Recent study and results for ionization efficiency theory in pure materials

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XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)

August 30, 2023

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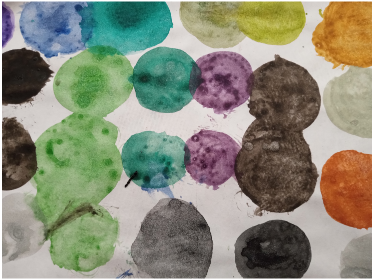
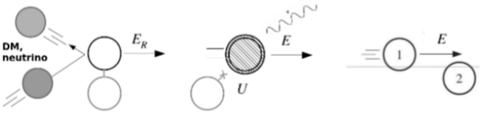
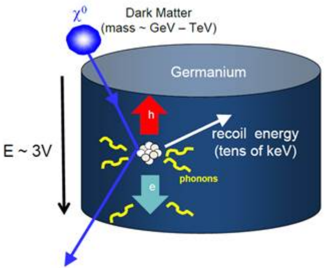


Ionization Efficiency (Quenching Factor)

When a particle, (e.g. DM) interact with a nuclei the energy splits in

E_n : Nuclear collisions. ($\bar{\nu} = C_0 E_n$[1])
E_I : Ionization (visible) energy [$\mathrm{keV_{ee}}$] ($\bar{\eta}$).





- *Quenching* $= \frac{\text{ionization energy}}{\text{deposited energy}} = \boxed{f_n = \frac{\bar{\eta}}{\varepsilon_R}.}$
- $\varepsilon_R = \varepsilon + u = \bar{\eta} + \bar{\nu}$, where ε_R is the recoil energy and
- u is the energy to disrupt the atomic bonding.
- This sets a cascade of slowing-down processes.
- DM or CEνNS searches are affected by quenching.

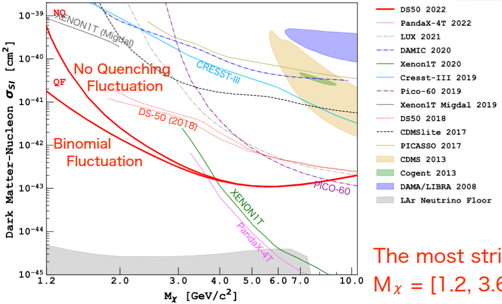
[1] Using dimensionless units ($C_0 = 16.26(1/\mathrm{keV})/\mathrm{Z_1 Z_2}(\mathrm{Z_1^{0.23}} + \mathrm{Z_2^{0.23}})$)

Motivation and Outlook

- Many Dark Matter and CEνNS experiments uses pure solid state ionization detectors, e.g., CONNIE, DAMIC, CDMS, etc.
- Reconstruction energy depends on *Quenching Factor*, specially at energies below 1 keV.

WIMP Exclusion Result

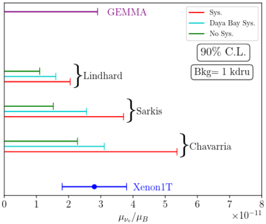
arXiv:2207.11966



The most stringent limit at
M_χ = [1.2, 3.6] GeV/c²

Physics Scope for CEνNS Experiments

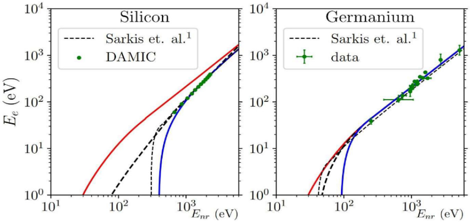
JHEP127 (2022)



1. CEνNS detection has motivated theoretical work.
2. Inspiring new constraints beyond the Standard Model.

- Standard Model weak mixing angle.
- Non Standard Interactions (NSI) of neutrinos.
  - Dark Photons.
  - Anomalous magnetic moment.
  - neutrino anapole moment.
- Sterile oscillations.
- Neutron form factor.

