On the possibility of positive ion detection in gaseous TPCs

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Motivation: accurate track reconstruction in rare-event searches

How accurate?

$$\sigma_{ions} = \sqrt{2Dt} = \sqrt{\frac{2k_BT}{q_e} \cdot \frac{L}{E}} = 0.225\sqrt{\frac{L}{E}} \quad (\sigma \,\&\, L \; in \; cm, E \; in \frac{V}{cm})$$

E.g. 10 bar Xe, E = 300 V/cm

$$\sigma_{ions} = \begin{cases} 1.3\;mm & L = 1\;m \\ 1.8\;mm & L = 2\;m \end{cases}$$

Electron diffusion under the same conditions:

$$\sigma_{electrons} \approx \begin{cases} 13\;mm & L = 1\;m \\ 18\;mm & L = 2\;m \end{cases}$$

Problem: ions are slow

Drift velocity of $\mathcal{O}(10^2)$ cm/s, thermal kinetic energies

↓

Detection must rely on a **potential-driven** process

Luckily, Nature provided us with Auger neutralization (AN)

What is AN?

- When a positive ion approaches a surface a first electron tunnels out and neutralizes it, leaving the system with excess energy
- This energy is simultaneously transferred, in an Auger-like process, to a second electron which may be emitted into the gas

Historical context

- First suggested by S. S. Shekhter in 1937
- Experimental and theoretical foundations laid by H. D. Hagstrum (Bell Labs) in 1953-1961: studied AN for single ions of all noble gases, impinging on metals (W, Mo) and semiconductors (Si, Ge)
- Was of central importance to the development of plasma panel displays
- Still an active field in surface science theory

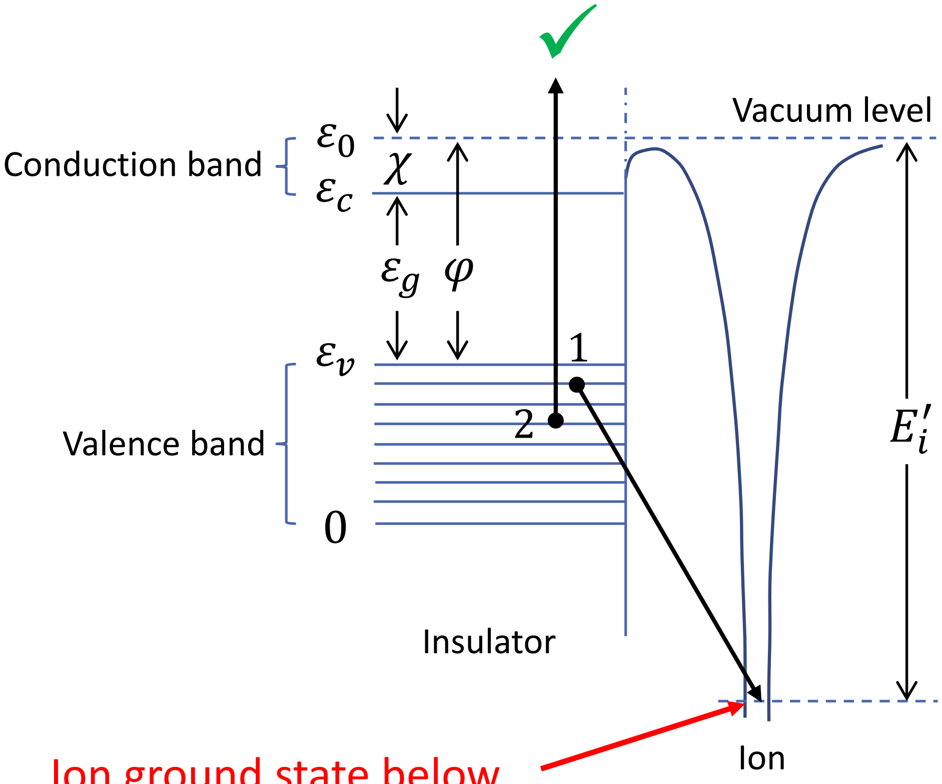
Key features of AN

- Driven by potential energy → ok for thermal ions
- Occurs for both atomic and molecular ions
- Occurs for metals and insulators/semiconductors
- Necessary condition: the ionization energy of the ion close to the surface must be larger than twice the work function: $E_i' > 2\varphi$
- γ_i : secondary electron yield = probability of ion-induced secondary electron emission (IISEE)
- γ_i generally increases with increasing E_i' and decreasing φ. Can be as large as tens of %

Other mechanisms?

- In some cases AN is the *only* possible mechanism for charge transfer (e.g., He^+ on metals and semiconductors). This requires that the ion ground and excited states are not resonant with occupied states in the solid.
- When resonant processes are possible secondary electron emission can still occur, but with lower probabilities. The condition $E_i' > 2\varphi$ still holds.

