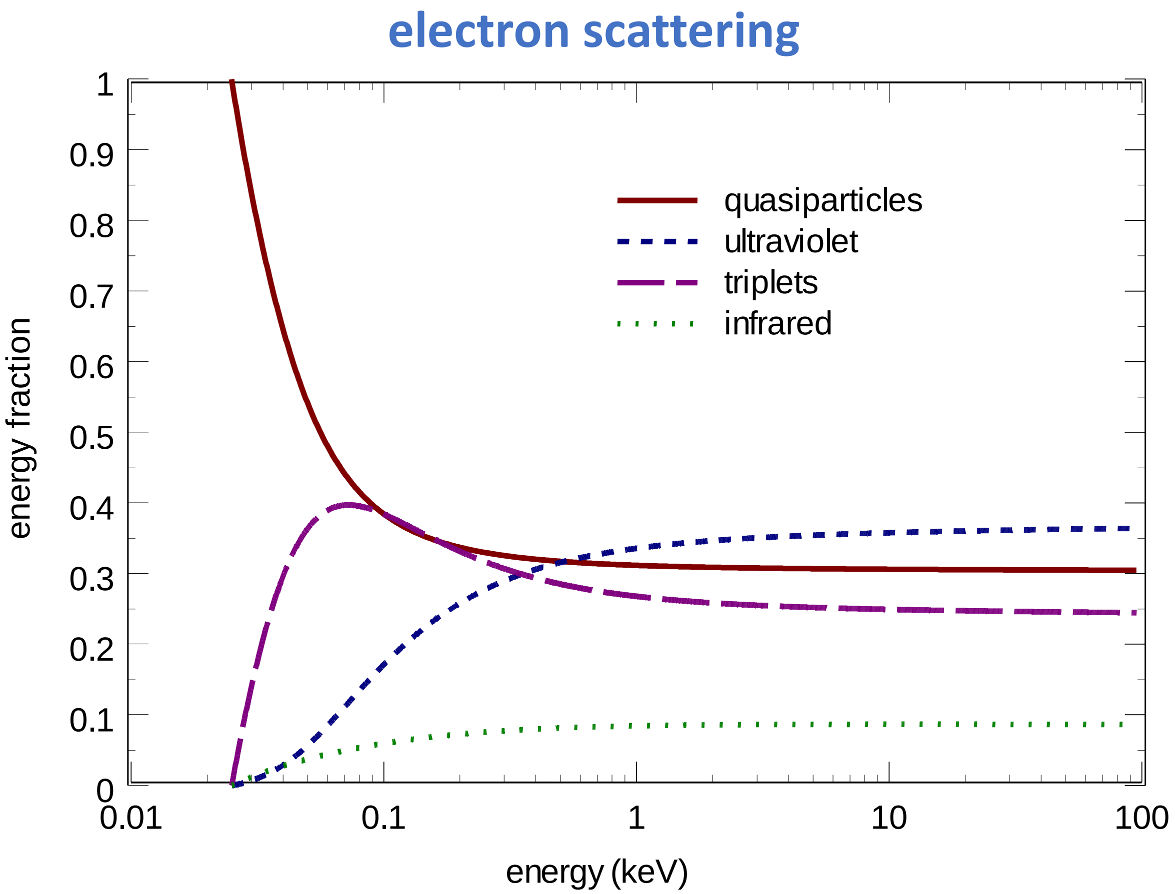
formation of dimers He_2^* , 2eV to qp
ratio of numbers in $A^1\Sigma_u^+$, and $a^3\Sigma_u^+$ states; 1.4/.14 after cascade
cascade by ir emission to $A^1\Sigma_u^+$, or $a^3\Sigma_u^+$ states; 2 eV to ir
decay to ground state same as with ionization