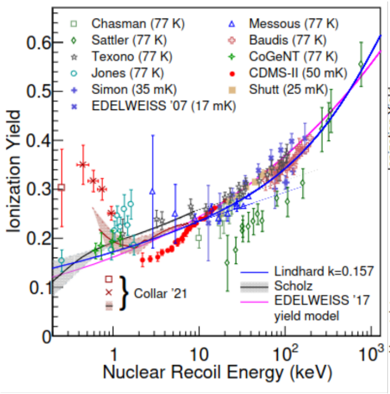
μ_B constraints & yields for solar ν studies

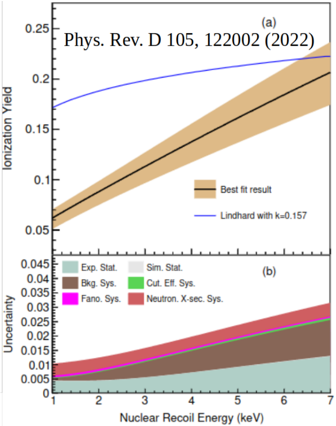


PRD106,015002 (2022)

Motivation

- There is tension among QF measurements, e.g. Ge, Si, Xe, ...
- Extrapolation at energies below 1 keV is not straightforward.





Signals affected by quenching

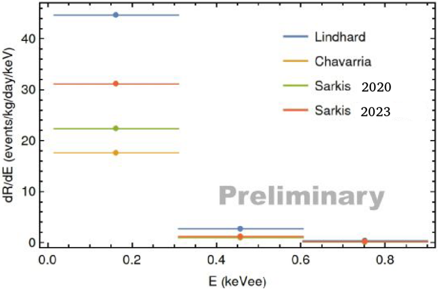
- Quenching change significantly the rate of a signal, e.g. CEνNs.
- Energy spectrum is shifted to lower energies.

$$\frac{dR}{dE_I} = \frac{dR}{dE_R} \underbrace{\frac{1}{f_n}\left(1 - \frac{E_I}{f_n}\frac{df_n}{dE_I}\right)}_{\frac{dE_R}{dE_I}}$$

$$f_n = \frac{E_I}{E_R},$$

For more, see CONNIE yesterday talk by Alexis

- **Quenching depends on:**
- Electronic Stopping S_e.
- Nuclear Stopping S_n.
- Atomic number Z.
- Electronic Straggling W_e.



CONNIE CEνNS limits for different quenching PRELIMINARY

Basic integral equation and approximations

Energy conservation for atomic motion $\bar{\nu}$ in all successive collisions[2],

$$\underbrace{\int d\sigma_{n,e}}_{\textit{total cross section}} \left[\underbrace{\bar{\nu}\left(E - T_n - \sum_i T_{ei}\right)}_{\text{All scatter-ions ions}} + \underbrace{\bar{\nu}\,(T_n - U)}_{\text{All Target ions}} - \underbrace{\bar{\nu}(E)}_{\text{Total initial energy}} + \underbrace{\sum_i \bar{\nu}_e\,(T_{ei} - U_{ei})}_{\text{Electrons contribution}} \right] = 0 \quad (1)$$

Lindhard's approximations

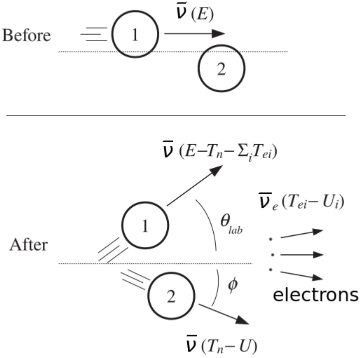
I Neglect contribution to atomic motion coming from electrons.

II **Neglect the binding energy, U = 0.**

III Energy transferred to electrons is small compared to that transferred to recoil ions.

IV Effects of electronic and atomic collisions can be treated separately.

V T_n is small compared to the energy E.