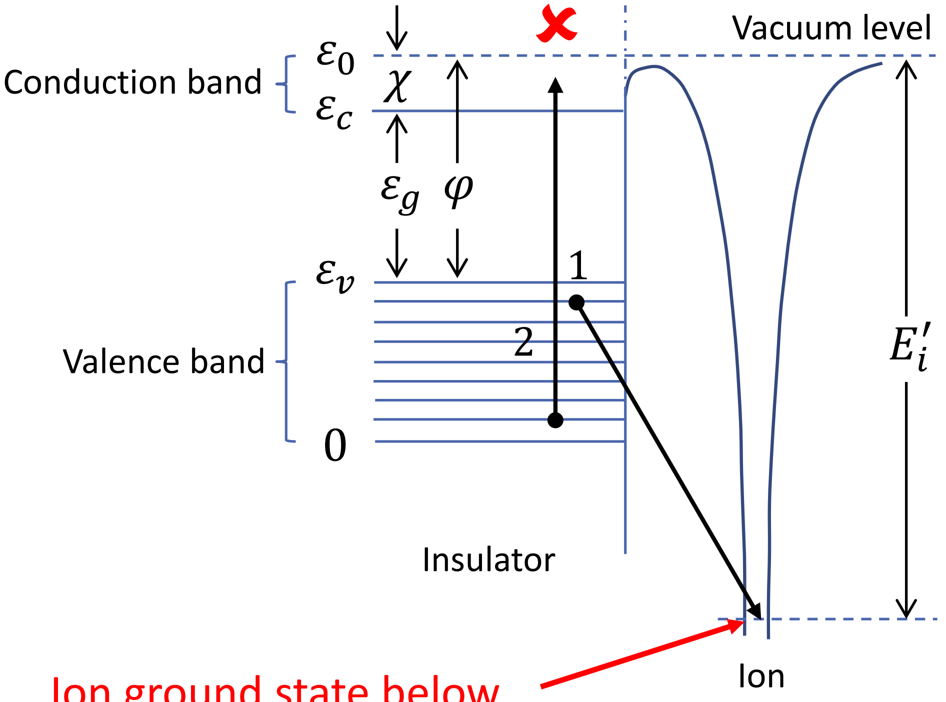
Auger neutralization – external emission



Ion ground state below bottom of valence band

- Energy lost by electron 1 is taken by electron 2
- If sufficiently large and electron 2 starts from the upper valence band it may be emitted externally

Auger neutralization – internal emission



Ion ground state below bottom of valence band

- If electron 2 starts from the lower valence band it may enter the conduction band without external emission

- Also useful?

S. Shchemelinin and A. Breskin, "Observation of electron excitation into silicon conduction band by slow-ion surface neutralization", arXiv:1607.02924

IISEE yields of noble gas ions

Target: atomically clean molybdenum, work function 4.3 eV

ion	$E_i[eV]$	$E_i - 2\varphi[eV]$	$\gamma_i[\%]$
He^+	24.59	16.0	30
Ne^+	21.56	13.0	25.4
Ar^+	15.76	7.2	12.2
Kr^+	14.00	5.4	6.9
Xe^+	12.13	3.5	2.2

Monolayer of N_2 on W reduces γ_i by a factor ranging from 1.6 (He) to 6.5 (Xe)

H. D. Hagstrum, Phys Rev 104 (1956) 672

IISEE yields of noble gas ions

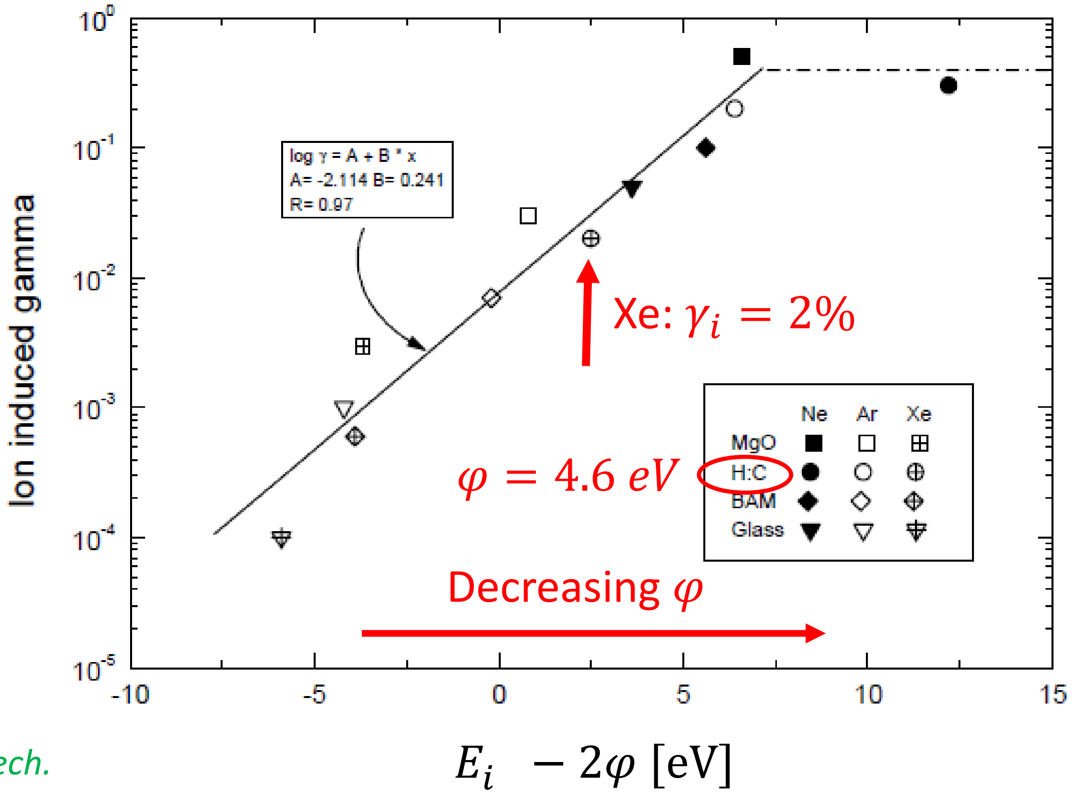
γ_i inferred from Paschen curves

H:C = Hydrogen terminated CVD diamond, with Negative Electron Affinity (NEA) of -0.8 eV

BAM = $BaMgAl_{10}O_{17}$ phosphor

Further decrease of φ in NEA-diamond expected to result in larger γ_i for Xe

Elsbergen et al, *SID Int. Symp. Dig. Tech. Papers*, 2000, 220–223.

