ELECTRONS IN LIQUID HELIUM

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1. Electron bubbles
2. Exotic ions
3. Future research opportunities in area

ELECTRONS IN HELIUM

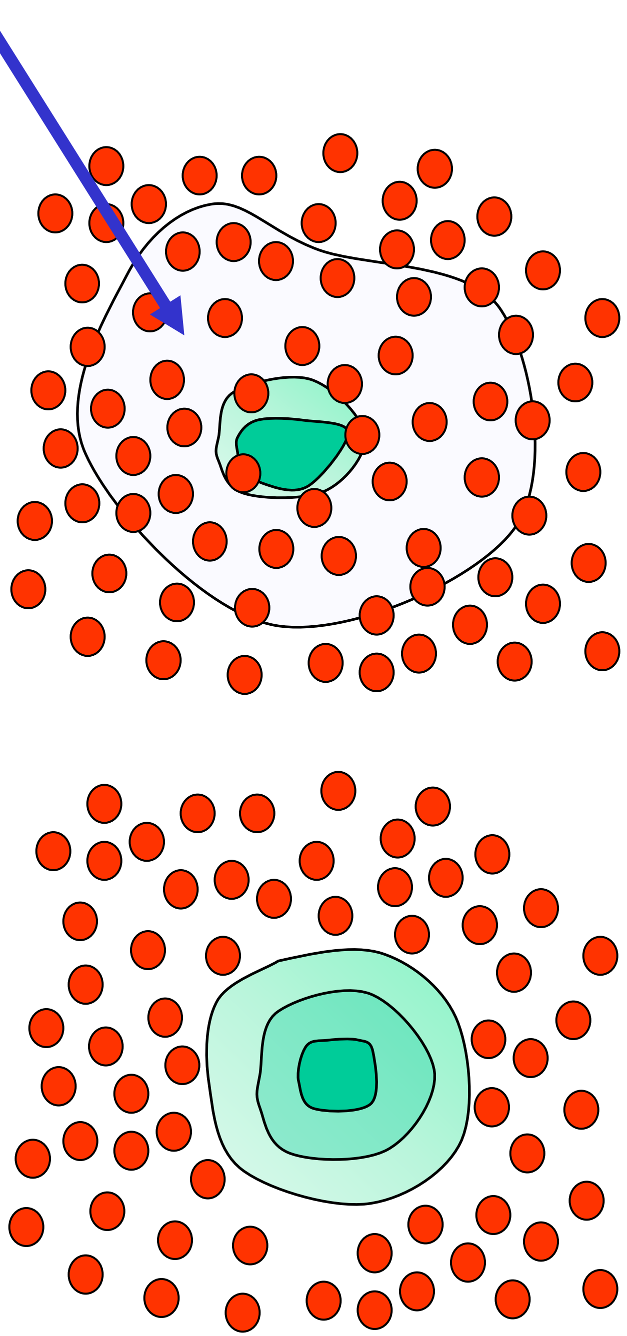
Send an electron into liquid helium from a radioactive source, a sharp tip, etc.

-- helium has a negative work function (-1 eV), unlike a metal

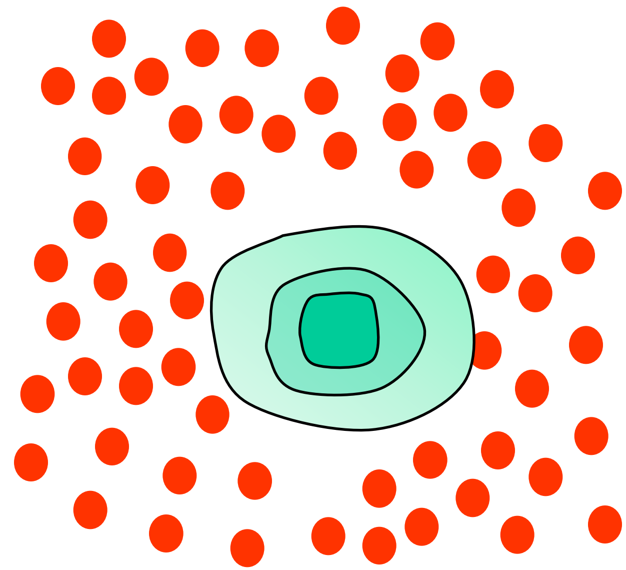
-- the electron is repelled by helium atoms

-- helium is very soft, about 12,000 times weaker than silicon

--electron forces open a cavity free of helium atoms



ELECTRONS IN HELIUM



Zero-point energy — Surface energy — Volume energy

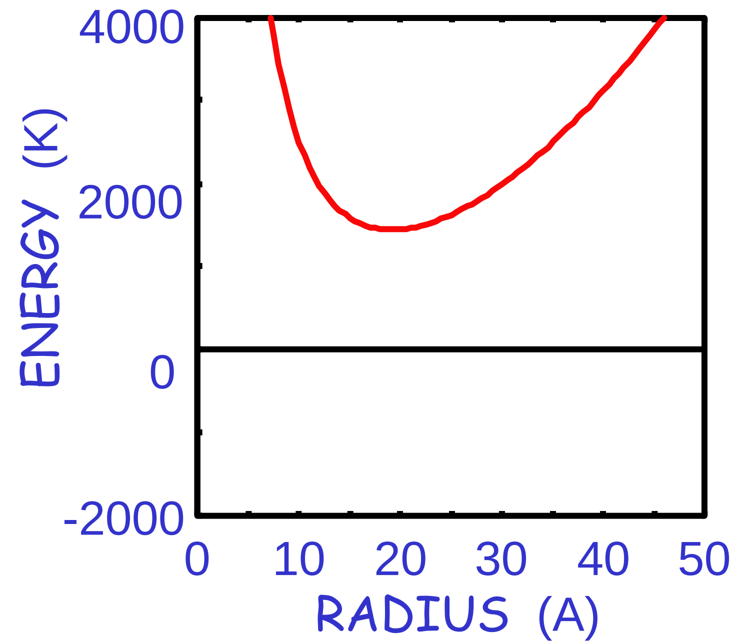
$$E_{\text{bubble}} = \frac{h^2}{8mR^2} + 4\pi R^2 \alpha + \frac{4\pi}{3} R^3 P$$

α = surface tension

P = pressure

Equilibrium radius of

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



ELECTRONS IN HELIUM

Bubbles are normally too small to detect

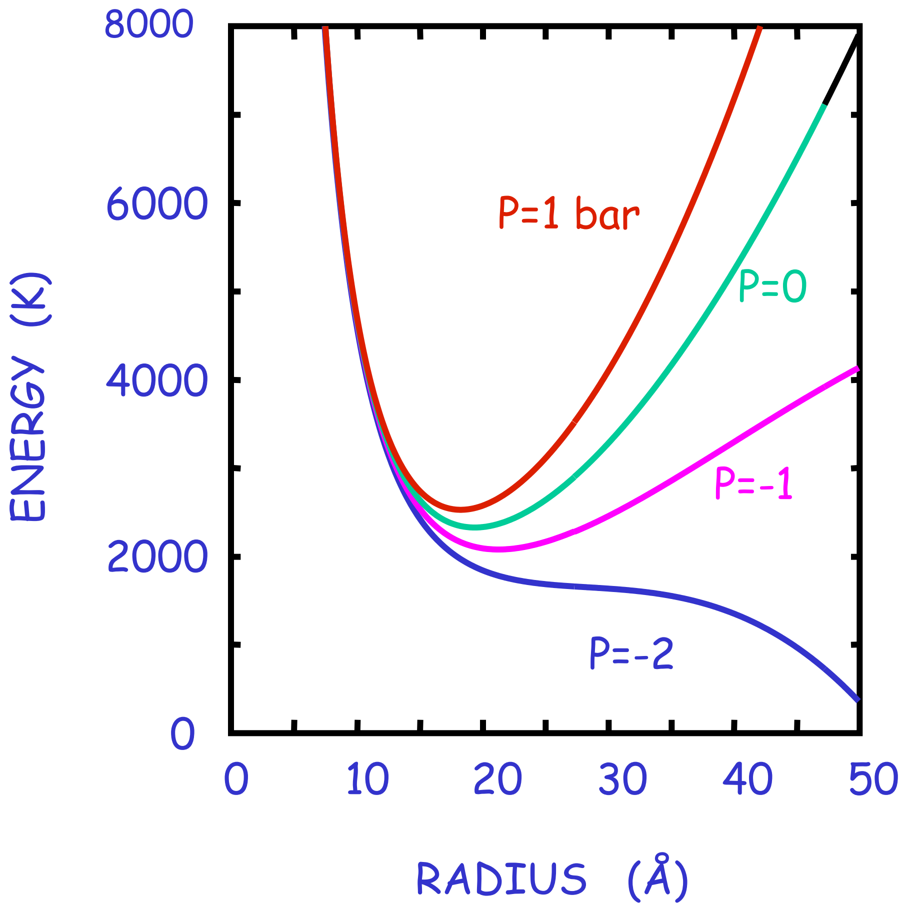
Light scattering from hole in helium gives cross-section ~10^{-23} cm^2

Scattering from electron is ~ 10^{-19} cm^2

But we can apply a negative pressure to explode the bubble.