[2] T_n : Nuclear kinetic energy and T_{ei} electron kinetic energy.

Lindhard simplified equation

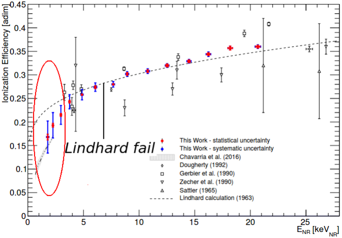
Using this approach, Lindhard deduced a simpler equation,

$$\underbrace{(k\varepsilon^{1/2})}_{S_e}\bar{\nu}_L'(\varepsilon) = \int_0^{\varepsilon^2} \underbrace{dt\frac{f(t^{1/2})}{2t^{3/2}}}_{d\sigma_n}[\bar{\nu}_L(\varepsilon - t/\varepsilon) + \bar{\nu}_L(t/\varepsilon) - \bar{\nu}_L(\varepsilon)], \qquad (2)$$

$$\Rightarrow \bar{\nu}_L(\varepsilon) \approx \frac{\varepsilon}{1 + kg(\varepsilon)},\ g(\varepsilon) = 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon.$$

Limitations:

- Based on high energy (> 10 keV) electronic stopping $S_e = k\varepsilon^{1/2}$, $k = 0.133Z^{2/3}/A^{1/2}$
- Formula (2) **derived for $\varepsilon > 1$**
- Still it is reasonable to extent the validity to $\varepsilon > 0.1$
- This recoil energy limit correspond to 4 keV for Si, 28 keV for Ge and 96 keV for Xe

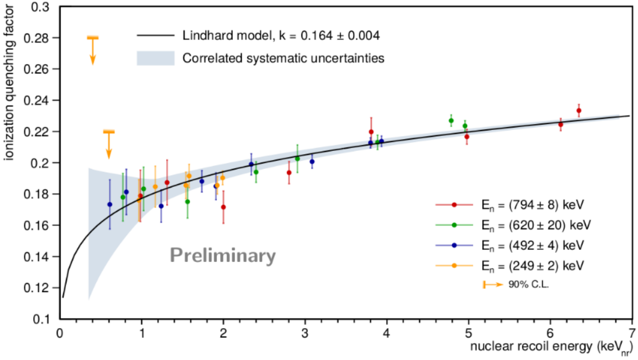


PRD Chavarria et all,94,082007 (2016)

Open question?

For Ge, formula in Eq. (2) is only valid up to ≈ 28 keV.
Why low energy measurements follow this trend?

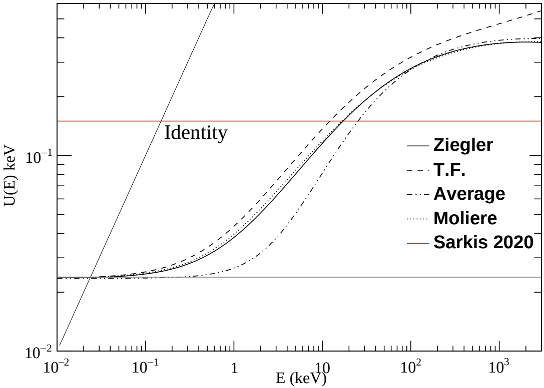
CONUS quenching factor measurement:



Eur.Phys.J.C (2022) 82,815

Binding energy Model

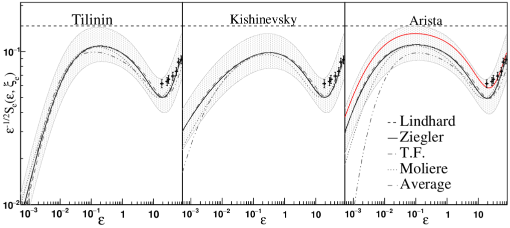
- **We add the effect of the binding energy U and predict a cut at $2U$.**
- The model for U is energy dependent,
  - Low energies considered the Frenkel energy (≈ 30 eV) and
  - High energies electron inner excitations (using T.F theory).