elastic scattering

all energy to qp

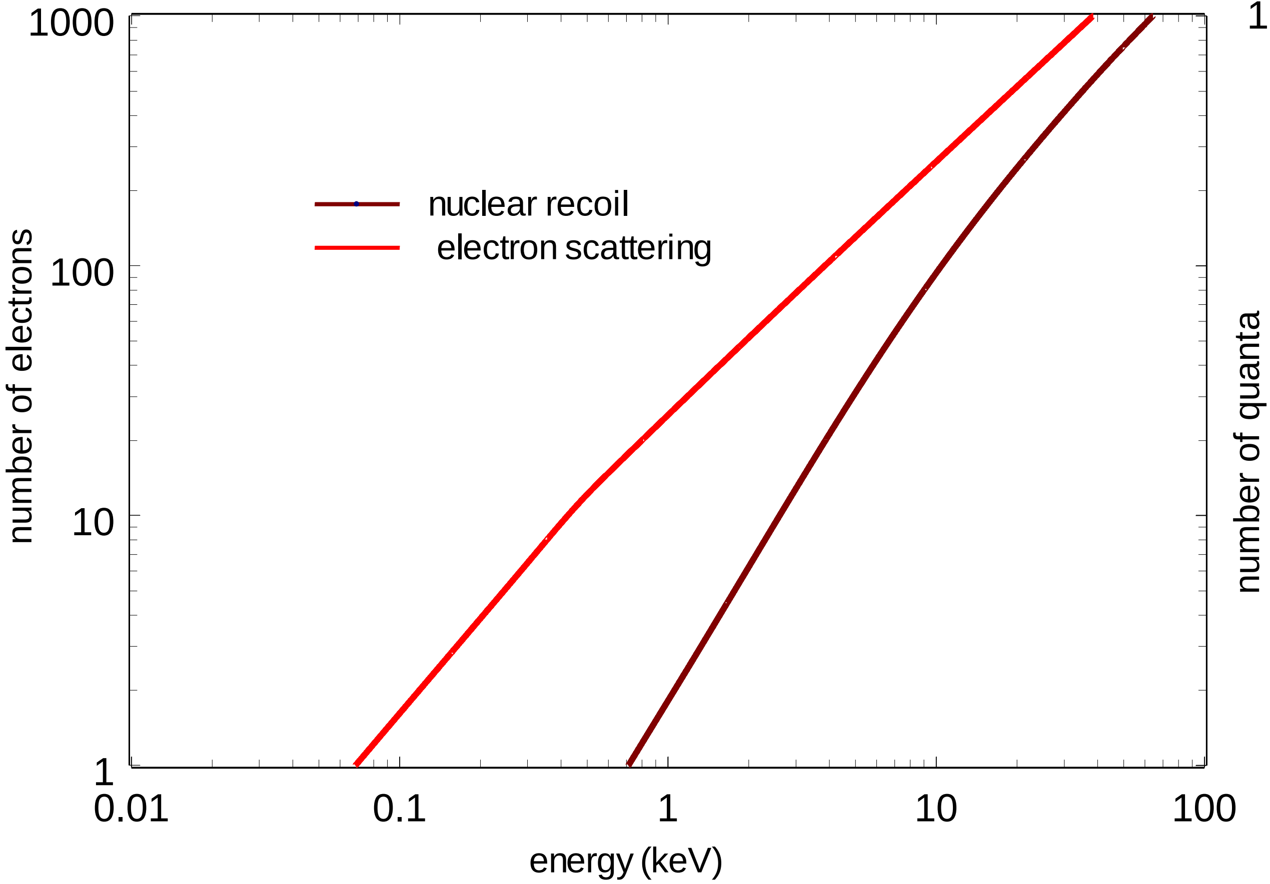
fraction of energy in output channels

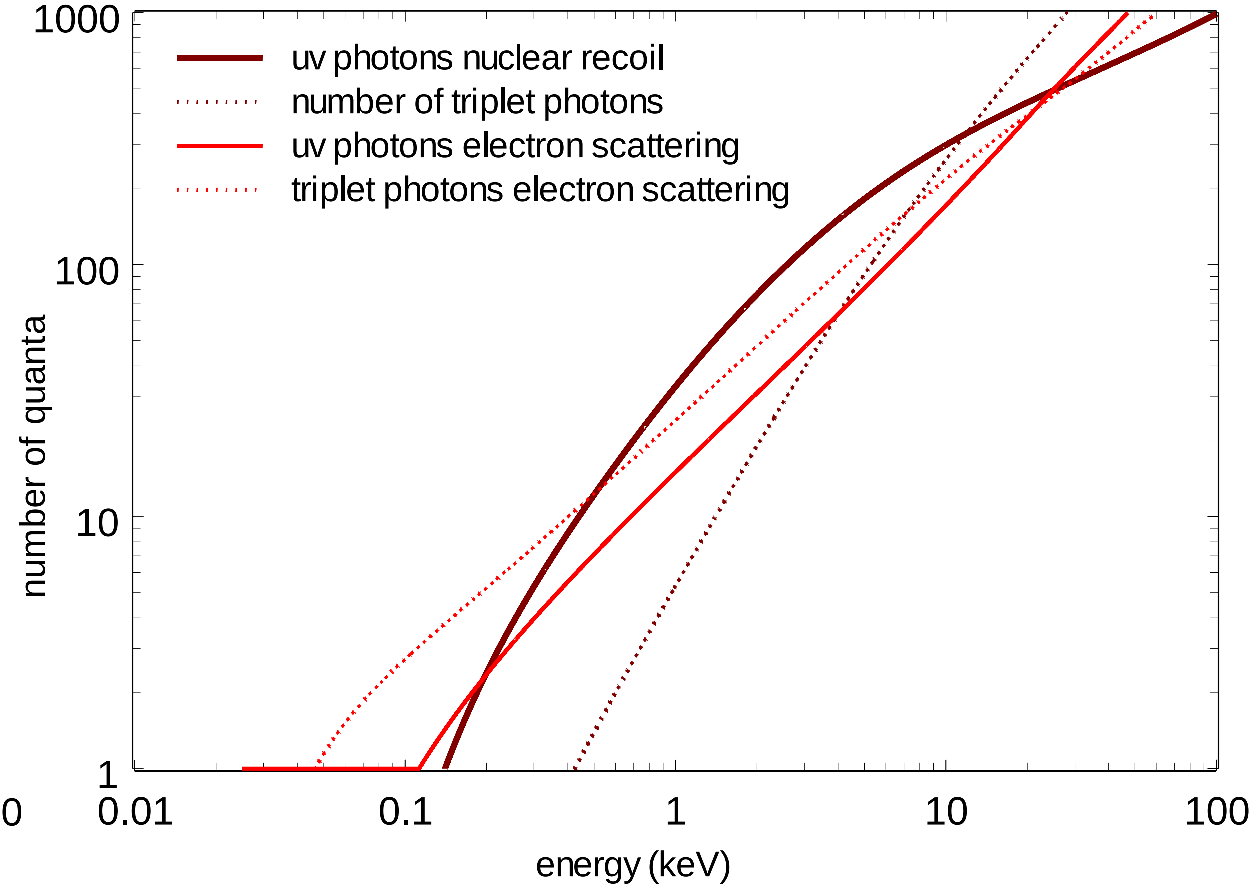




now need discussion of distribution of particles along track

Numbers in Output Channels

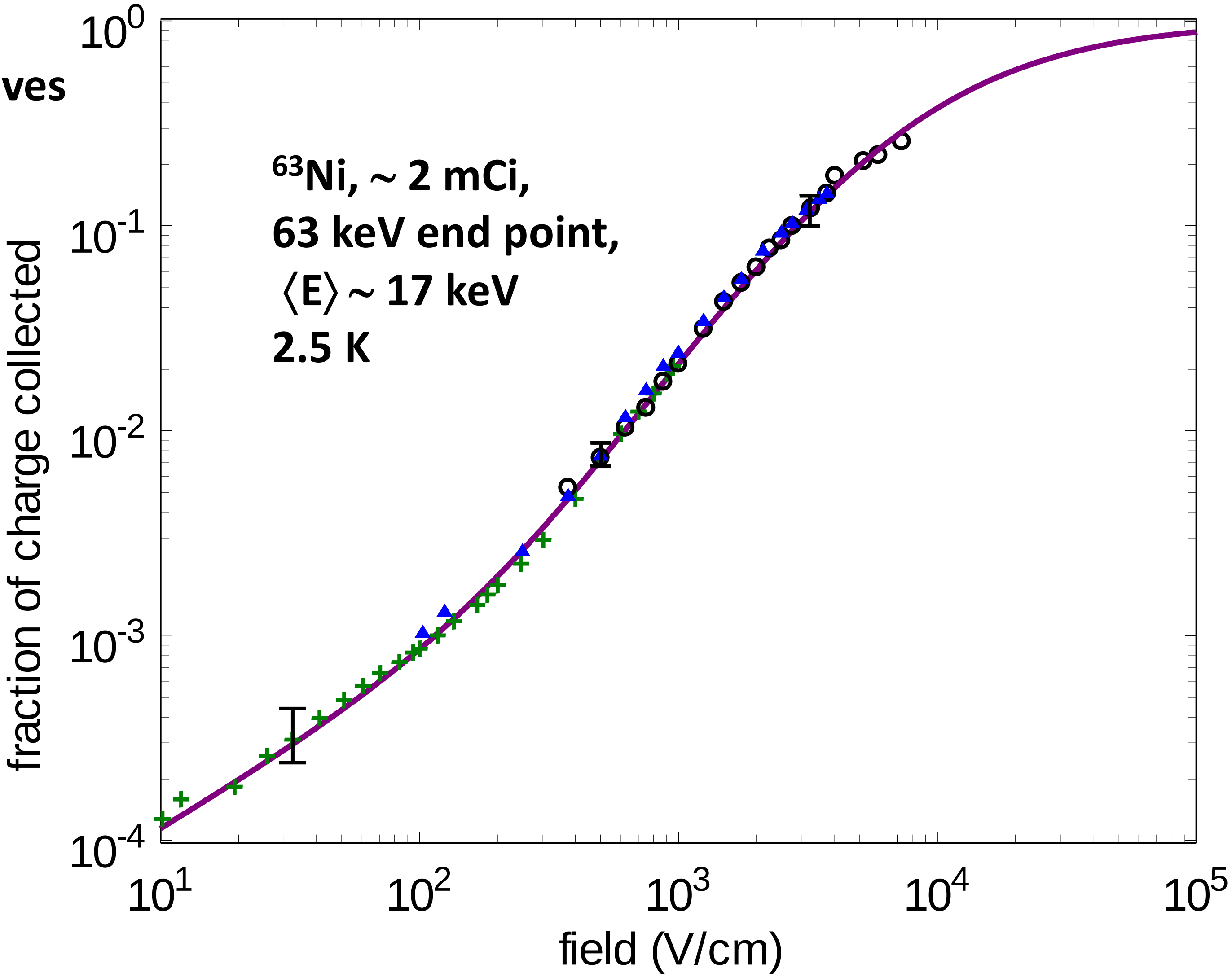




A Current Measurement

- measure current as function of field
- for geminate recombination, electron moves in applied field and that of its positive ion partner