Critical pressure of -1.9 bars.

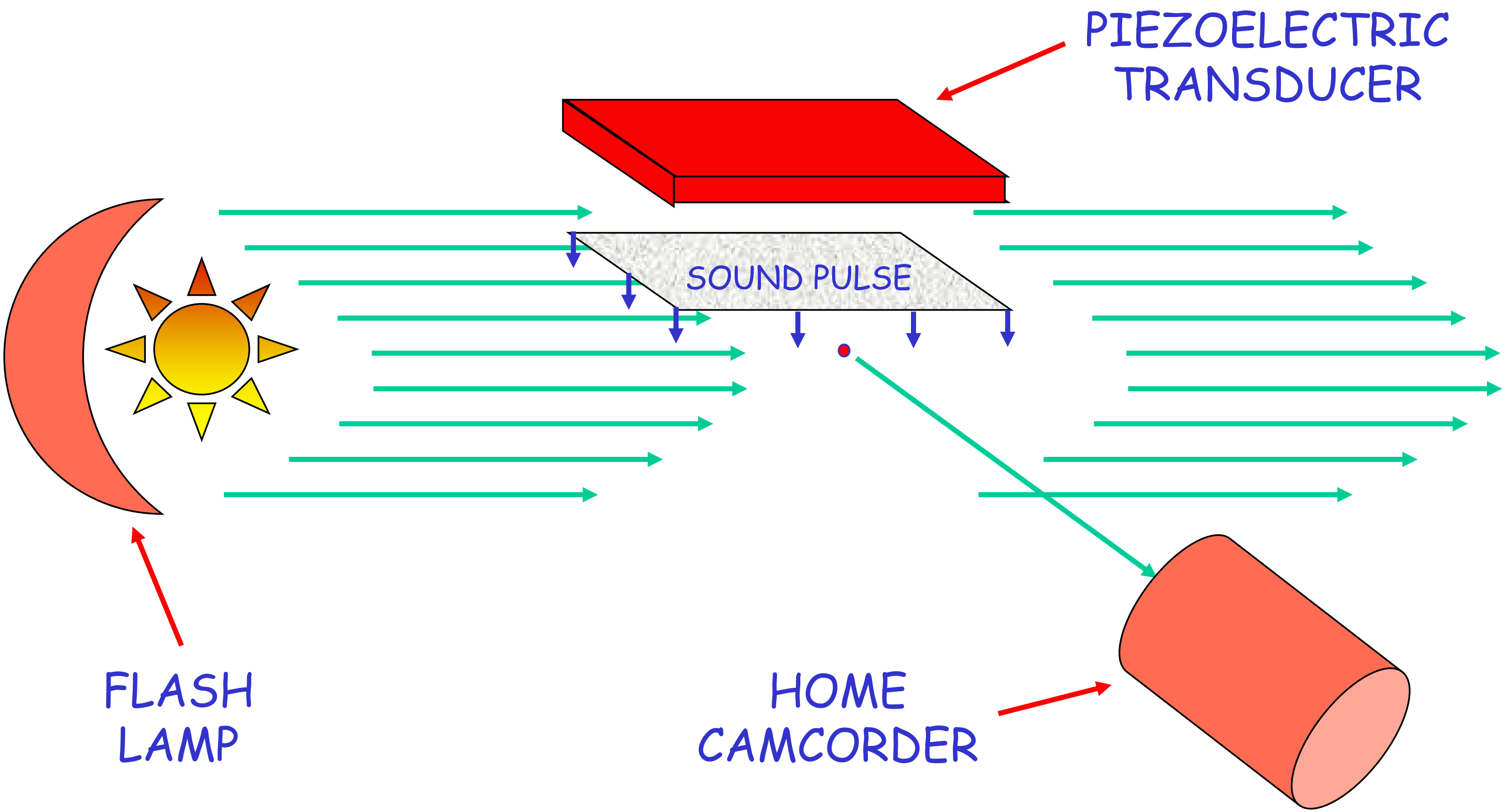
Bubble grows rapidly and there is a large scattering of light from the hole in the helium.



ELECTRONS IN HELIUM

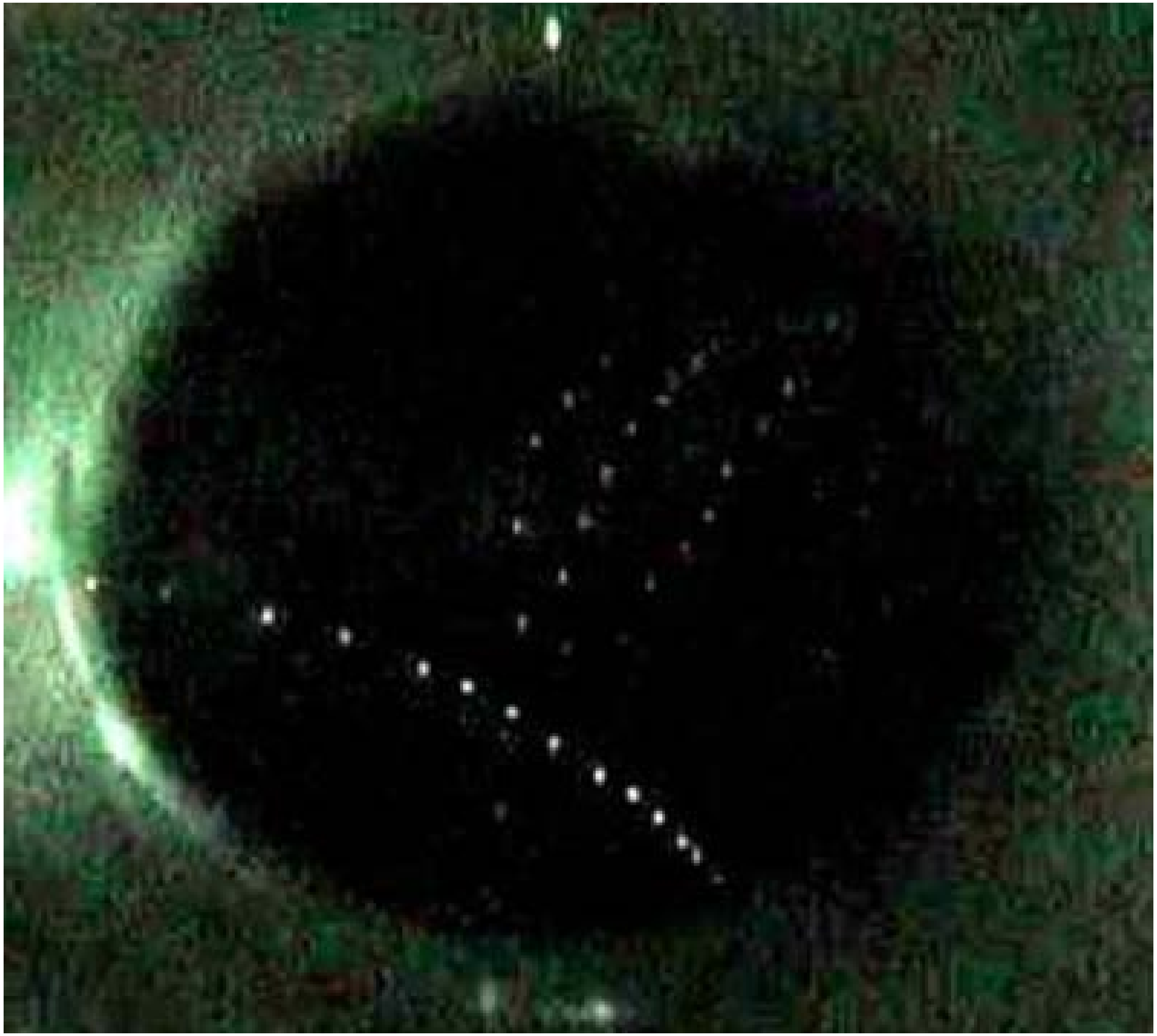
To make a movie one needs to explode an electron no matter where it is

--illuminate electron each time it explodes



ELECTRONS IN HELIUM

Four electrons moving under influence of flow of the normal fluid and an applied electric field.