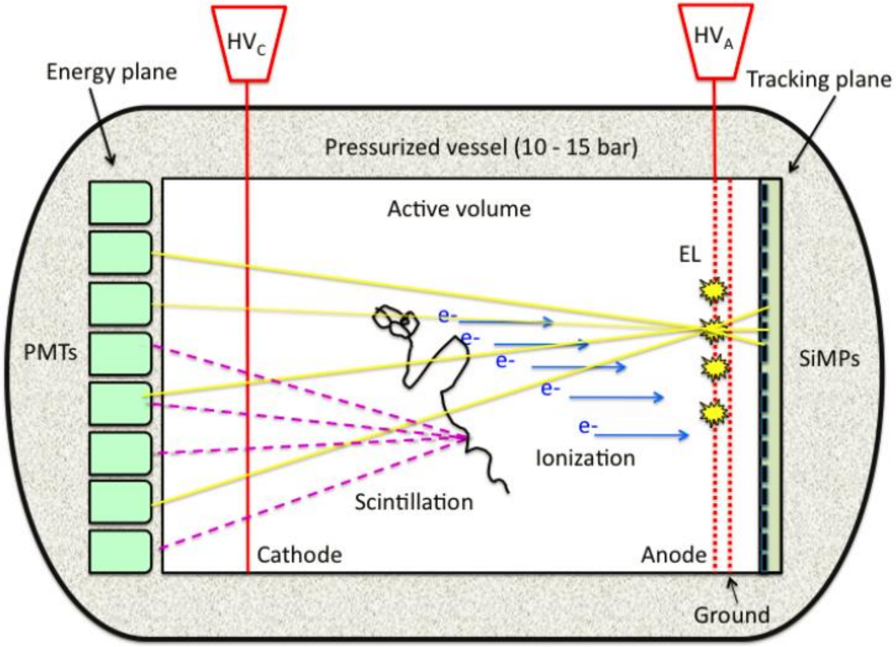


Xe: $\gamma_i = 2\%$

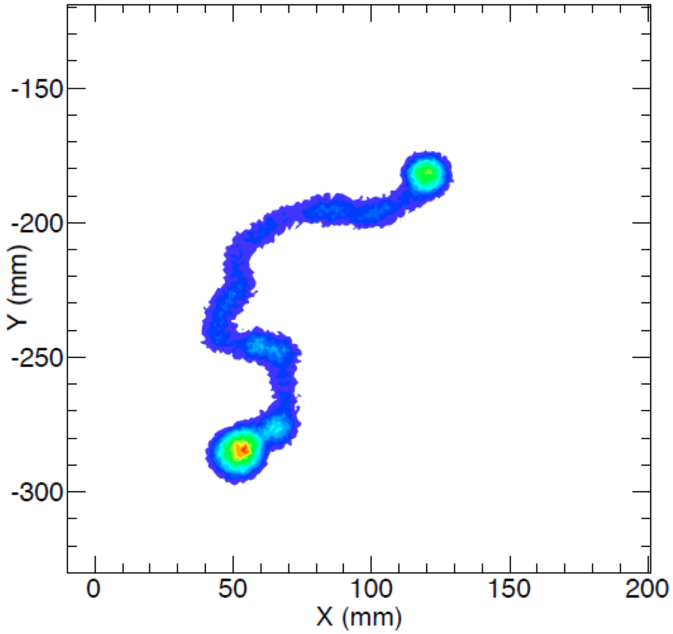
$\varphi = 4.6\ eV$

Decreasing φ

So what's NEXT?



MC of ββ0ν event – 2 blobs at the ends



Compromise?

Searching for $\beta\beta0\nu$ in HPXe at the ton scale → compromise between energy resolution and accuracy in track reconstruction

Design option	**Intrinsic FWHM Energy resolution**	**rms diffusion (1 m)**	**rms diffusion (2 m)**
Pure Xe	0.33%	$\sim 13\ mm$	$\sim 18\ mm$
Xe + 0.05% CO_2	0.47%	$4.8\ mm$	$6.8\ mm$
Xe + 0.5% CH_4	0.53%	$3.1\ mm$	$4.4\ mm$
Xe + 1.0% CH_4	0.8%	$2.3\ mm$	$3.2\ mm$
Pure Xe using ions for topology and electrons for energy	0.33%	$1.3\ mm$	$1.8\ mm$