- bubbles and snowballs obey Stokes law viscous motion diffusion negligible at time scale of recombination
- can obtain charge distribution from field dependence of current

Seidel etal, PhysRevC(2014)



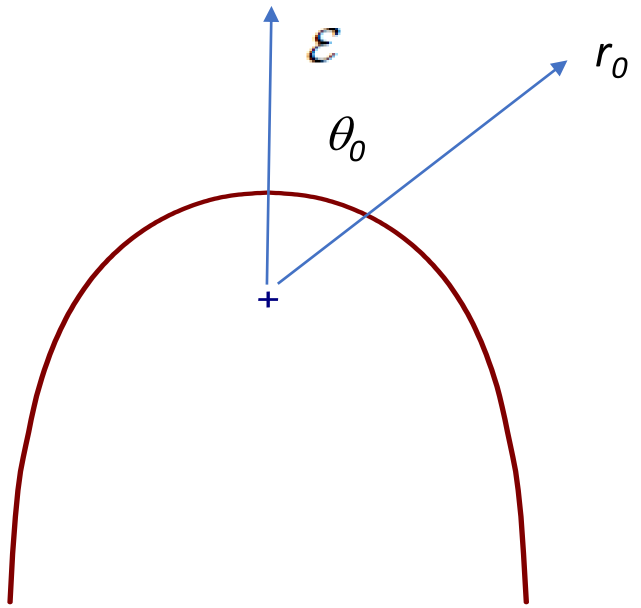
Determination of Density

- **integration over angle leads to**

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

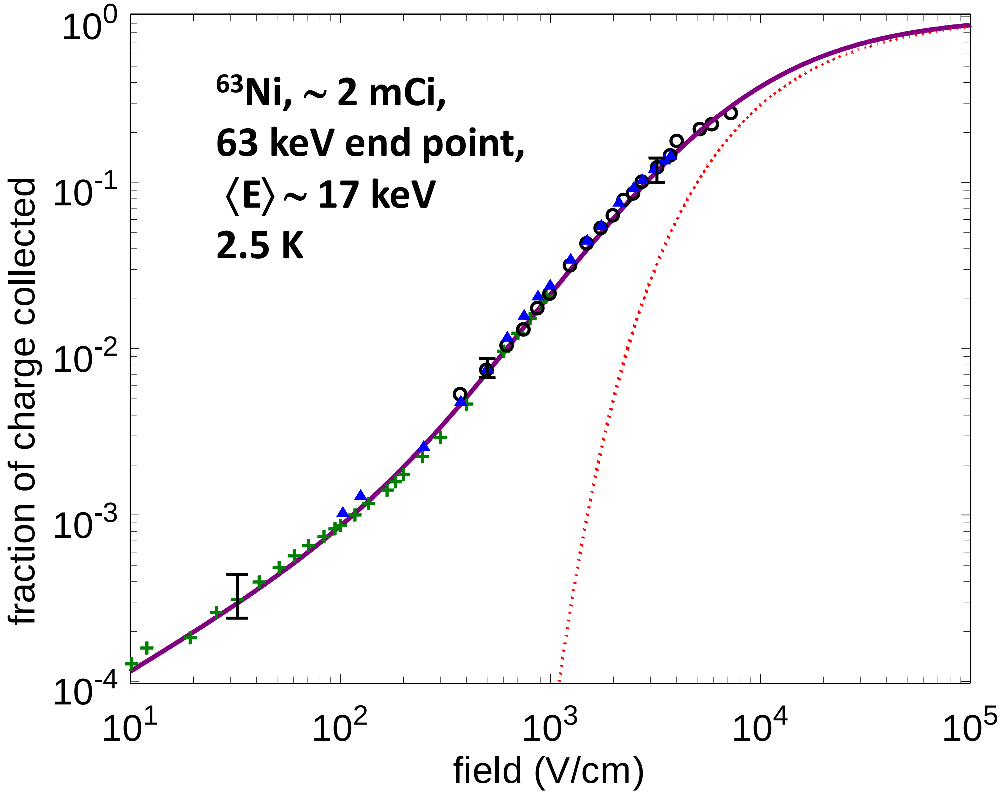
$$D(r) = \frac{4\pi^{1/2}\epsilon_0^{3/2}\mathcal{E}^{5/2}}{e^{3/2}} \frac{d}{d\mathcal{E}}\left(i + \mathcal{E}\frac{di}{d\mathcal{E}}\right)$$

