The submitter filled some comments Ionization efficiency in silicon from 50 eV to 3 MeV[1]

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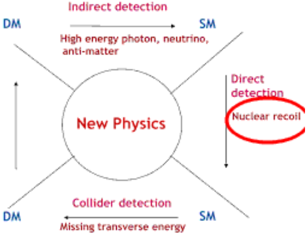
[1]Based on: **Phys. Rev. A 107, 062811**

Contents

Introduction: Dark Matter, CEνNS and Other Exotic Physical Process detections.

Detection Strategies

Credit:Institute of High Energy Physics, CAS,BI Xiaojun



- WIMP's scatter nuclei give an exponential nuclear recoil (NR) spectrum.
- Hence a lower threshold will increase the rate.
- But what we detect is ionization signals generated by NR.

DAMIC at SNOLAB with skipper CCDs
arXiv:2306.01717

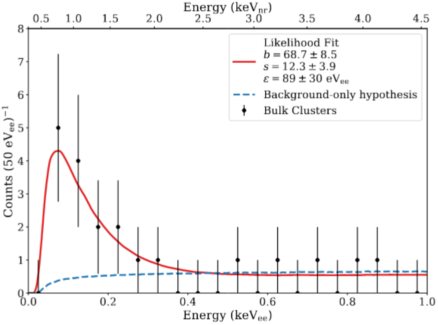


Figure: Fit result to bulk events with excess and background (red) and background (blue dashed). **Signal could be explained with a WIMP** $M_\chi \approx 2.5\mathrm{GeV/c^2}$ **and** $\sigma \approx 3 \times 10^{-40}\mathrm{cm^2}$.

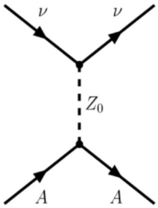
CEνNS (ν floor for DM searches)

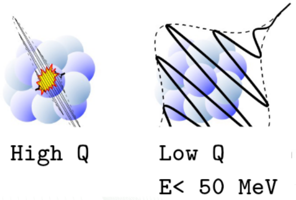
Coherent elastic Neutrino Nuclear Scattering [2]

1. Neutral-current process mediated by the Z-boson.
2. Low momentum transfer.

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_v^2}\right) Q_w^2 \left[F_w\left(q^2\right)\right]^2 \quad (1)$$

3. G_F Fermi constant, $T = E_\nu - E'_\nu$ NR energy, $F_w^2(q^2)$ weak Form Factor, M target mass and $Q_w = Z\left(1 - 4\sin^2\theta_W\right) - N$.





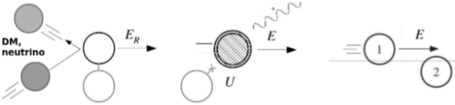
[2] D.Z. Freedman, Coherent effects of a weak neutral current, Phys. Rev. D 9 (1974) 1389.

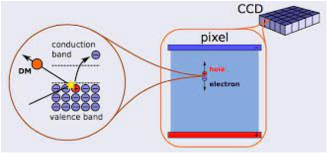
Ionization Efficiency; the Challenge of Low Energy Detection.

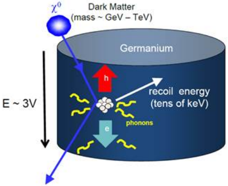
Ionization Efficiency (Quenching Factor)

χ, ν, have to deposit an energy grater than the Frenkel-pair energy (≈ 30 eV).

Deposited energy splits in;
E_ν : Nuclear collisions[3]. ($\bar{\nu}$)
E_I : Ionization (visible) energy $[\mathrm{keV_{ee}}]$ ($\bar{\eta}$).