* Azevedo et al, JINST 11 (2016) C02007 arXiv:1511.07189 – 10 bar, 300 V/cm

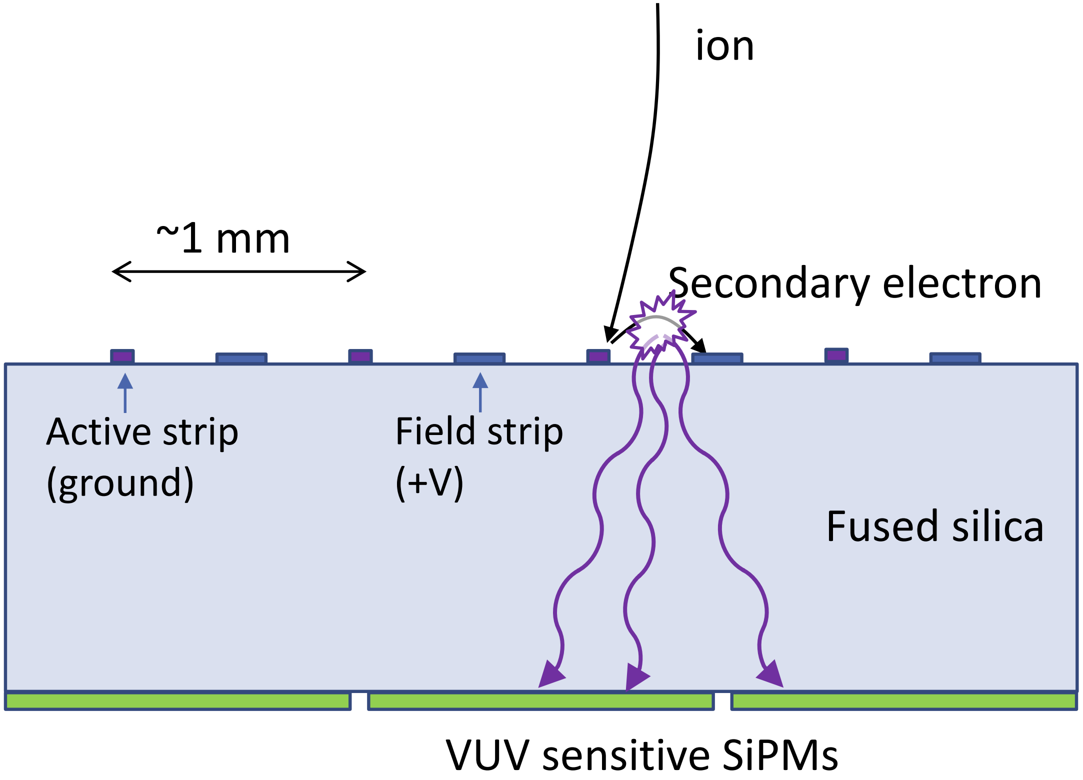
Let’s take this one step at a time

- $1 \cdot 10^5$ electron-ion pairs for event at $Q_{\beta\beta}$
- All Xe^+ ions immediately ($\sim 10^{-10}$ s) convert to Xe_2^+
- Electrons quickly reach EL region near anode (at +HV)
- Energy + (smeared) track image measured by electrons EL signal
- Xe_2^+ ions reach cathode plane within <1 s
- Xe_2^+ ions ionization energy = 11.2 eV (lowest of all impurities) → no charge-exchange collisions → all Xe_2^+ ions make it to cathode

Now here comes the fun part

- Cathode plane comprised of tiled array of fused silica plates, each with MSGC-like pattern of active strips at ground, interlaced with field strips at modest +HV. Spacing between active strips ~1 mm.
- Ions landing on active strips release secondary electrons by AN
- Emitted electrons follow field lines to positive field strips. Field tuned to gain of $\mathcal{O}(10)$ → $\mathcal{O}(10^3)$ photons per detected ion
- EL light produced by electrons recorded by dense array of VUV-SiPMs immediately behind cathode plane
- Recorded light pattern provides track topology with spatial resolution governed by ion diffusion (+ some smearing by readout granularity)

Cathode plane cartoon



Some numbers

- EL signals sufficiently large ($\mathcal{O}(10^3)$ photons)

⇩

Ion Detection efficiency $= \gamma_{eff} = \gamma_i \cdot \varepsilon_{ext}$

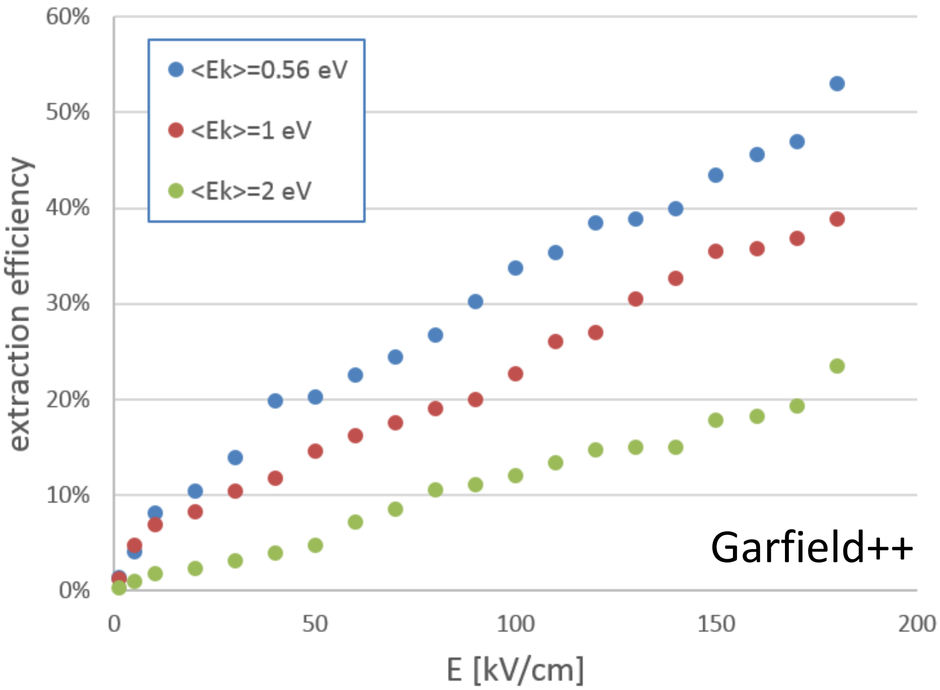
where ε_{ext} is the extraction efficiency = probability that the emitted electron is not backscattered to the surface

- ε_{ext} can be readily >20% → γ_i of a few % will provide several hundred detected ions (out of $1 \cdot 10^5$)
- E.g. $\gamma_i = 2\%$ & $\varepsilon_{ext} = 20\%$ → 400 detected ions with ~0.5 mm spacing for 20 cm track