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



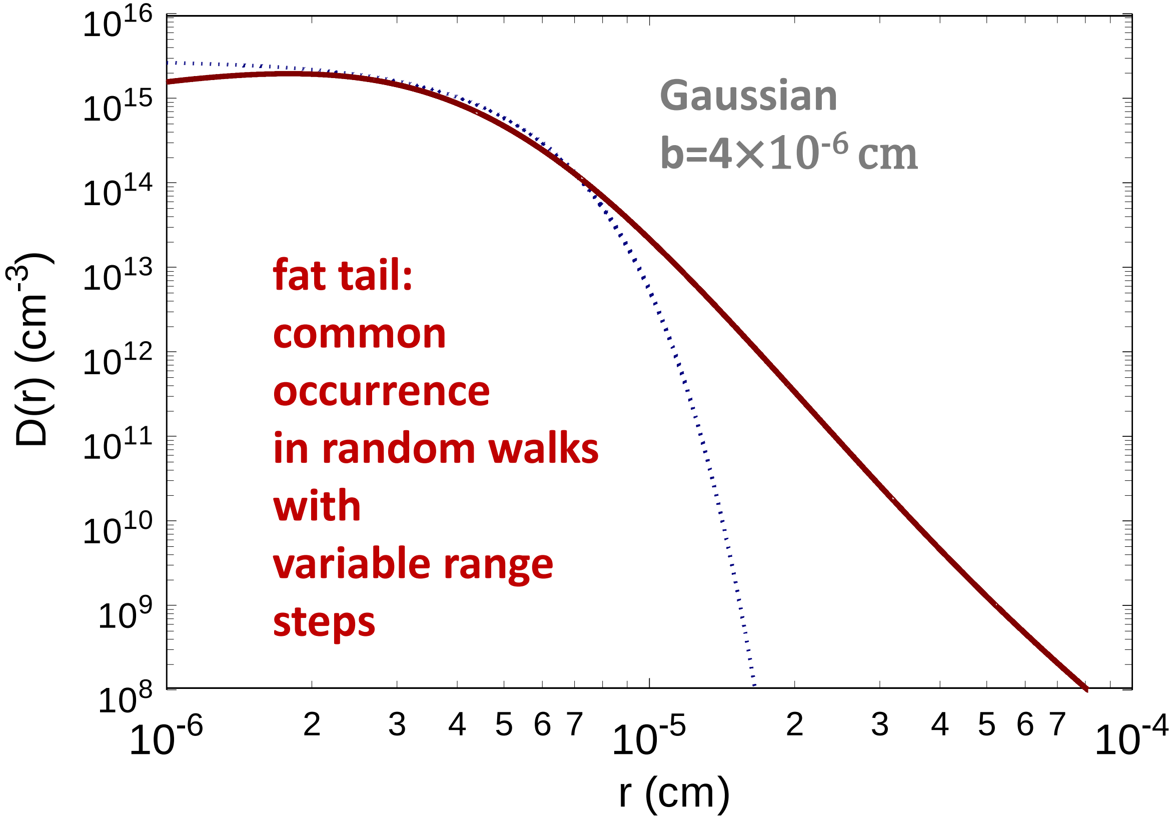
$$r_0^2(1+\cos\theta_0) \geqslant \frac{2e}{4\pi\epsilon_0\mathcal{E}}.$$

current vs field



range determined by elastic scattering and by how an electron forms a bubble

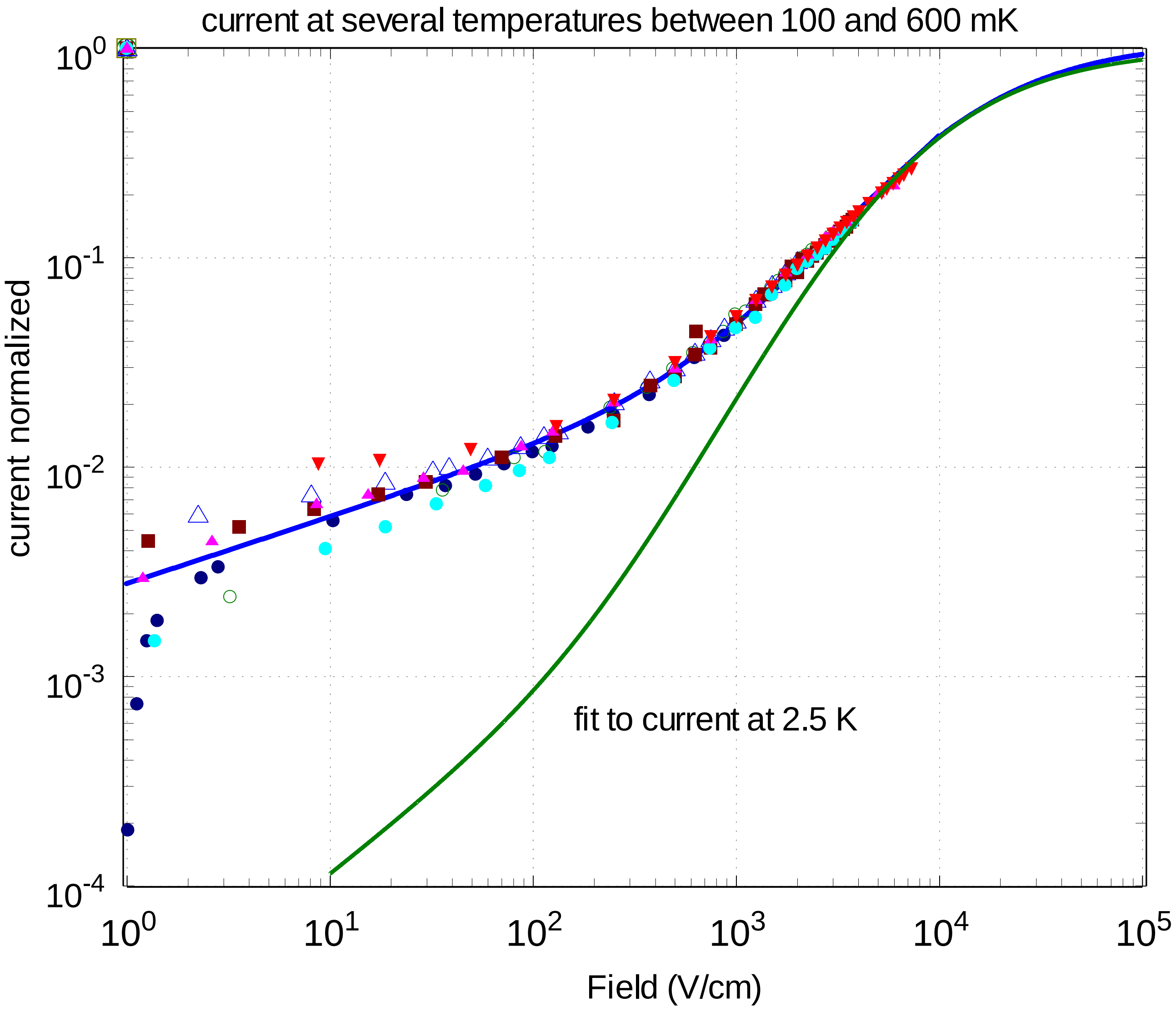
density vs distance



from the stopping power and energy distribution can obtain the total number of various species and the track length, hence can calculate the density