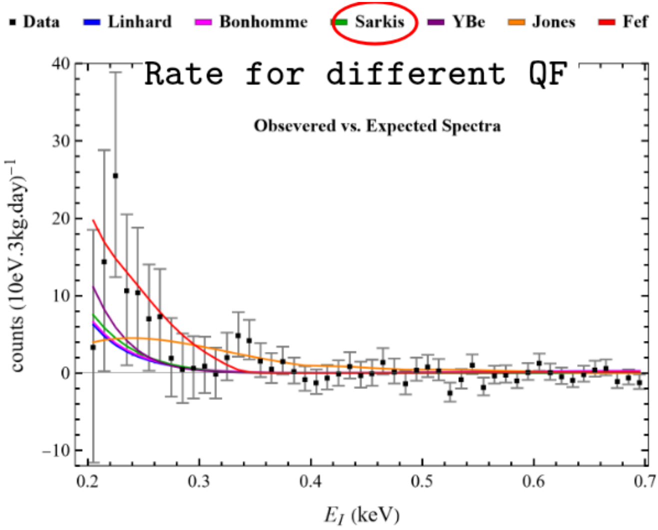




- $quenching = \frac{\text{total ionization energy}}{\text{total deposited energy}} = \boxed{f_n = \frac{\bar{\eta}}{\varepsilon_R}}$.
- $\varepsilon_R = \bar{\eta} + \bar{\nu}$, where ε_R is the recoil energy.
- Energy u is lost to some disruption of the atomic bonding: $\varepsilon_R = \varepsilon + u$.
- This sets a dissipative cascade of slowing-down processes

[3]Using dimensionless units ($\varepsilon = 16.26 E(\mathrm{keV})/\mathrm{Z}_1\mathrm{Z}_2(\mathrm{Z}_1^{0.23} + \mathrm{Z}_2^{0.23})$)

Ionization Efficiency Changes Spectrum Final Rate



arXiv:2203.08892 [hep-ph] Ge Reactor Data.

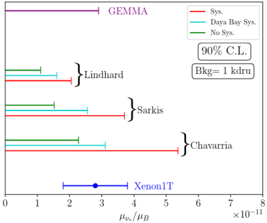
Physical Motivation

Physics Scope for CEνNS Experiments

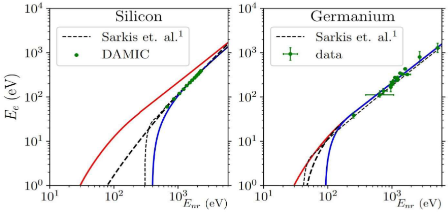
1. CEνNS detection has motivated theoretical activity in high-energy physics.
2. Inspiring new constraints on beyond the Standard Model.

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

J.HEP 2022 127 (2022)



μ_B constraints & yields for solar ν studies



PRD 106 015002 (2022)

NSI with u and d quarks

- New interactions specific for neutrinos.

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta,\mu,\tau}} \left[\bar{\nu}_\alpha \gamma^\mu \left(1-\gamma^5\right) \nu_\beta\right] \times \left(\varepsilon_{\alpha\beta}^{qL} \left[\bar{q}\gamma_\mu \left(1-\gamma^5\right) q\right] + \varepsilon_{\alpha\beta}^{qR} \left[\bar{q}\gamma_\mu \left(1+\gamma^5\right)\right.\right.$$

- $\varepsilon_{\alpha\beta}^{qP}$ (q = u,d & P = L,R), non-universal and flavor changing.

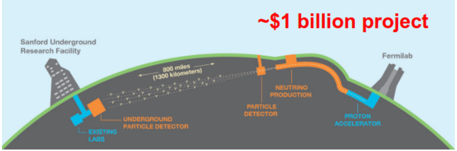
J. H J. High Energy Phys. 03(2003) 011

TABLE I. Constraints on NSI parameters, from Ref. [35].

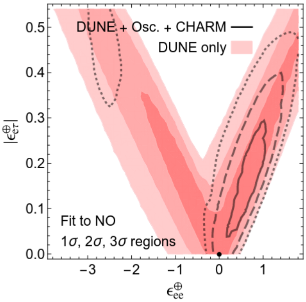
NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

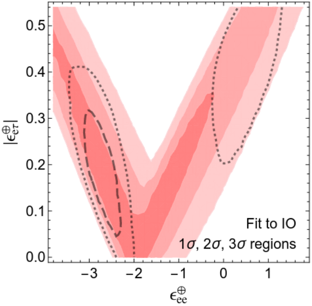
Figure: See also Juan Barranco et al JHEP12(2005)021

NSI can create degeneracy for DUNE



- If NSI have non-zero contribution, degeneracy appears.
- Can not tell the neutrino mass ordering in DUNE without constraints on NSI.