ELECTRONS IN HELIUM

Some electrons become attached to quantized vortices in the liquid and slide along them

ELECTRONS IN HELIUM

Bubble mobility measurements

-- apply an electric field and measure the velocity

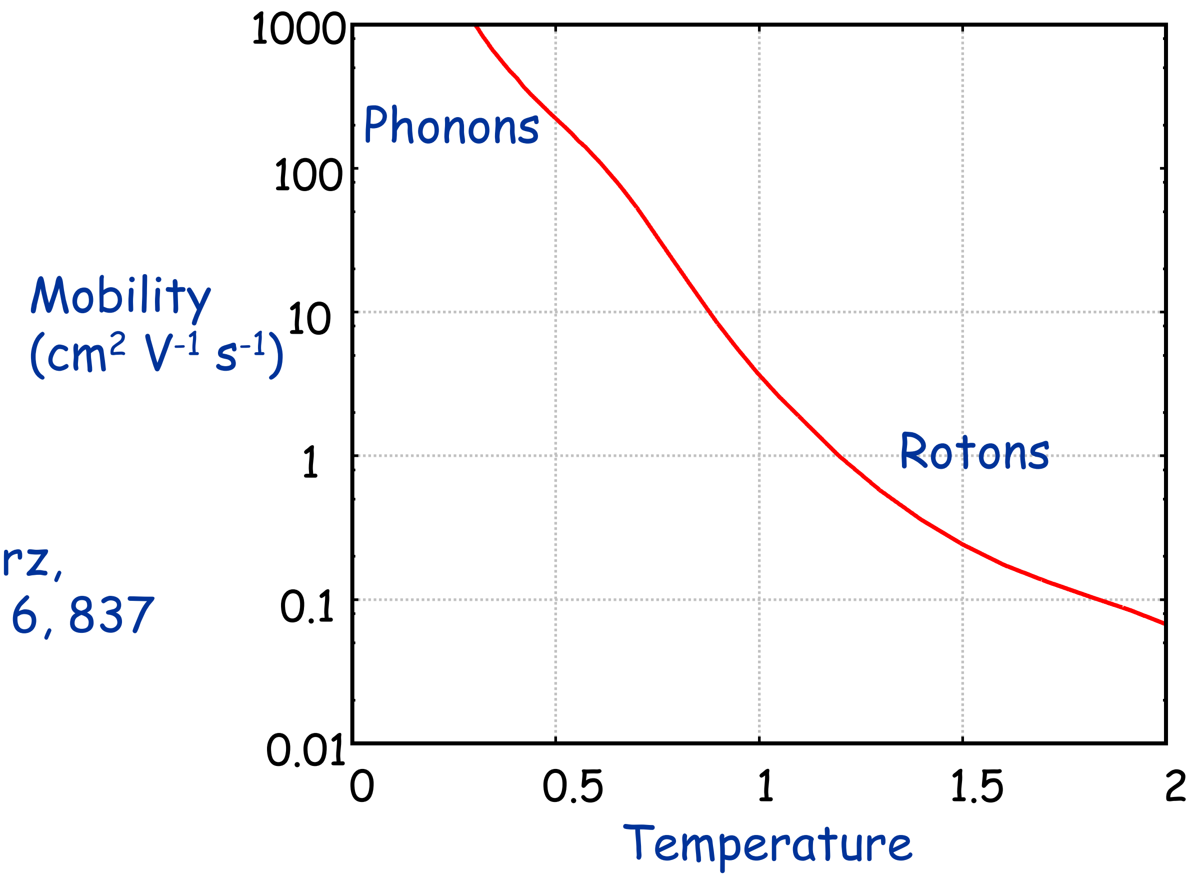
$$eE = \text{drag force}$$

-- drag force due to collisions with phonons and rotons (mostly rotons)

-- drag force proportional to bubble velocity and bubble radius squared

$$eE \propto v\, n_{rotons}\, R^2$$

$$\mu = \frac{v}{E} \propto \frac{1}{n_{rotons} R^2}$$



K.W. Schwarz, Phys. Rev A 6, 837 (1972)

EXOTIC IONS

Discovery of a fast ion by Doake and Gribbon, Phys. Lett. 30A, 251 (1969); Doake thesis (1972).

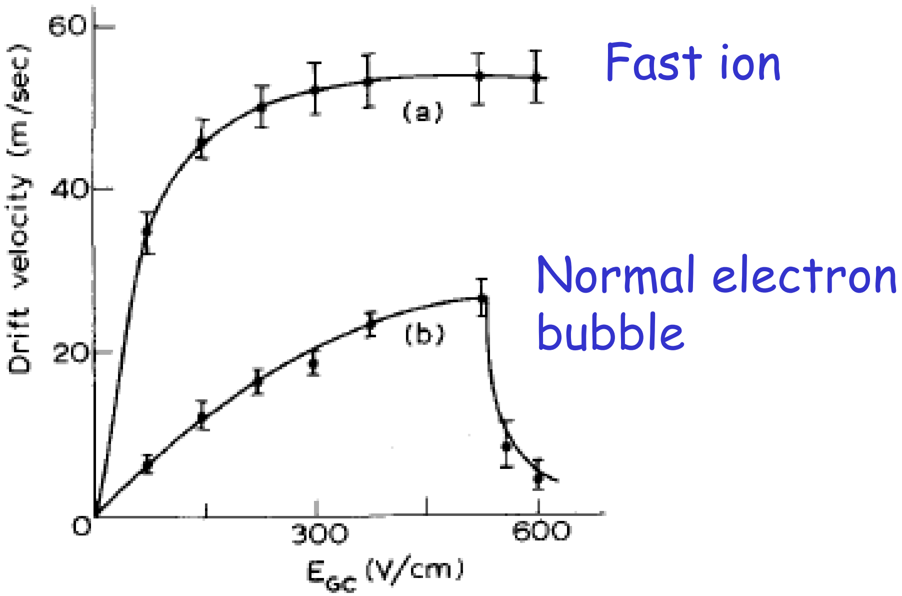
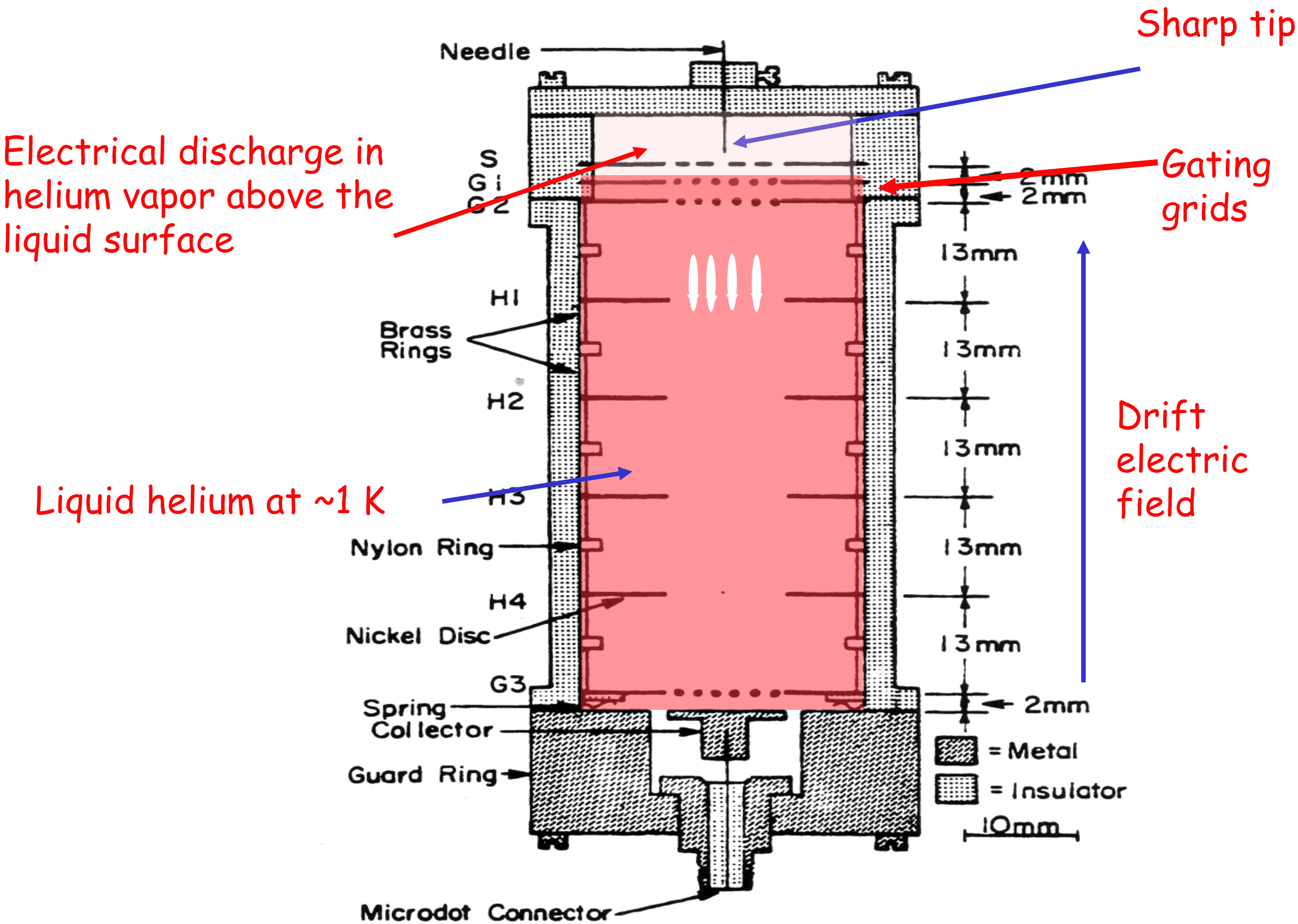


Fig. 1. Ion drift velocity in m/sec versus electric field E_{GC} in V/cm curves for $T = 0.92\,^{\circ}K$. Curve (a), fast ion current; (b) normal ions, forming Reif vortex rings.