Electronic Stopping Considerations for low energies

- We consider Coulomb repulsion effects, high energy electron stripping, and Z oscillations.
- We include electronic straggling $\Omega^2 = \langle \delta E - \langle \delta E \rangle \rangle^2$ ($\frac{d\Omega^2}{d\rho} \equiv W$) effects

$$-\frac{1}{2}\varepsilon S_e(\varepsilon)\left(1+\frac{W(\varepsilon)}{S_e(\varepsilon)\varepsilon}\right)\bar{v}''(\varepsilon)+S_e(\varepsilon)\bar{v}'(\varepsilon) = \int_{\varepsilon u}^{\varepsilon^2} dt \frac{f\left(t^{1/2}\right)}{2t^{3/2}}\left[\bar{v}(\varepsilon - t/\varepsilon)+\bar{v}(t/\varepsilon - u)-\bar{v}(\varepsilon)\right]. \quad (3)$$



Results for Si

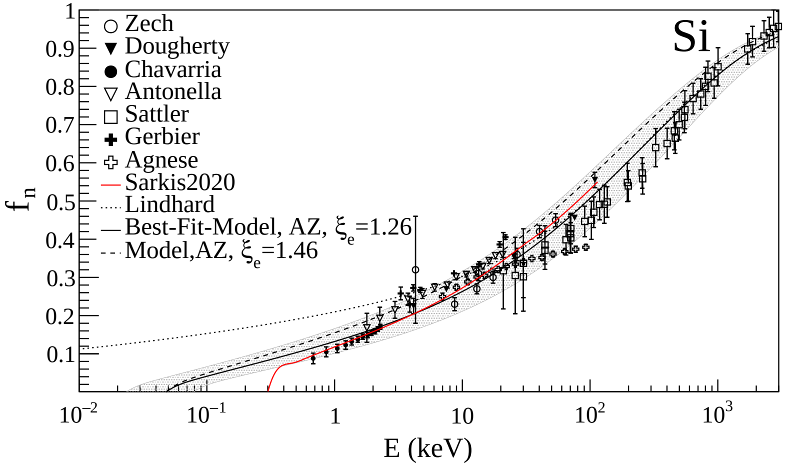


Figure 1: For details see Phys. Rev. A 107, 062811 (2023)

The Model can also be apply to Dual TPC's

Dual Phase TPC's

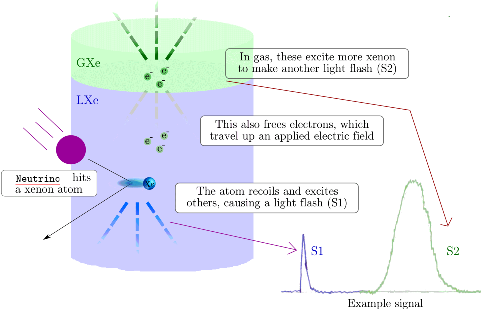
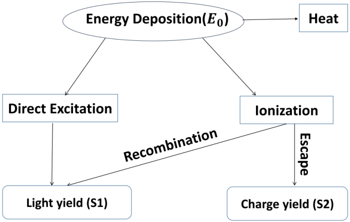


Image from: https://science.purdue.edu/xenon1t

- TPC's can detect ionization (N_i) and excitation (N_{ex}) signals.
- Recombination model depends on **ionization efficiency** f_n.

$$E_R = W_{sc}\left(\frac{S_2}{g_2} + \frac{S_1}{g_1}\right)/\mathbf{f_n}, \quad \mathbf{N_i} = \frac{\mathbf{E_R f_n}}{\mathbf{W_{sc}(1+\beta)}}$$

- Total energy deposited in the detector is divided into:
  1. Direct Excitation.
  2. Ionization.
  3. Atomic movement.
- Ionization → light due to recombination.