Extraction efficiency of electrons into 10 bar Xe at room temperature

For $E_i' = 10 - 11\ \text{eV}$,
$\varphi = 3 - 4\ \text{eV}$:

$$\langle E_k \rangle \approx \frac{1}{3} E_k^{max} \approx 0.6 - 1.6\ \text{eV}$$



Some more numbers

- For 6 mm SiPMs with array PDE=10%, 3 mm behind the cathode plane, the emission of 2000 EL photons into 4π gives $\sigma_{xy} \approx 0.5\ mm$ for center-of gravity (COG) determination
- For avalanche gain = 10, the required EL is then ~200 photons/e over a trajectory of ~0.5-1 mm (NEXT-100 TDR: 2500 photons/e over 5 mm)
- To avoid continuous ion feedback we need $gain \cdot \gamma_{eff} < 1$ – readily satisfied for gain of $\mathcal{O}(10)$ and $\gamma_{eff} < 1\%$
- EL signals will last $\mathcal{O}(10 - 100\ ns)$. Contribution of SiPM dark counts (even if 10^5 Hz/mm^2) will be small over the total area of the SiPM pixels used for COG
- EL photon feedback expected to be low (for active material of low QE and thin strips)
- **BUT: Field emission must be kept very low (roughly <10^{-14} A/cm^2)**

Candidate materials

CVD diamond with negative electron affinity (NEA)

- Either nanoparticles (UNCD – ultrananocrystalline diamond) or single-crystal layers
- ‘Tunable’ NEA depends on surface termination (e.g. by H, D or Mg) and annealing → work function can be tuned to 3-4 eV

  (at $\varphi = 4.6\ eV$ $\gamma_i = 2\%$ for Xe ions; naively $\varphi = 3\ eV$ → $\gamma_i \approx 10\%$)
- Passivation through surface termination → no monolayer of impurities
- Can be used to form thin strips on fused silica
- Field emission may be high for UNCD (much less for single-crystal layers), but can possibly be kept low enough by tweaking the parameters

Candidate materials

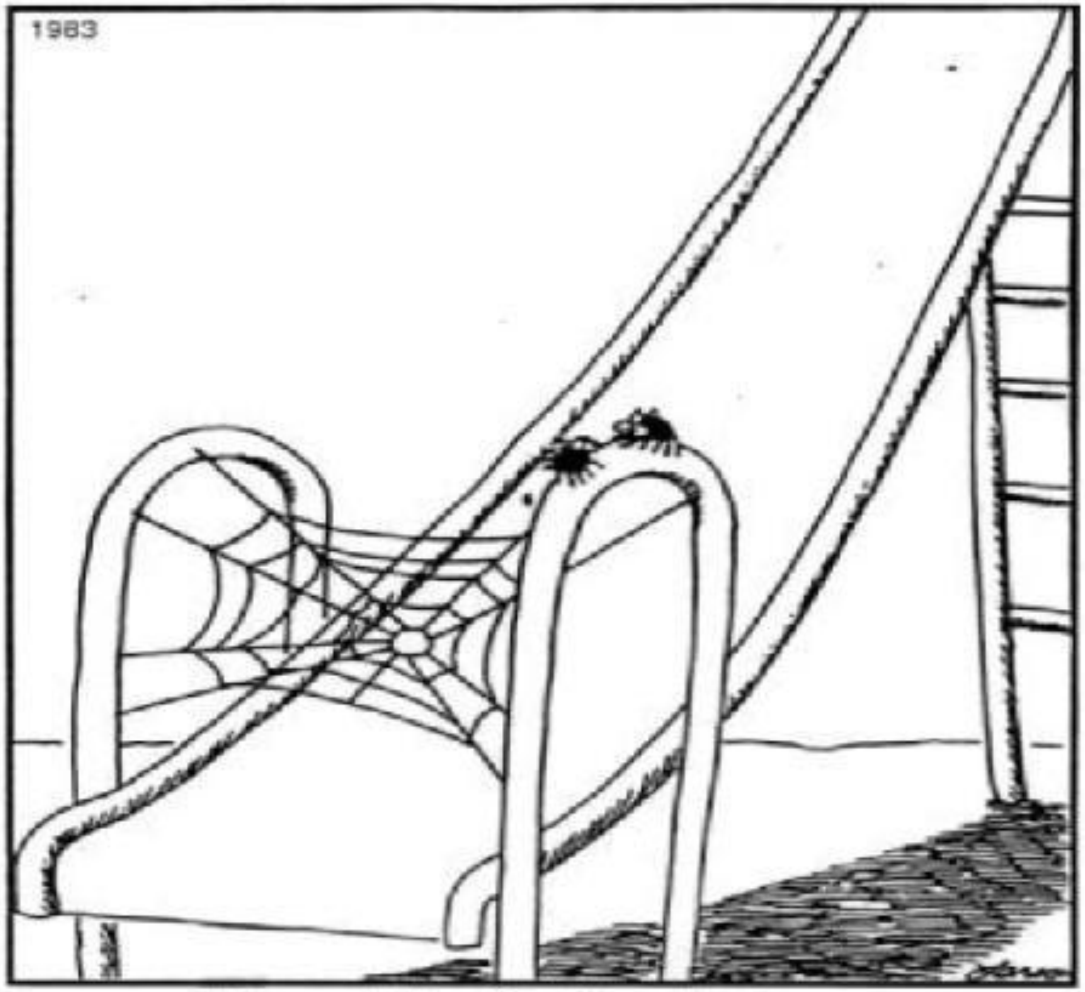
Thin MgO film on molybdenum

- Few atomic layers of MgO grown on single-crystal Mo
- Work function 3.2 eV
- Passivation provided by MgO → no monolayer of impurities
- No known issues with field emission