Current vs. Field at Low Temperature

at low temperature motion of charges in tail is ballistic (low thermal roton density) but in gaussian core qp density is high and motion is viscous

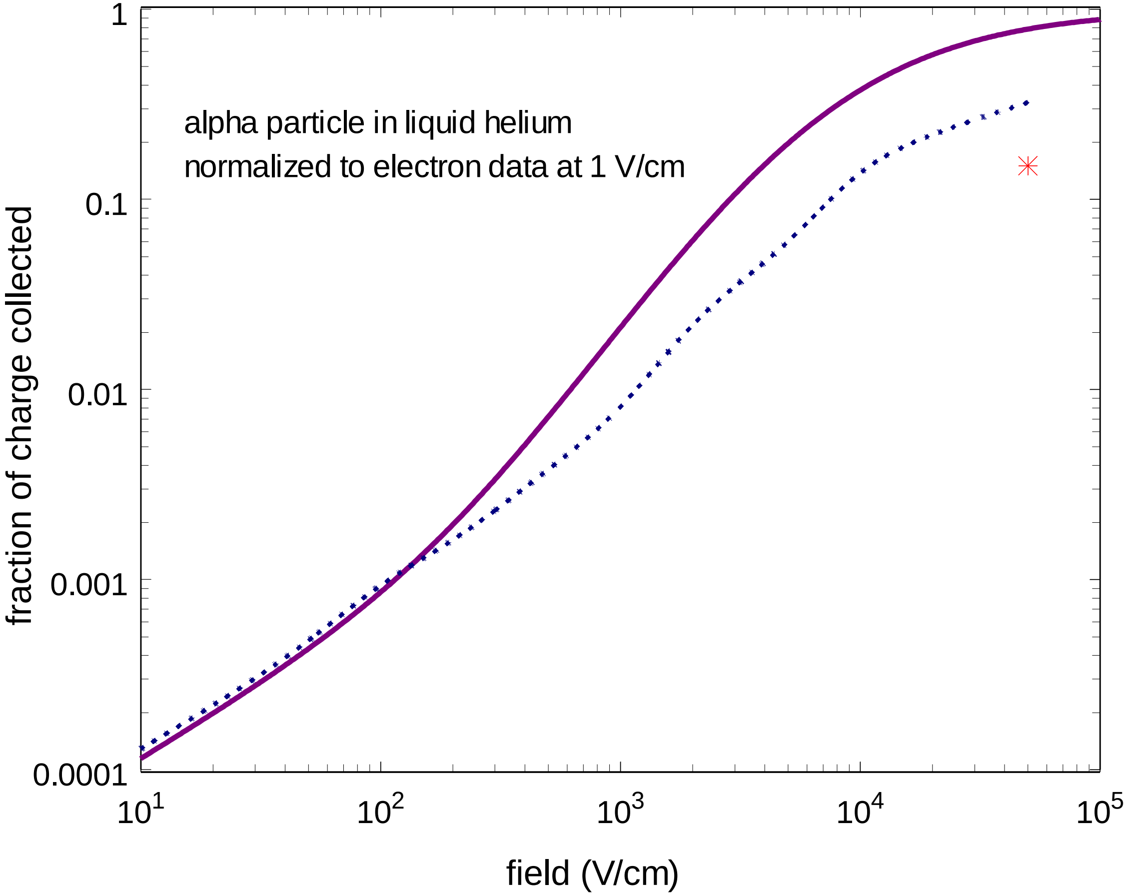


Charge Separation

distribution of elections about track of a highly ionizing particle under same conditions expected to mimic that as along track of an electron

current vs field for alphas same at low field but different at high field

at 10^3 V/cm only ~ 2% of electrons collected, at Ar an Xe number is closer to 50%