J. Phys. G: Nucl. Part. Phys. 44 (2017) 055001

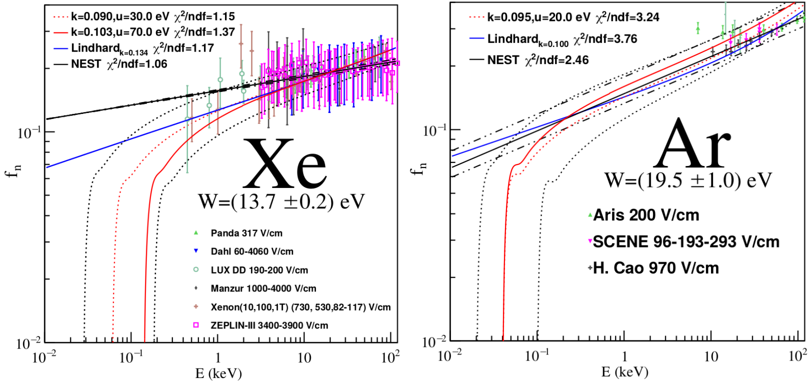
Calibration constants:

$g_1 \approx 0.12$, $g_2 \approx 12.10$

$(N_R)_s$ ionization efficiency for LAr and LXe

Ionization Yield with Constant Binding energy

➢For details see Y. Sarkis et al 2023 JINST 18 C03006



Best fit to available data by using $S_e = k\varepsilon^{1/2}$, with $0.1 < k < 0.2$ and $u =$cte .

Work in Progress: **Further studies of Coulomb repulsion effects and electron straggling at low energies.**

Conclusions and future work

1. *We present a general model based on an integral equation for ionization in pure materials.*
2. *We incorporate corrections due to electronic straggling and binding energy.*
3. *For Si, Coulomb effects allow us to fit the data up to 3 MeV, having a threshold near Frenkel-pair creation energy.*
4. *For LXe and LAr, our model has the potential to explain recent measurements.*
5. *Much work to be done: Ge quenching factor, nuclear Fano factor, etc.*
6. *More information:* ➢ *Y. Sarkis, et al works*

Thank You!

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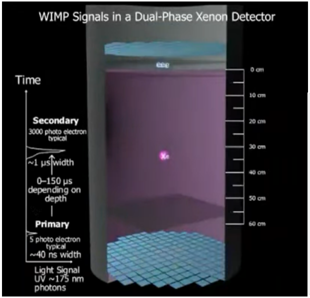
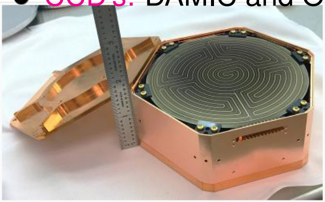
❈ *This research was supported in part by DGAPA-UNAM grants PAPIIT-IT100420 and PAPITT-IN106322, SNI, and CONAHCYT grant CB2014/240666.*

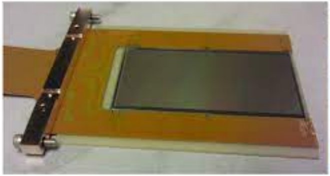
Backup

Relevant DM Experiments



- TPC's detectors: LUX, XeNT, ZEPLIN, etc.
- Bolometers: Super CDMS, EDELWEISS, etc.
- CCD's: DAMIC and OSCURA.



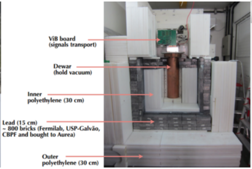


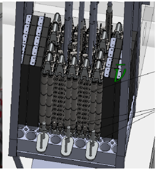
These detectors detect signals by ionization due to WIMP's that produce NR's in the material.