-- mobility about 6 times larger than normal bubble
-- indicates radius of around 8 Å
-- what is this?

EXOTIC IONS

Discovery of 12 exotic ions by Ihas and Sanders, PRL 27, 383 (1971), Ihas thesis 1972.



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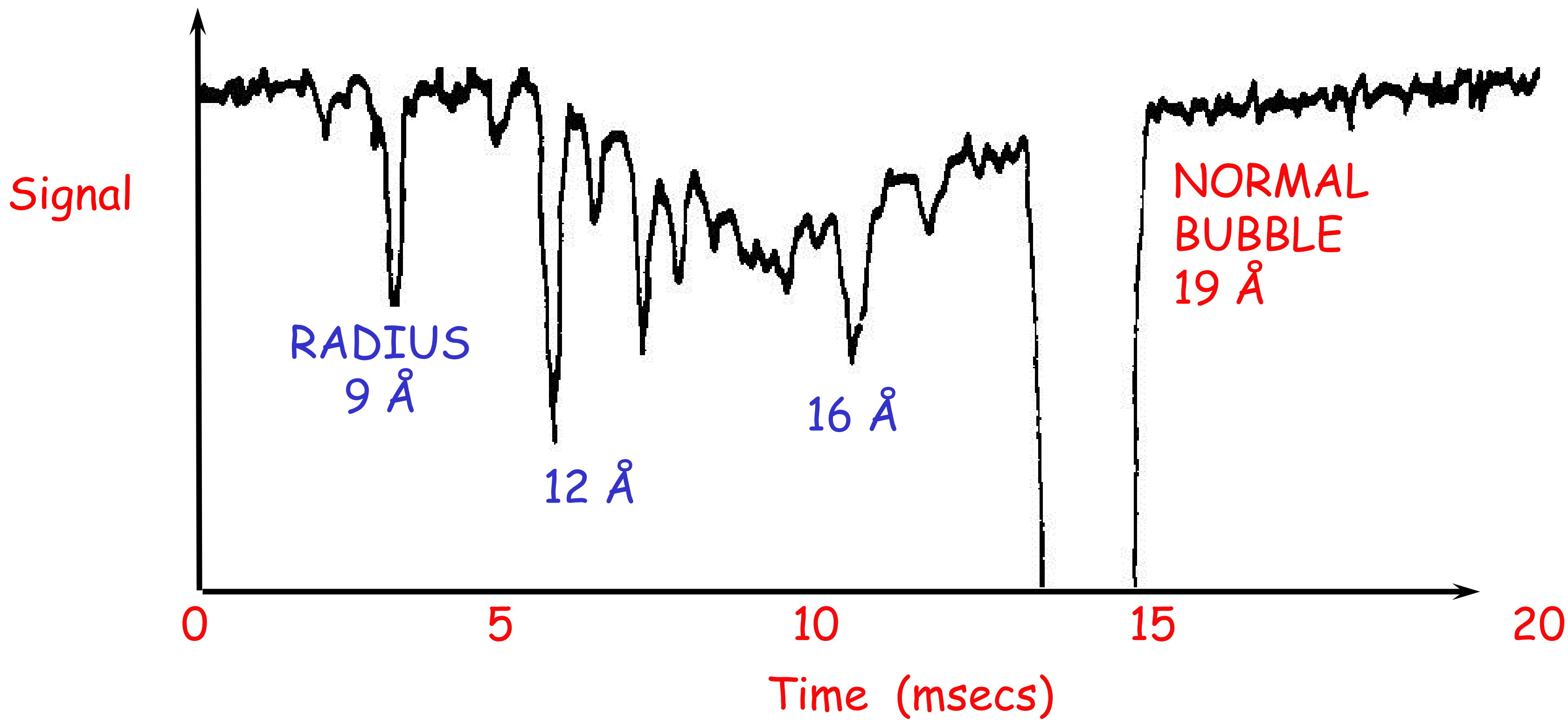
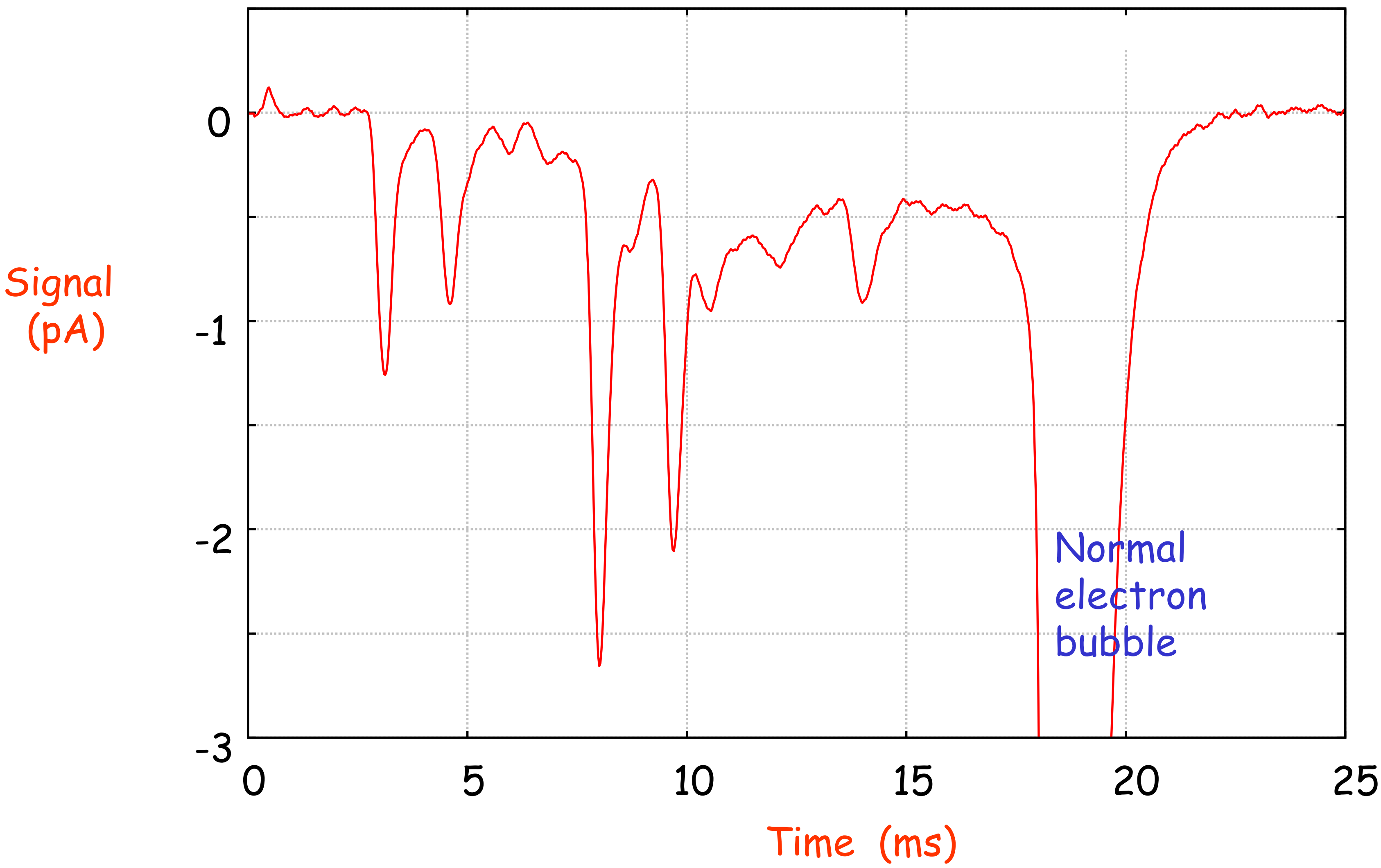


Also studied by Eden + McClintock Phys. Lett. 102A, 197 (1984), V. Eden, thesis 1986, Williams, Hendry, McClintock LT18 conference (1987).

EXOTIC IONS

New measurements with improved sensitivity and stability. W.Wei, Z. Xie, L.N. Cooper, G.M. Seidel, H.J. Maris, JLTP 178, 78 (2015).