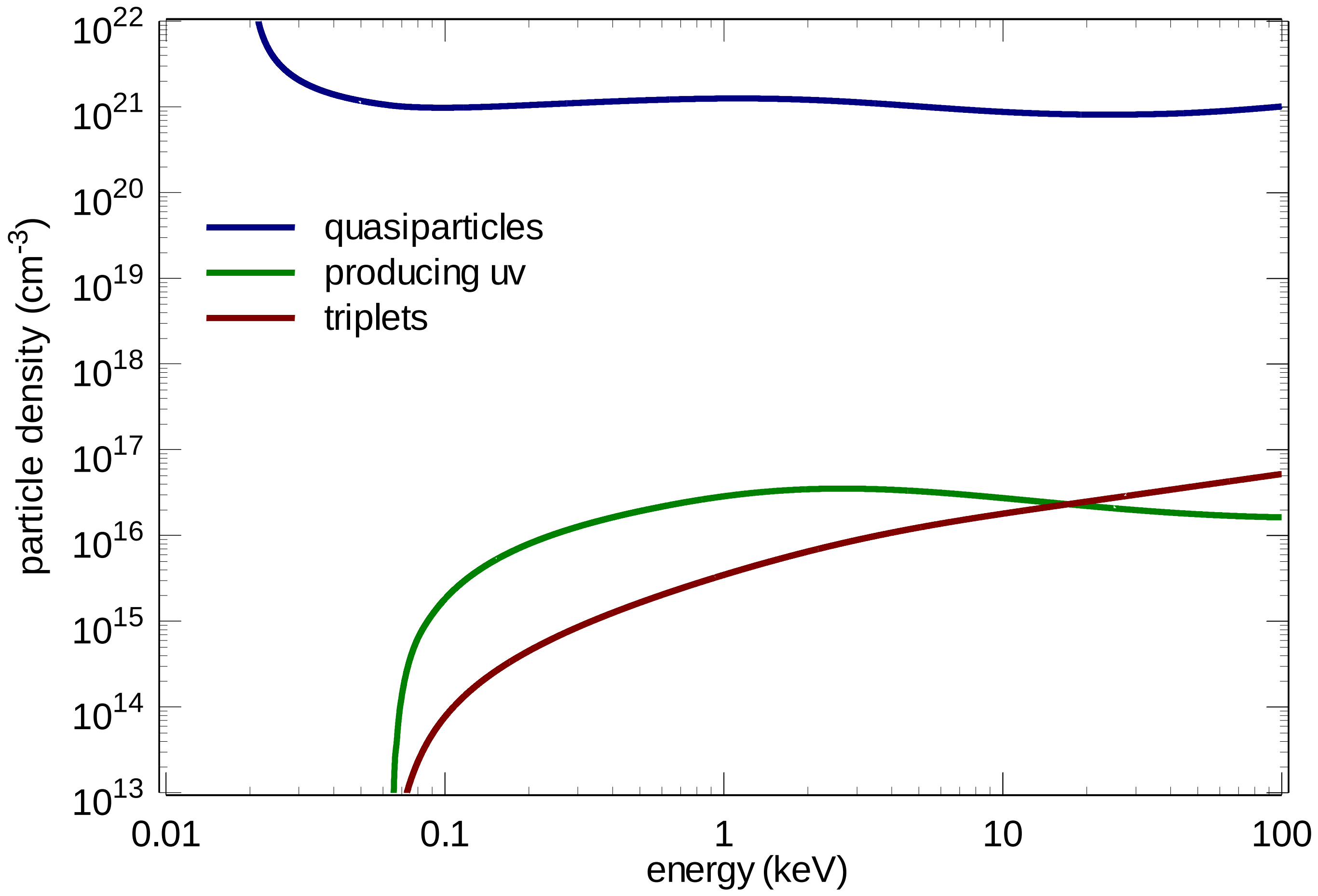


Particle Density

assume particles are in within 4×10^{-6} cm of track

quasiparticle density of 10^{21} cm^{-3} corresponds to a temperature of 2 K

with density of 10^{16} cm^{-3} can quench radiation with $\tau = 1.6 \times10^{-6}$ s



Effect of Bimolecular Processes

Penning process

$He_2^* + He_2^* \rightarrow 3\,He + He^+ + e^-$

$\rightarrow 2\,He + He_2^+ + e^-$

$\rightarrow 3\,He + He^*$

$He_2^* + He^* \rightarrow 2\,He + He^+ + e^-$

exothermic; non radiative ; no restriction on type of excimer (or atom in excited state)
simply to 3 equations (prompt, delayed, triplet), neglect diffusion,
$dn_i/dt = -\alpha_i n_i^2 - \alpha_j n_j n_i - n_i/\tau_I$

for triplet excimers α measured to be 1.5 to 6 $\times 10^{-10}$ cm^3/s
Keto etal PhysRevA(1974);Eltsov etal JLTP(1998)

if $\alpha n > 1/\tau$ then have quenching
for $n = 10^{16}$ /cm^3, $\alpha n > 10^6$ /s; quenching of signal with $\tau = 1.6\times10^{-6}$ s

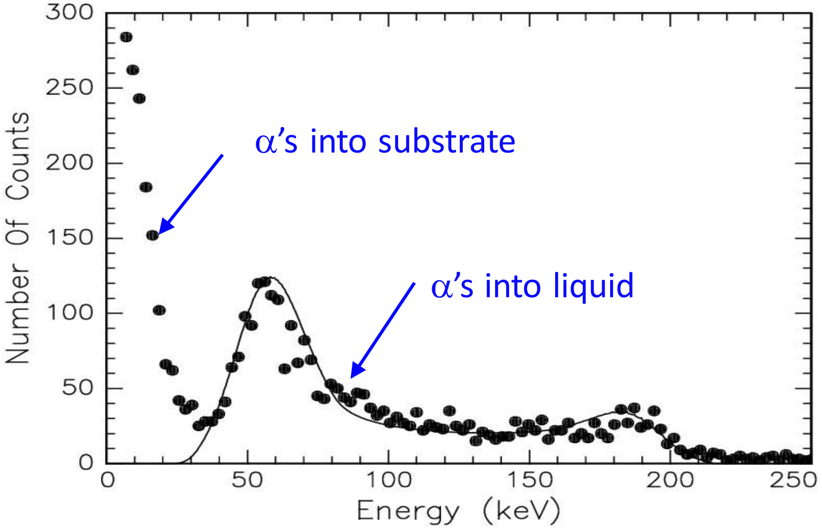
Summary

a two phase-detector will require high drift fields in the liquid to observe electrons with energy recoils in the keV range

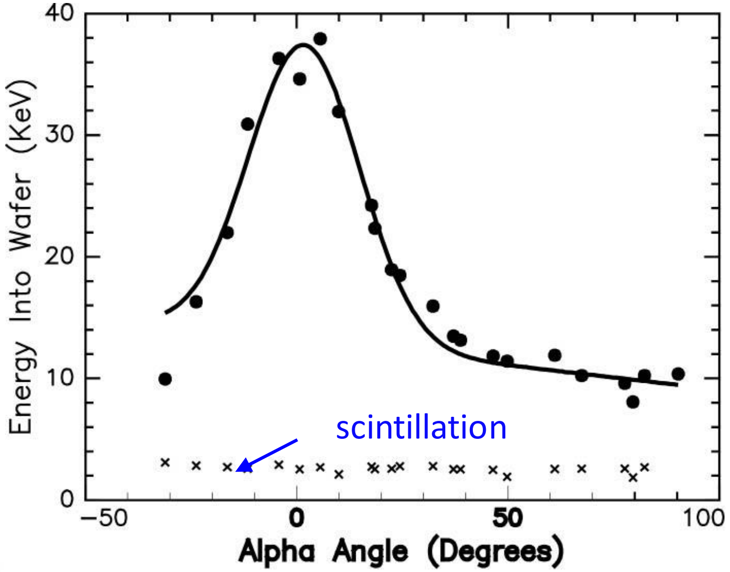
although much is known about the energy deposition of nuclear and electron recoils in helium, present knowledge is insufficient to predict the viability of pulse shape discrimination