Stuckenholz et al, J. Phys. Chem. C 2015, 119, p. 12283

Summary and outlook

- Positive ion detection in ton-scale $\beta\beta0\nu$ searches in HPXe may enable having both superb intrinsic energy resolution (0.3% intrinsic FWHM at $Q_{\beta\beta}$) and accurate track reconstruction ($\sigma < 1.8$ mm over 2 m drift)
- It will also enable having a t_0 signal from S1 (likely lost for Xe + admixtures)
- Since we start with 10^5 ions a modest IISEE yield of a few % will be sufficient for detecting several hundred ions with sub-mm spacing → should be enough to identify the two blobs + other track features
- Such yields appear at hand using existing materials (but must keep an eye on field emission)
- First samples for testing are expected soon from Argonne National Laboratory
- Careful studies required to translate this to actual sensitivity to $\beta\beta0\nu$
- Can AN be also used in directional dark matter searches?



“If we pull this off, we’ll eat like kings.”

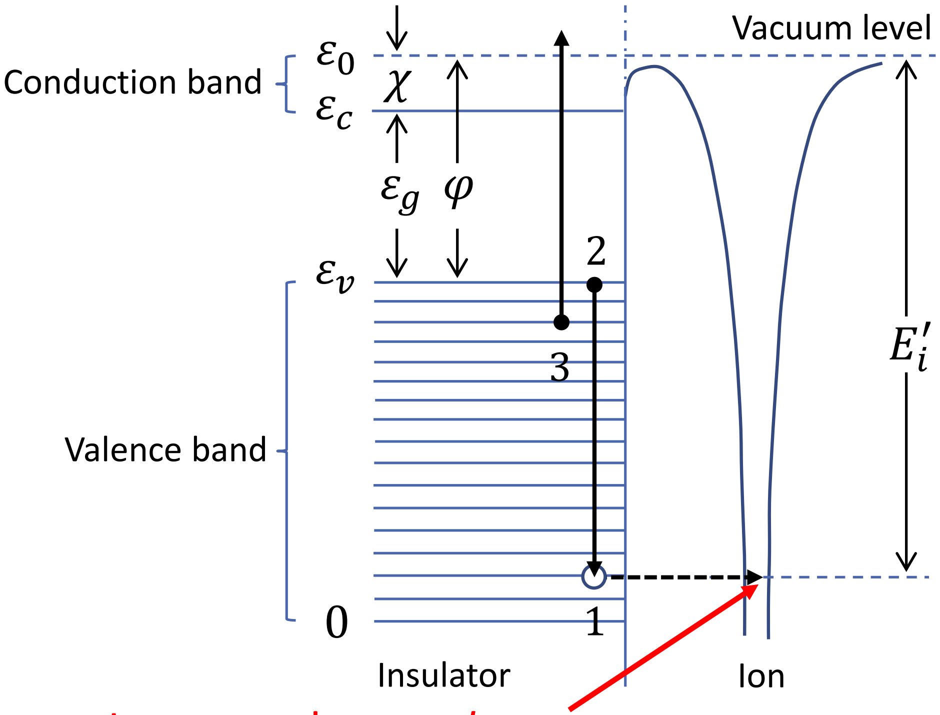
G. Larson, “The Far Side” (1983)

Backup slides

Resonance neutralization

- Dominant when the ground state of the ion lies above the bottom of the valence band (in insulators)
- A first valence electron tunnels resonantly to the ion ground state and neutralizes it, without losing energy
- A second valence electron drops to fill the hole left by electron 1
- The energy lost by electron 2 can be taken by a third electron only if it puts it in the conduction band (and may then be emitted) – otherwise it will be lost through other channels.
- Electron emission out of the solid still requires $E_i' > 2\varphi$ and happens with lower probability than the pure AN case.

Resonance neutralization – external emission



Ion ground state *above* bottom of valence band

If the energy lost by electron 2 as it drops to fill the hole is large enough, electron 3 can make it out.

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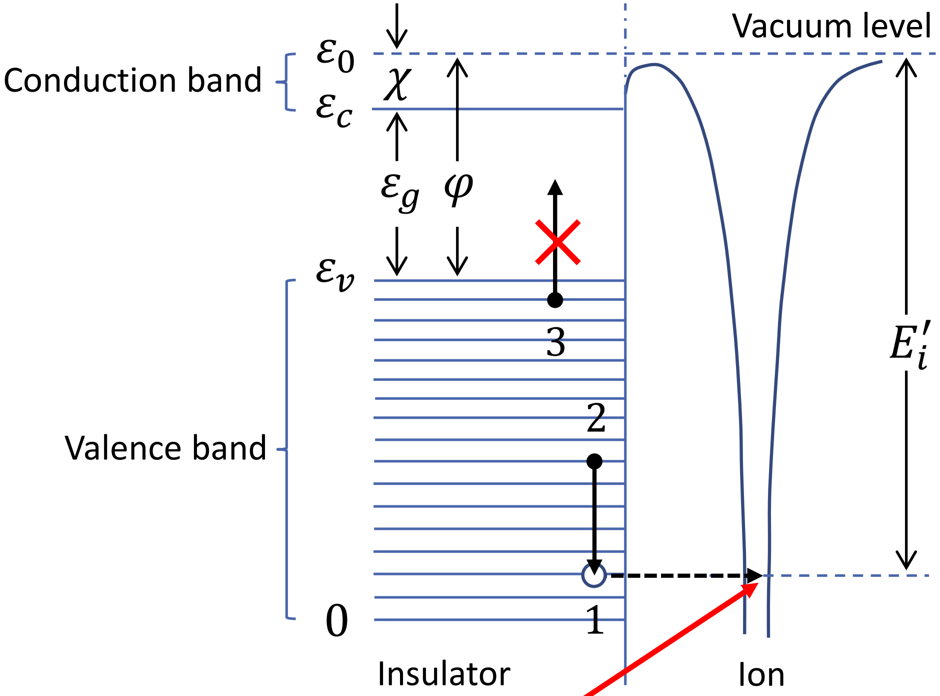
Resonance neutralization – forbidden transitions



Ion ground state *above* bottom of valence band

If the energy lost by electron 2 is smaller than the band gap the transition is forbidden and the excess energy is released by other mechanisms (e.g., photon emission).