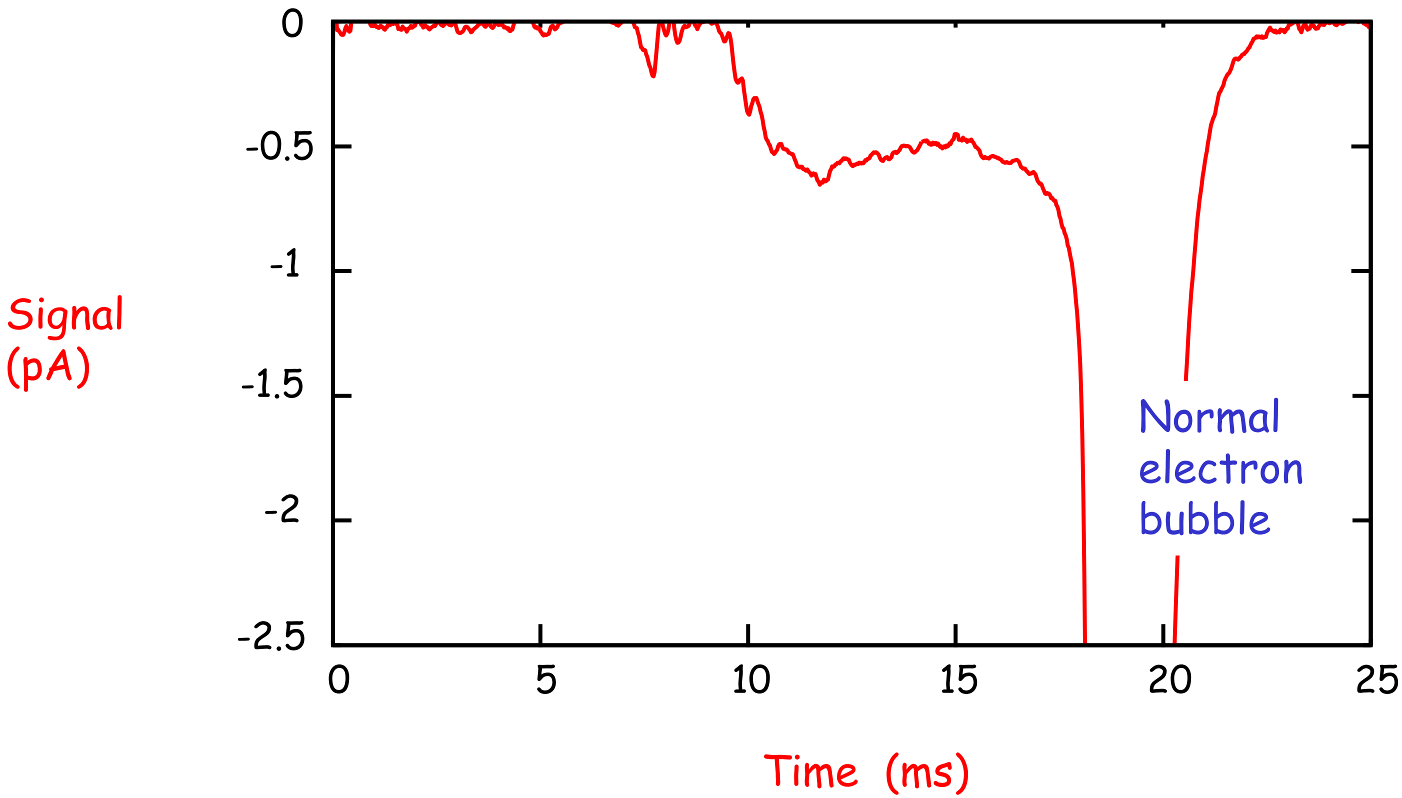


EXOTIC IONS

KEY RESULTS

1) There are at least 18 ions with different mobility
-- these include the ions seen previously by Ihas and Sanders.
-- estimated radius varies from ~ 8 Å to 16 Å.

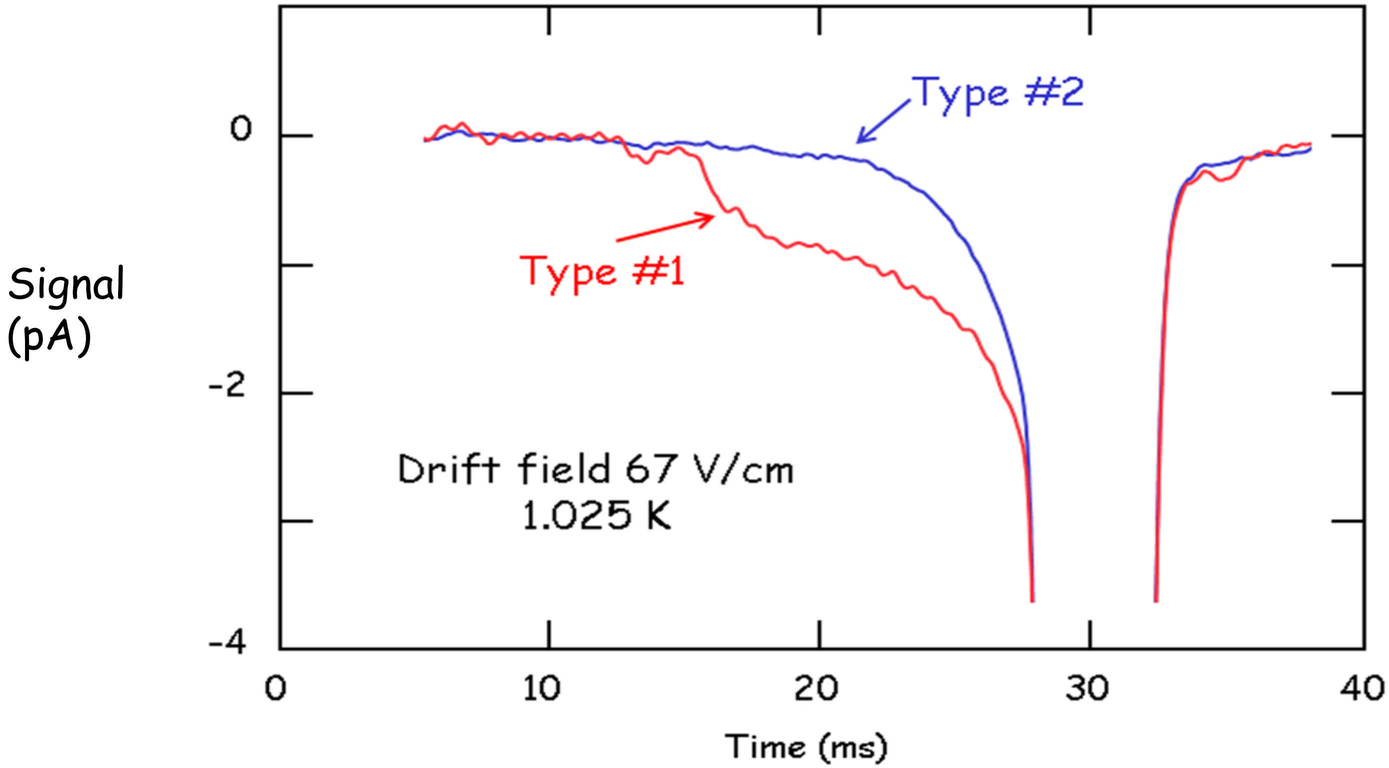
2) There is a continuous background signal revealed when peaks are removed



EXOTIC IONS

3) The continuous background comes from negative ions with a continuous mobility distribution and therefore a continuous size distribution !!

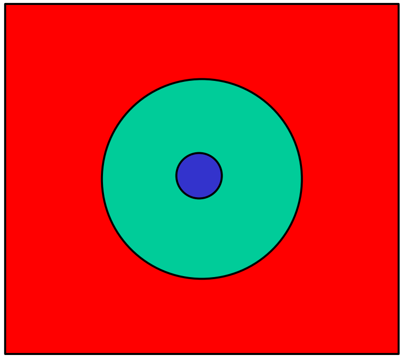
4) Continuous background has two forms #1 and #2.
-- sudden switch between forms #1 and #2 when plasma conditions are changed
-- background can appear even when no peaks are present



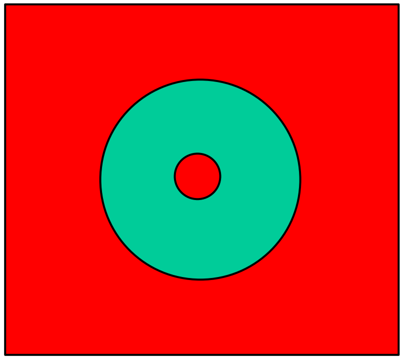
EXOTIC IONS

Possible explanations

A) Impurities with weakly bound electron
-- very few in superfluid helium
-- 18 different impurities ?? !!
-- cannot explain continuous background



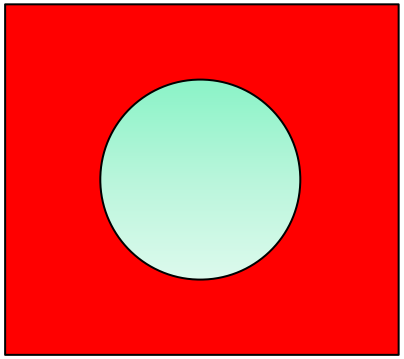
B) Helium negative ions
-- there are two known ions but both have very short lifetimes
-- cannot explain continuous background
-- cannot explain 18 objects



C) "Fission"
-- the exotic ions are bubbles each containing only a fraction of the wave function

$$\int |\psi|^2 \, dV < 1$$

-- and so these bubbles would be smaller and move faster.