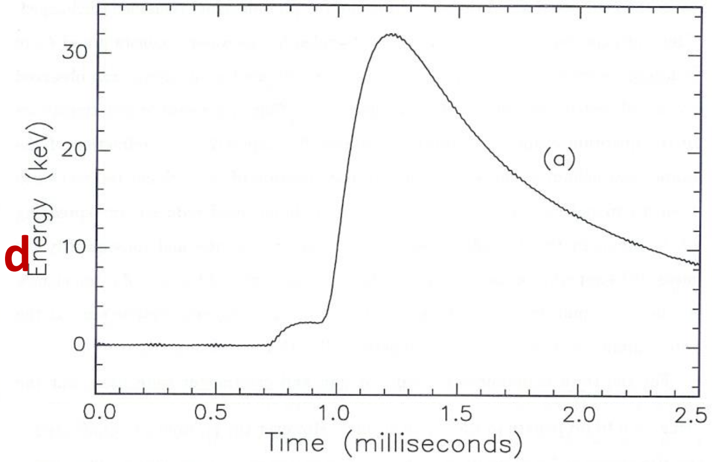
Directionality in QP channel (an aside)

uncollimated ^{241}Am source evaporated on SS substrate



angular dependence with *collimated* source





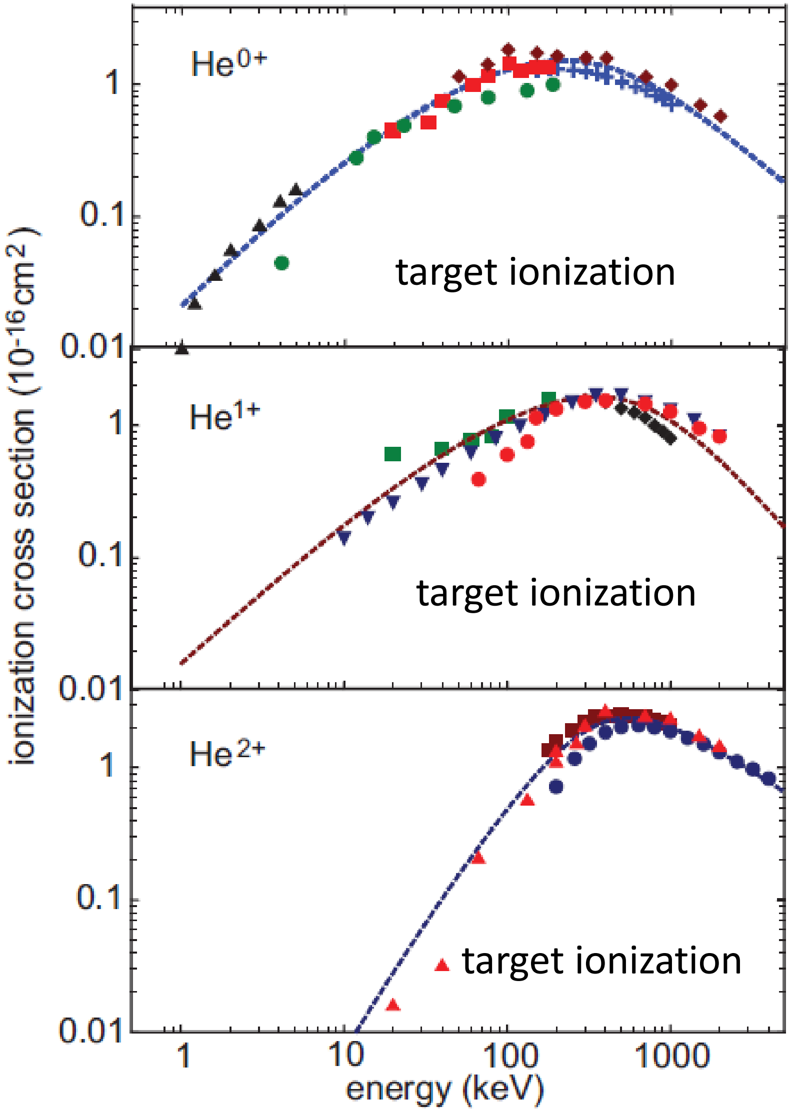
hot rod model

- along a nuckear recoil track the density of rotons is very high and they undergo scattering
- the qps preferentially escape the dense cloud perpendicular to the track direction and propagate ballistically into the surrounding liquid
- track directionality

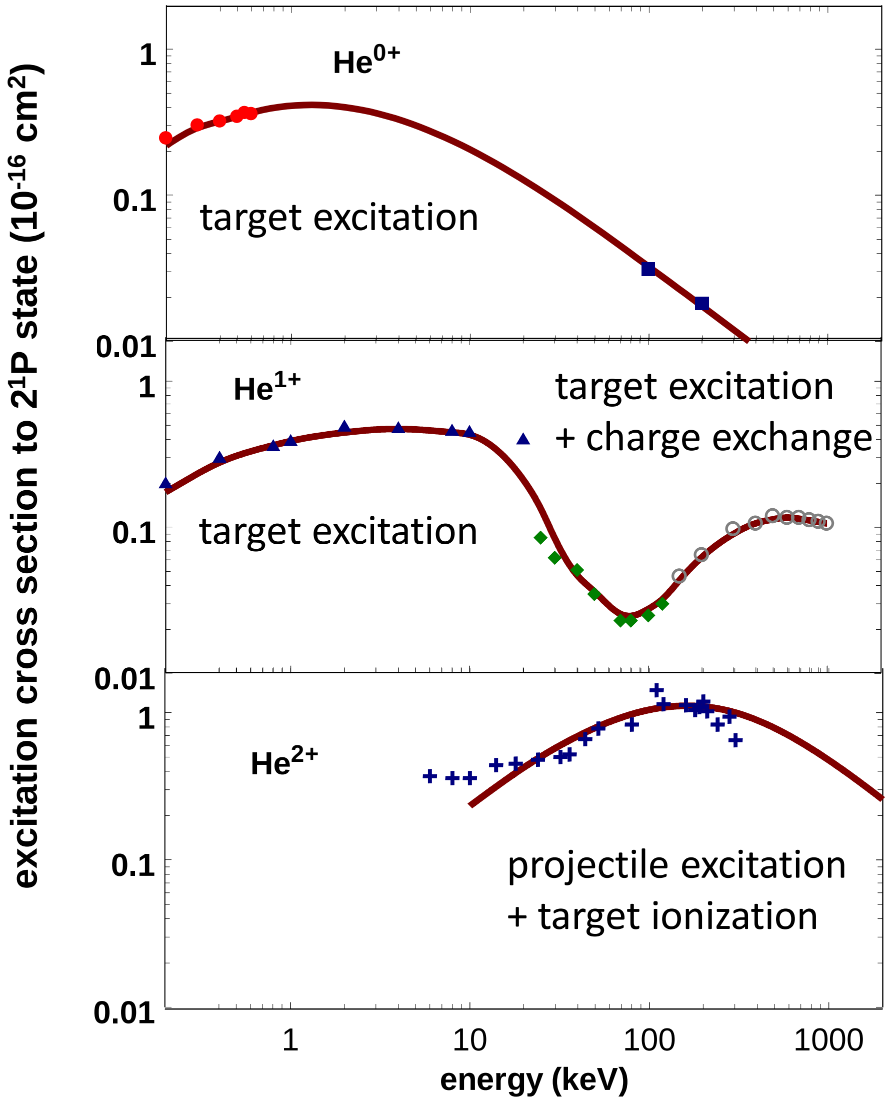
2^3S	19.82 eV
2^1S	20.62
2^3P	20.96
2^1P	21.22