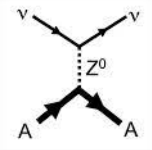
Figure 2: Credit images:M. Szydagis 2021 SCU AAP Conference `https://damicm.cnrs.fr/en/detector/`, `https://supercdms.slac.stanford.edu/overview`

Relevant Experiments

- CCD's: CONNIE.
- Ge detectors: CoGeNT, TEXONO, νGeN , CONUS.
- Low-temp. bolometers: RICOCHET, MINER, ν-cleus.
- Noble liquid detectors: LAr Livermore, LXe, ITEP& INR, LXe ZEPLIN-III.
- Neutron Spallation: COHERENT.







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CAPTAIN – "Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos"

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https://coherent.ornl.gov/,Coherent Captain Mills: The Search for Sterile Neutrinos Ashley Elliott et al, https://indico.cern.ch/event/MINER_MI_workshop.pdf,http://icra.cbpf.br/twiki/bin/login/CONNIE

NSI; Vector and Axial-vector Interactions

- Higher-dimensional Lagrangian effective operators.

$$\mathscr{L}_{\mathrm{NSI}} \supset -2\sqrt{2}G_F \sum_{\alpha,\beta} \sum_{P,q} \varepsilon^{q,P}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{q}\gamma_\mu P q\right) \tag{4}$$

- CEνNS experiments are primarily sensitive to light vector and scalar mediator models.

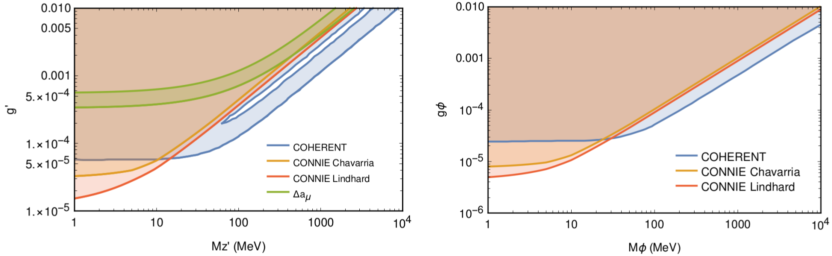
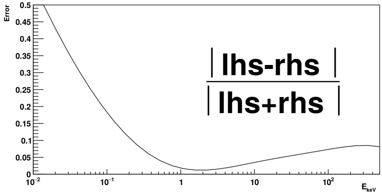


Figure 3: JHEP04(2020)054

Lindhard QF and Other Works

- Lindhard used a primitive computer(DASK).
- His formula just solved approximately Eq. (3).



- Using Lindhard formula $\Rightarrow$ Systematic error, large at lower energies.
- Other authors [3], try to include binding energy.
- But fail to realize in changing the integration limit, reporting nonphysical results.
- One of the achievements of this work is to include in a consistent mathematical and physical way the binding energy.

[3] PHYSICAL REVIEW D 91, 083509 (2015)

First results for Si

❁ The high energy cutoff is due to the limitations of the constant binding energy model.

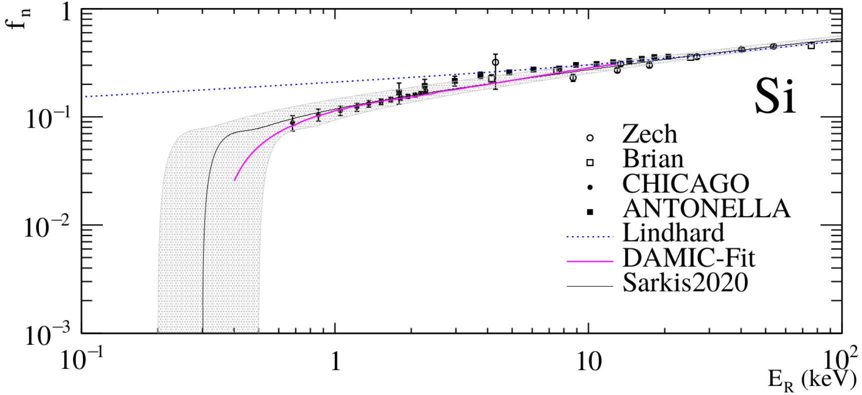


Figure 4: QF measurements for Si, compared with Lindhard model, the ansatz, and the numerical solution; U = 0.15 keV y k = 0.161.