EXOTIC IONS

Can fission explain?

A) About 18 ions with discrete mobility

B) Background type #1

C) Background type #2.

Current situation:

A) A qualitative explanation – predicts 21

B) Not explained yet, but a continuous distribution is possible

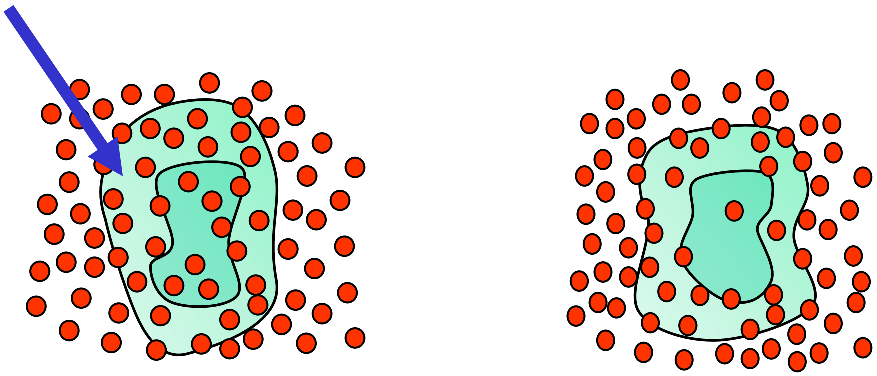
C) A quantitative explanation !

EXOTIC IONS: -- 18 DISCRETE

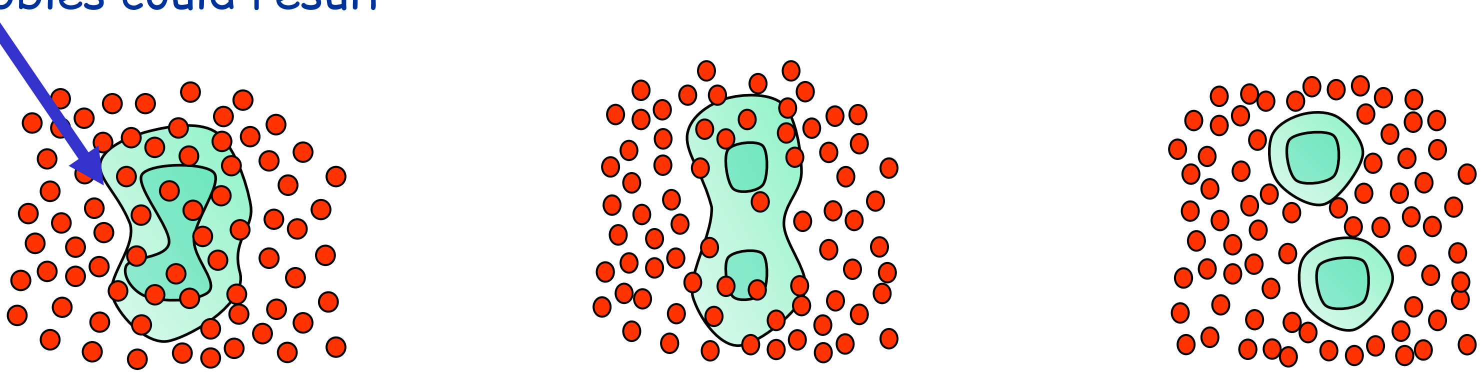
A) How can there be 18 ions with discrete mobility?

Consider how the electron wave function evolves after it enters into the liquid. As already noted:

If the wave function is spread over a small region it would collect to form one bubble

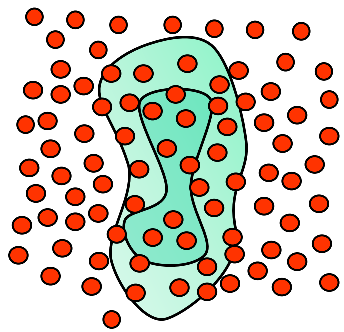


But if the wave function is spread over a large enough distance two bubbles could result

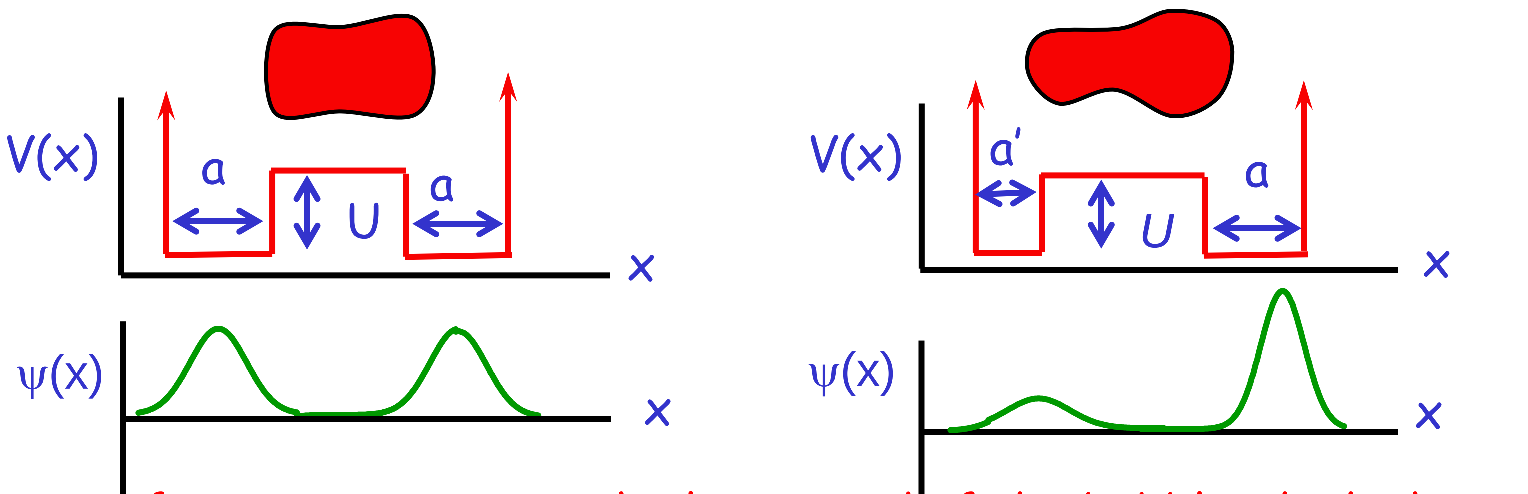


EXOTIC IONS: -- 18 DISCRETE

At first sight it would seem that this would give a continuous distribution of F, bubble size R, and mobility μ.
Not so simple! Suppose first that the initial situation looks like



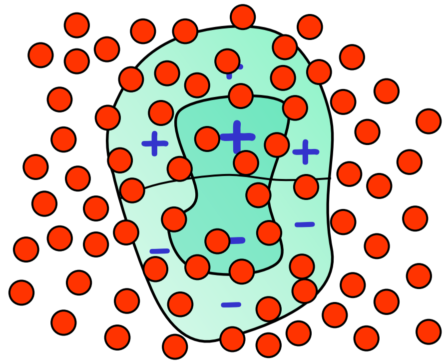
Model a splitting bubble by two wells with the wave function in the ground state.



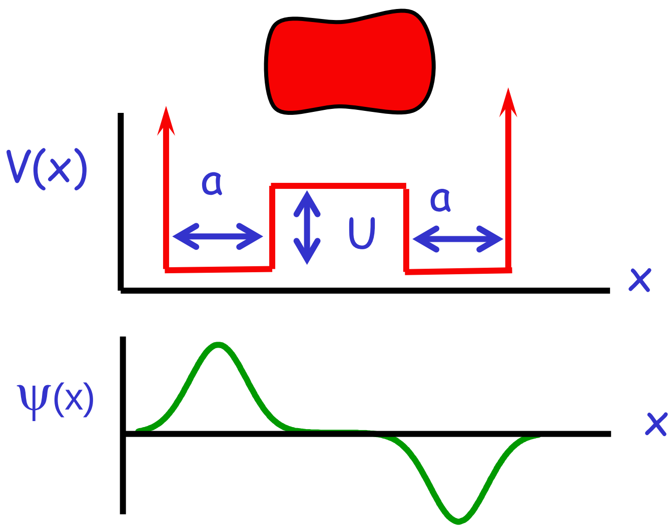
The wave function moves into the larger end of the bubble which then gets bigger. The smaller end eventually disappears leaving one bubble containing all of the wave function.