back up

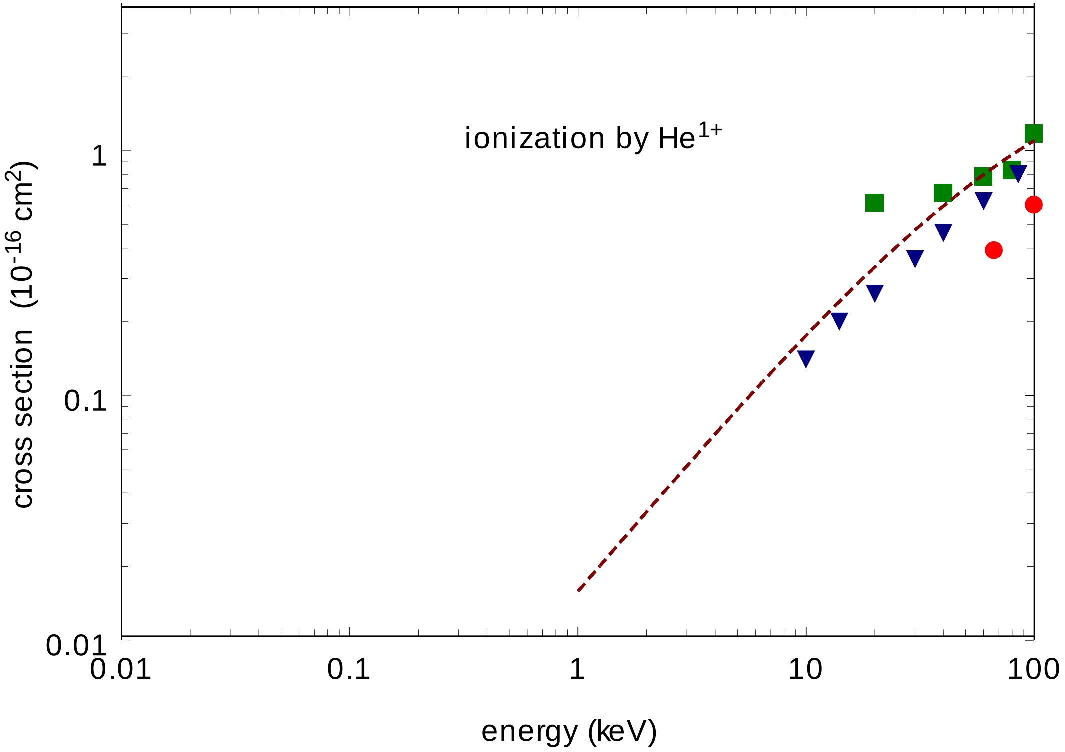
ionization cross section

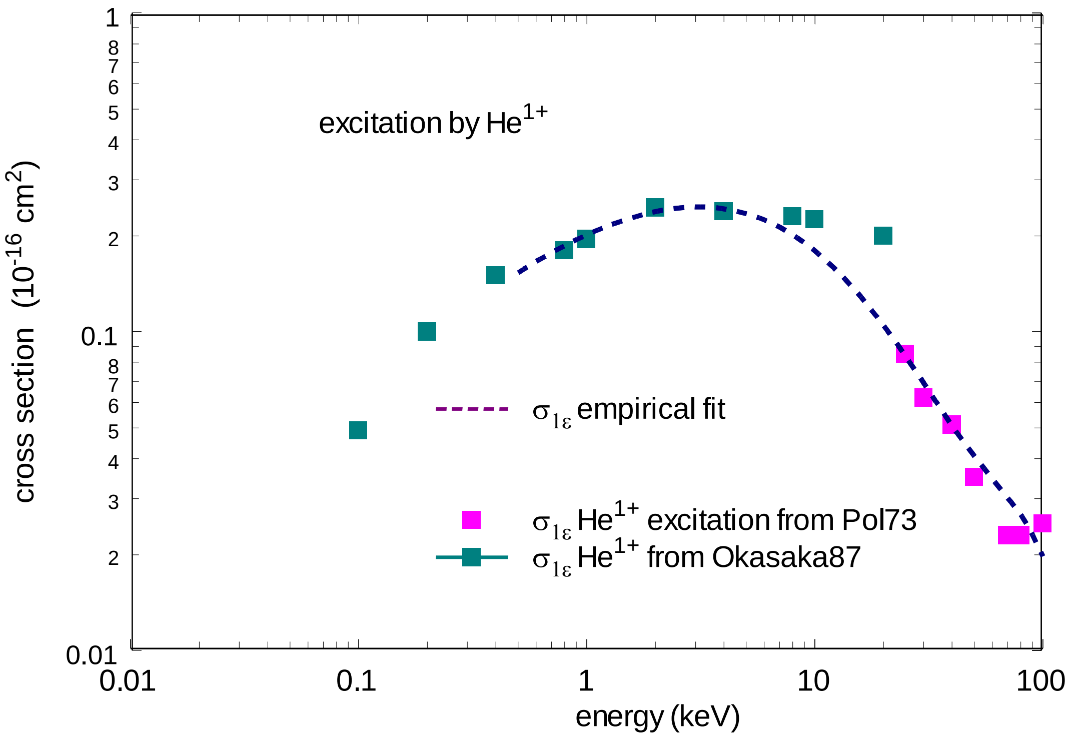


excitation cross section



Cross Section for He^{+1}





Particle Density Electron Scattering