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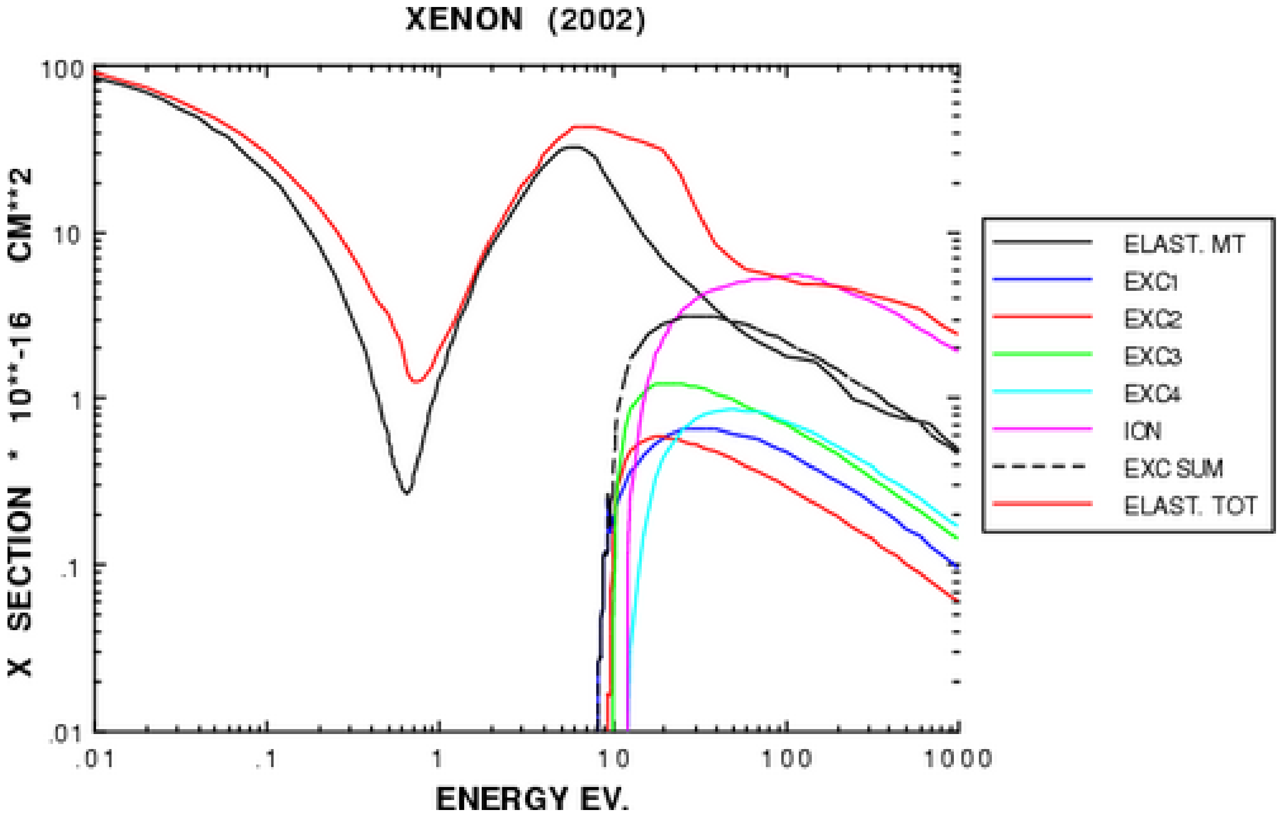
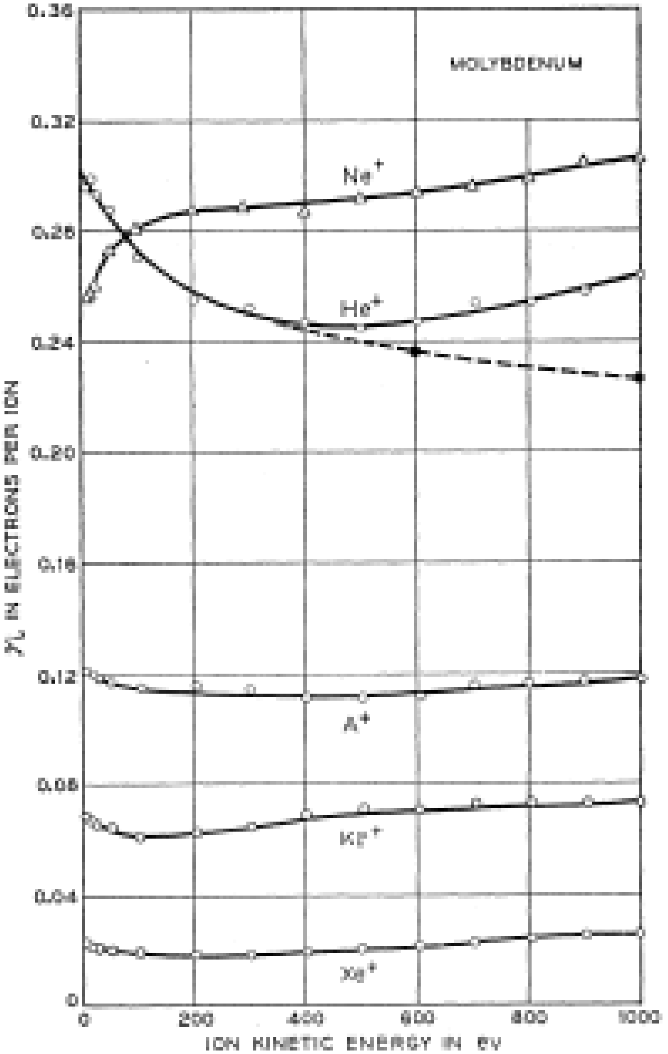
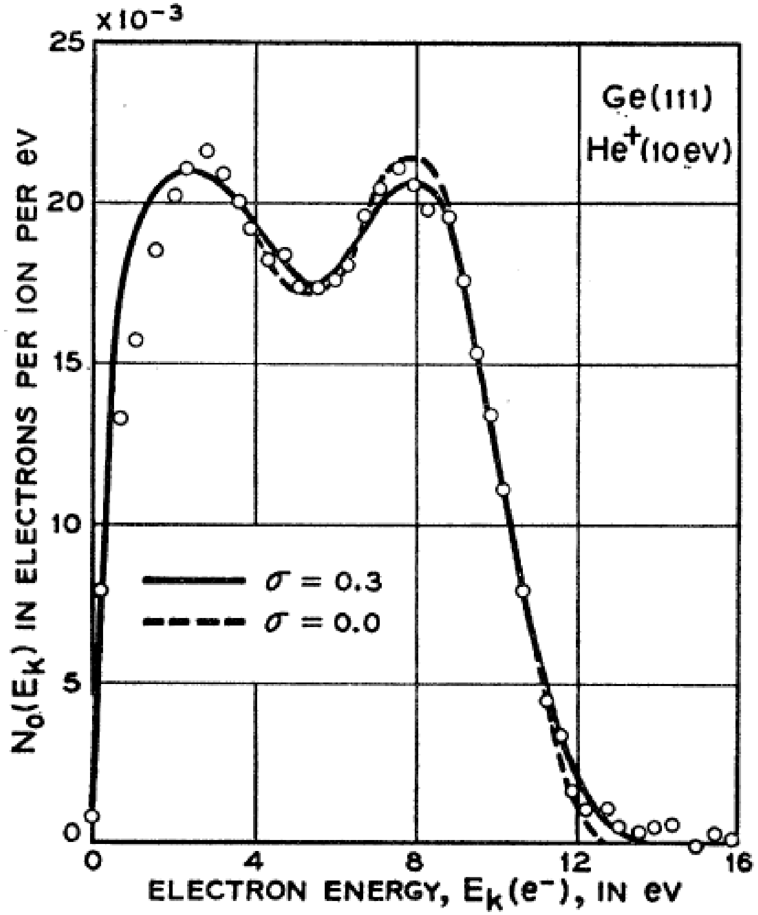
Xe cross sections (Magboltz)