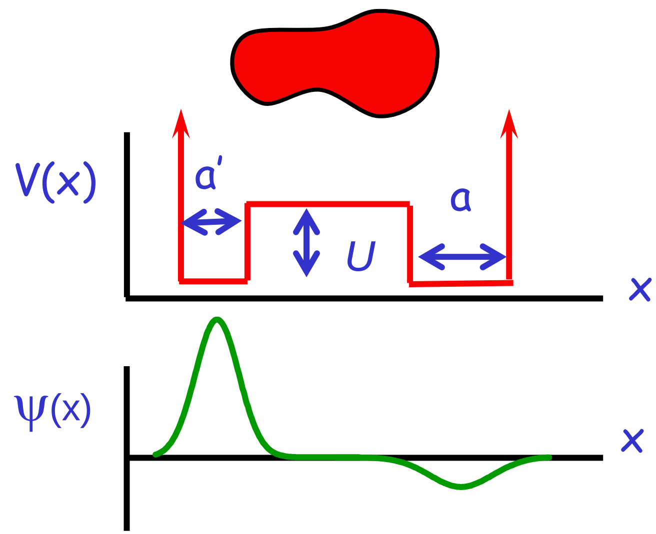
EXOTIC IONS: -- 18 DISCRETE

But now suppose the wave function is the first excited state



Then





The wave function flows into the smaller end making it expand and driving the system back to an equal division.

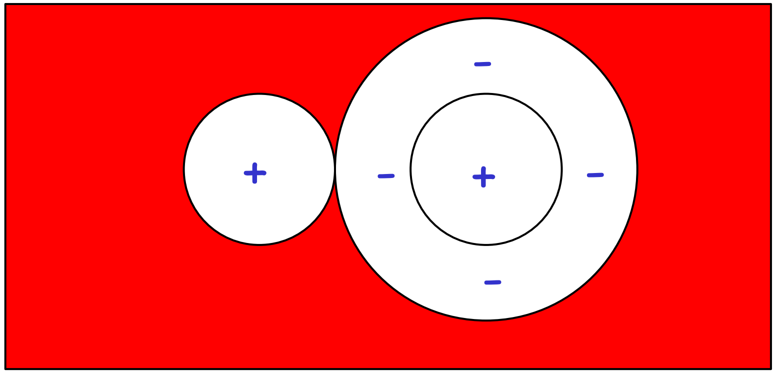
EXOTIC IONS: -- 18 DISCRETE

<u>More general result</u> Bubbles are driven so that at the moment of breakup:

a) each part is in mechanical equilibrium with the electron pressure balancing the surface tension

b) the eigenvalue of the energy is the same in each bubble

This gives 21 different sizes!!



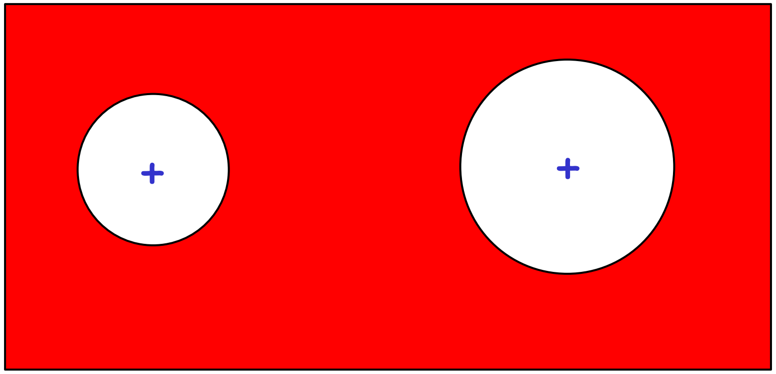
Example: 1S + 2S

At separation

$$F_1 = 1/5 \qquad F_1 = 4/5 \qquad R_2 = 2R_1$$

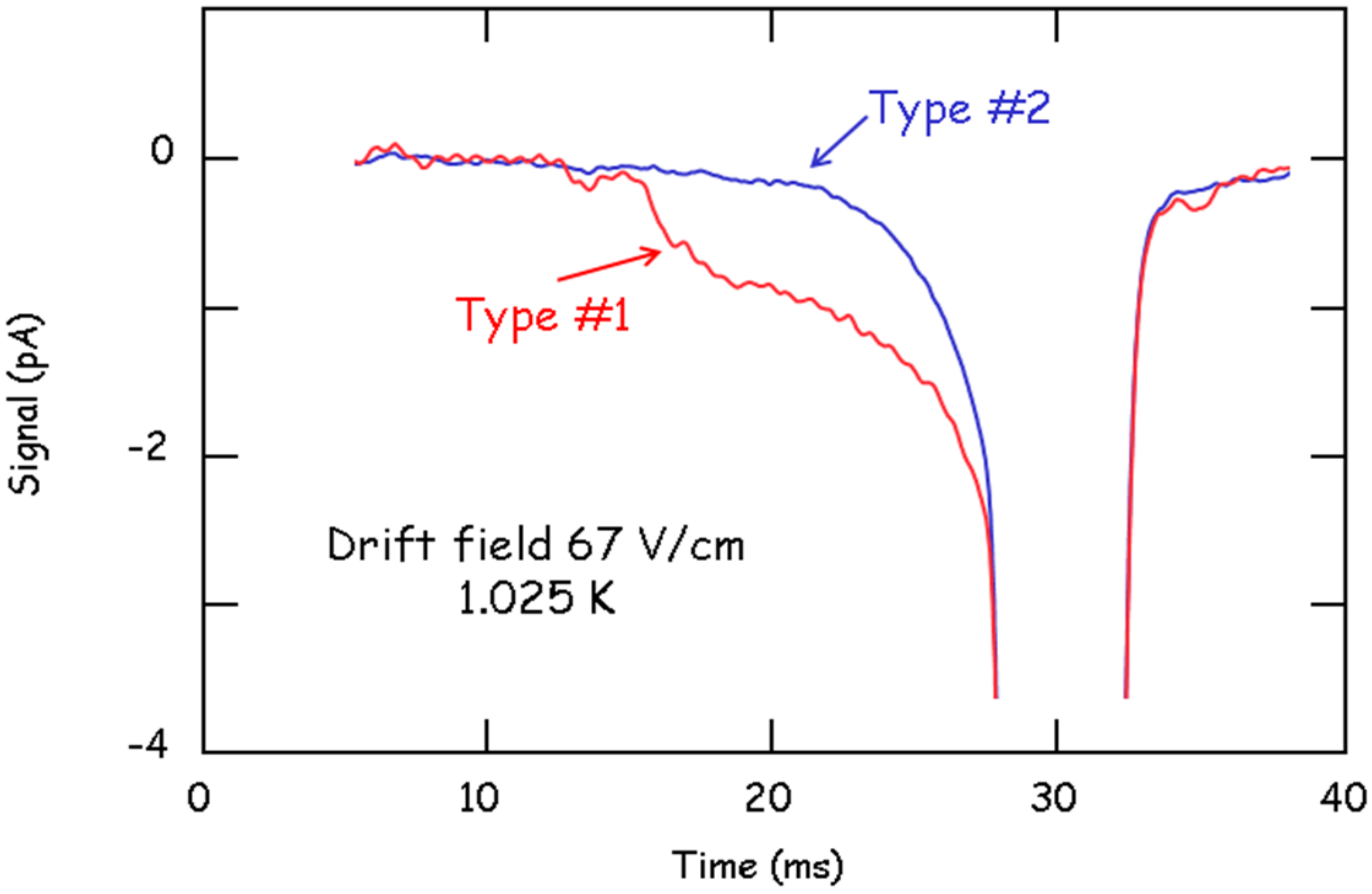
After 2S bubble relaxes to 1S the bubble radii are

$$\left(\frac{1}{5}\right)^{1/4} R_{NEB} \text{ and } \left(\frac{4}{5}\right)^{1/4} R_{NEB}$$