Ge with recent data.

Results (Band is build to cover data)

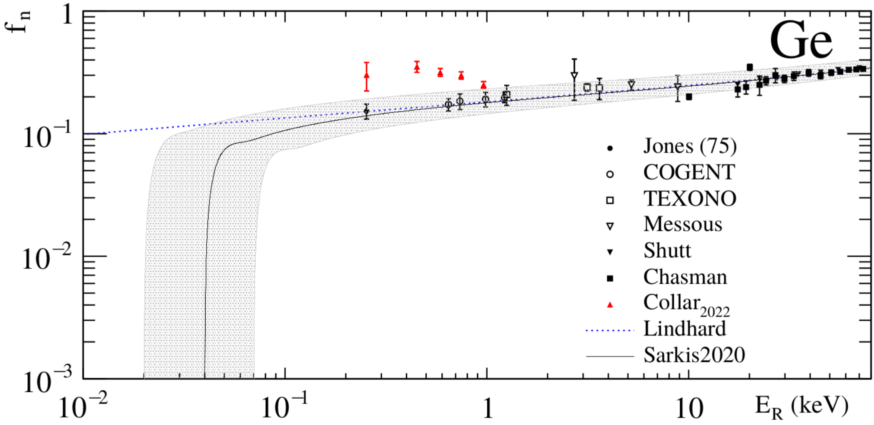


Figure 5: QF measurements for Ge, compared with Lindhard model, the ansatz, and the numerical solution; U = 0.02 keV y k = 0.162.

Low Energy Effects for S_e

§ *Coulomb repulsion effects*

- At low energies S_e departures from velocity proportionality.
- Colliding nuclei will partially penetrate the electron clouds.

$$S_e = (\Xi)Nmv\int_0^{\infty} v_F\sigma_{tr}(v_F)N_e dV \rightarrow (\Xi)Nmv\int_R^{\infty} v_F\sigma_{tr}(v_F)N_e dV$$

R distance closest approach and Ξ is a geometrical factor[4] , negligible for $Z < 20$.

- Three models will be considered; **Tilinin[4], Kishinevsky[5] and Arista[6]**
- Models change details of the inter-atomic potential.
- Hence affect $f(t^{1/2})$ and S_e at low energies.

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[4] I.S.Tilinin Phys. Rev. A 51, 3058 (1995)

[5] Kishinevsky, L.M., 1962, Izv. Akad. Nauk SSSR, Ser. Fiz. 26, 1410.

[6] J.M. FernÃ¡ndez-Varea, N.R. Arista, Rad. Phy. and C.,V 96, 88-91, (2014),

Exciton-Ion Behavior

- Exciton to ion fraction $\beta = \frac{N_{ex}}{N_i}$ usually is modeled by a constant.
- With our formalism, we can built an Int.Diff. equation taking in to account the excitation and ionization cross sections (work in progress).
- A preliminary study justify that $\frac{N_{ex}}{N_i}$ changes slowly for energies > 1 keV.
- So if the total quanta $N_i + N_{ex} = N$ with $N = E_{er}/W$, hence $E_{er} = WN_i(1+\beta)$.
- If $N_{er} = f_n E_R$ then, $N_i = f_n(\frac{E_R}{W(1+\alpha)})$, where f_n can be computed with our model. spatially small tracks.

- In the following we show the Charge and Light Yiels for Ar and Xe, using the constant binding energy model and $S_e = k\varepsilon^{1/2}$.
- Where also we are taking β and $\frac{\alpha}{4a^2 v} \equiv \gamma$ as constants.