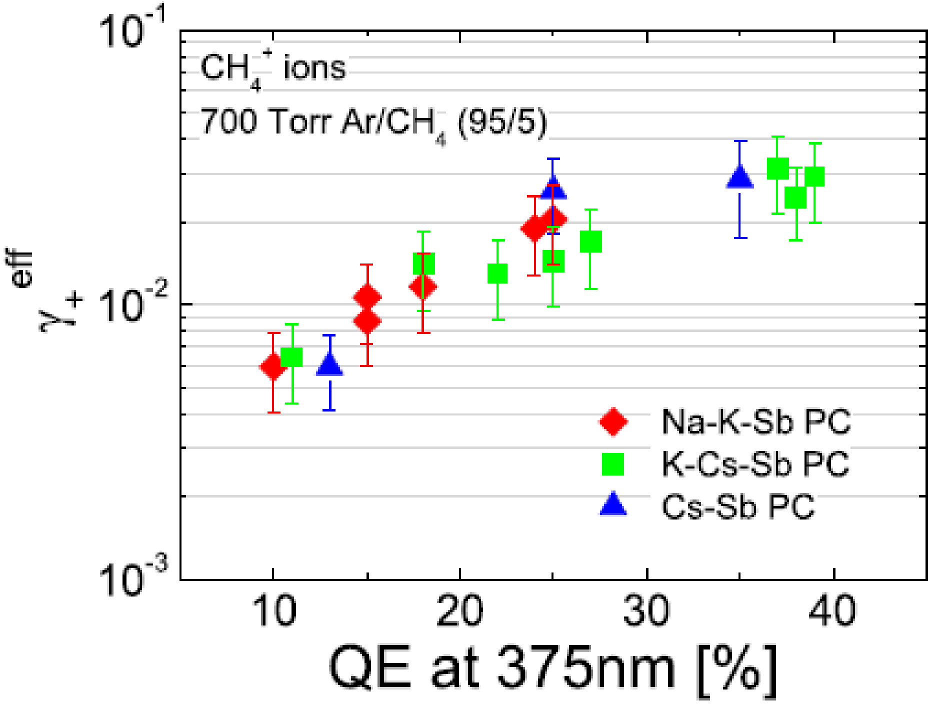


H. D. Hagstrum, Phys Rev 104 (1956) 672



H. D. Hagstrum, Phys Rev 122 (1961) 83

γ_i and γ_{eff} for CH_4 ions on bialkali photocathodes



$$\varepsilon_{ext} = 6\%$$

$$\gamma_i = 47 - 49\%$$

Lyashenko et al, J. Appl. Phys. 106 (2009) 044902