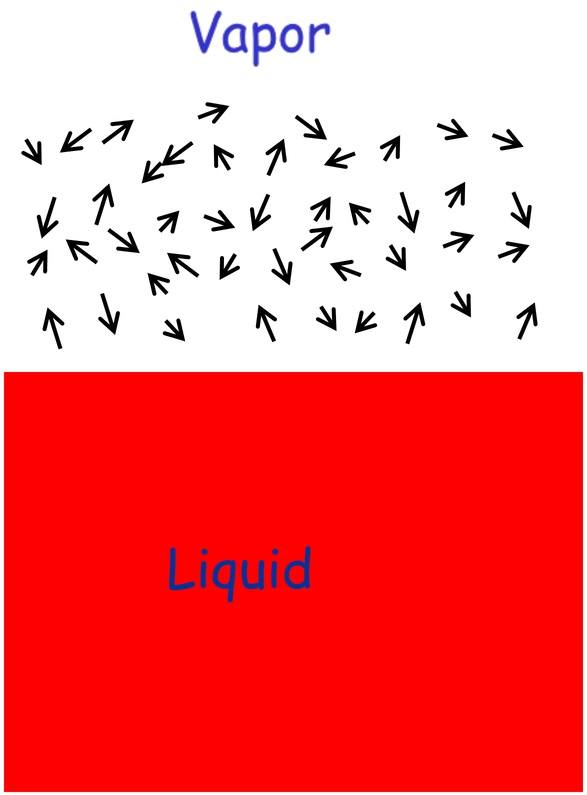
EXOTIC IONS: BACKGROUND #2

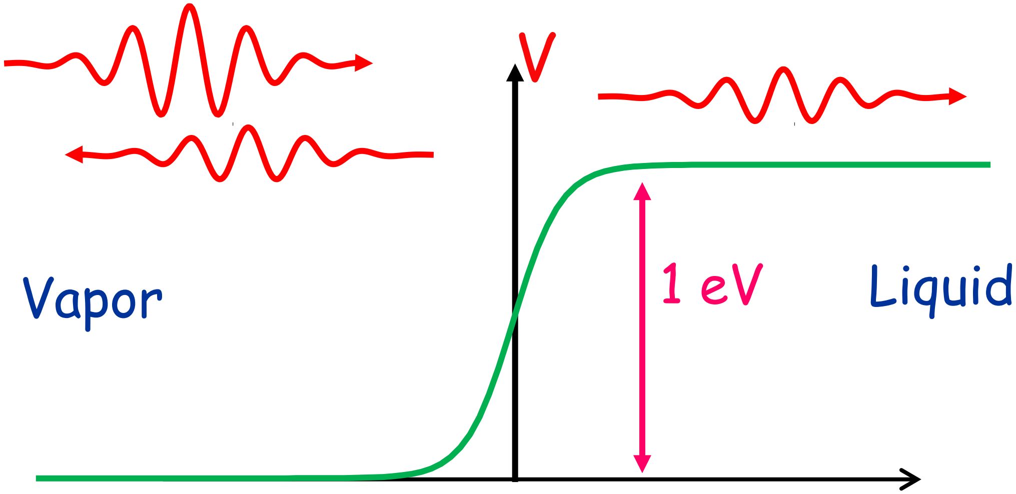
C) Explanation of background type #2.



EXOTIC IONS - BACKGROUND #2

Plasma above the liquid contains electrons with a continuous distribution of energies
-- the wave functions of electrons with energy above the barrier will be only partially transmitted
-- these will produce bubbles with a distribution of size and therefore a distribution of mobility





EXOTIC IONS - BACKGROUND #2

Electron energy distribution in plasma is

$$n(\varepsilon)\,\delta\varepsilon = \frac{2n_e}{\Gamma(3/4)}\frac{\varepsilon^{1/2}}{\varepsilon_0^{3/2}}\exp\left(-\varepsilon^2/\varepsilon_0^2\right)\,\delta\varepsilon$$

with

$$\varepsilon_0 = \Lambda eE\sqrt{\frac{M}{3m}}$$

Experimental density profile of liquid near the surface is well described by

$$V(z) = \frac{\phi}{1+\exp(-z/a)}$$

with $\phi = 1\ \mathrm{eV}$ and $a = 1.59$ Å.

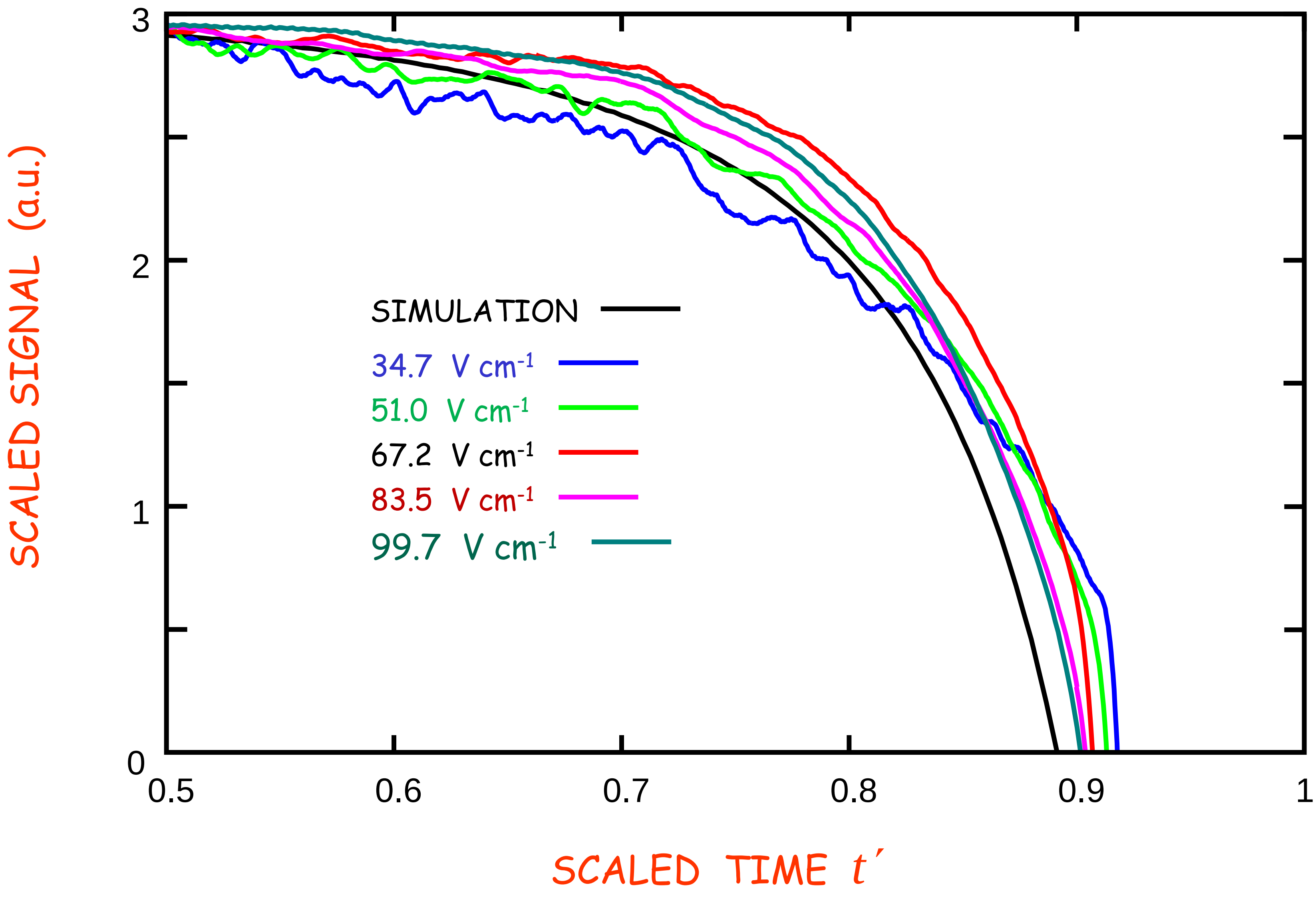
Transmission coefficient is

$$T = 1 - \frac{\sinh^2\left[\pi\left(k_z - k_z'\right)a\right]}{\sinh^2\left[\pi\left(k_z + k_z'\right)a\right]}$$

Only uncertain parameter is the field E at the surface
-- this is fixed by the magnitude of the background compared to the normal electron peak

EXOTIC IONS – BACKGROUND #2

Fix field E to get right ratio of background to normal electron bubble signal.



FUTURE DIRECTIONS

Current experiments

Would like to measure other properties of the exotic ions in addition to mobility

1) Mechanical properties of exotic ions
-- apply a negative pressure
-- measure critical pressure at which they explode explode?

2) Optical measurements
-- what photon energies are absorbed by exotic ions?
-- this would give information about their structure.
-- challenging but possible.

3) Are exotic ions completely stable?
-- experiments to set lower bound on the lifetime.

FUTURE DIRECTIONS

Experiments requiring collaborators

1) Can one create exotic ions in helium-3?
-- create discharge in plasma above liquid at ~ 0.5 K
-- need sufficient liquid helium-3 and cooling power.

2) Can one use mono-energetic electrons to test Cooper's above the barrier transmission idea?
-- requires electron source
-- requires long mean free path and low density in the vapor (temperature below 100 mK)

Going further

1) Can one detect exotic ions near the helium surface?
-- assuming they behave in a way similar to ordinary electron bubbles, they could be trapped above or below the surface.
-- can one measure the effective mass (Poitrenaud and Williams)?
-- what is the escape rate through the surface?
-- what is the mobility parallel to surface?

FUTURE DIRECTIONS

Imaging for outreach/education

1) More polished movies of electrons suitable for outreach/education.

2) Movies showing field emission of electrons from a sharp tip
-- one electron at a time.

3) Movies of helium rain and effects near the critical point.