Phys. Rev. D 95, 079903 (2017)

Integral Equations Governing Ionization Process

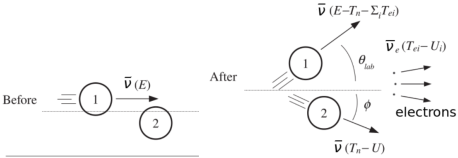
Basic Integral Equation and Approximations

(T_n : Nuclear kinetic energy and T_{ei} electron kinetic energy.)

$$\underbrace{\int d\sigma_{n,e}}_{\text{total cross section}} \left[\underbrace{\bar{\nu}\left(E - T_n - \sum_i T_{ei}\right)}_{\text{A}} + \underbrace{\bar{\nu}\left(T_n - U\right)}_{\text{B}} + \underbrace{\bar{\nu}(E)}_{\text{C}} + \underbrace{\sum_i \bar{\nu}_e\left(T_{ei} - U_{ei}\right)}_{\text{D}} \right] = 0 \qquad (2)$$

Lindhard's (five) approximations

- I Neglect contribution to atomic motion coming from electrons.
- II **Neglect the binding energy, U = 0. (Now taken into account)**
- 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 also small compared to the energy E.



Lindhard Simplified Equation

Using the five approximations Lindhard deduced an integral simplified equation,

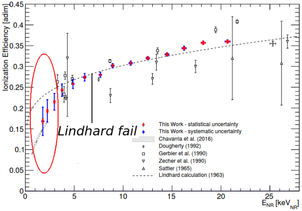
$$\underbrace{\left(k\varepsilon^{1/2}\right)}_{S_e}\bar{\nu}'(\varepsilon) = \int_0^{\varepsilon^2} \underbrace{dt\frac{f\left(t^{1/2}\right)}{2t^{3/2}}}_{d\sigma_n}\left[\bar{\nu}(\varepsilon - t/\varepsilon) + \bar{\nu}(t/\varepsilon) - \bar{\nu}(\varepsilon)\right], \qquad (3)$$

L.H.S R.H.S

---

only valid at high energies, since $\bar{\nu}(\varepsilon \to 0) \to \varepsilon$, by the above equation we get $\bar{\nu}'(0) = 0$!

- Elec. stop. valid for $E > 10\ keV$ $S_e = k\varepsilon^{1/2}$, $k = 0.133Z^{2/3}/A^{1/2}$.
- Lindhard deduce a parametrization valid at high energies (U=0).
- But fails below 4 keV in Si.



PRD Chavarria et all, 94, 082007(2016)

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

Simplified Integral Equation With Binding Energy

A previous work[a] didn't notice the necessity to change the lower limit of integration in order to be consistent with the term $\bar{\nu}(t/\varepsilon - u)$. In our publication, we take this into account so Eq.2 becomes:

$$\boxed{-\frac{1}{2}k\varepsilon^{3/2}\bar{\nu}''(\varepsilon)} + \underbrace{k\varepsilon^{1/2}}_{S_e}\bar{\nu}'(\varepsilon) = \int_{\boxed{\varepsilon u}}^{\varepsilon^2} \underbrace{dt\frac{f\left(t^{1/2}\right)}{2t^{3/2}}}_{d\sigma_n}[\bar{\nu}(\varepsilon - t/\varepsilon) + \bar{\nu}(t/\varepsilon - \boxed{u}) - \bar{\nu}(\varepsilon)] \quad (4)$$

This equation can be solved numerically from $\varepsilon \geqslant u$. The equation predicts a threshold energy of u ($\varepsilon_R^{threshold} = 2u$).

The equation admits a solution featuring a "kink" at $\varepsilon = u$ (discontinuous 1st derivative). We assume that the binding energy is a constant $u = u_0$

[a] PhysRevD 91 083509 (2015)

First results for Si

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

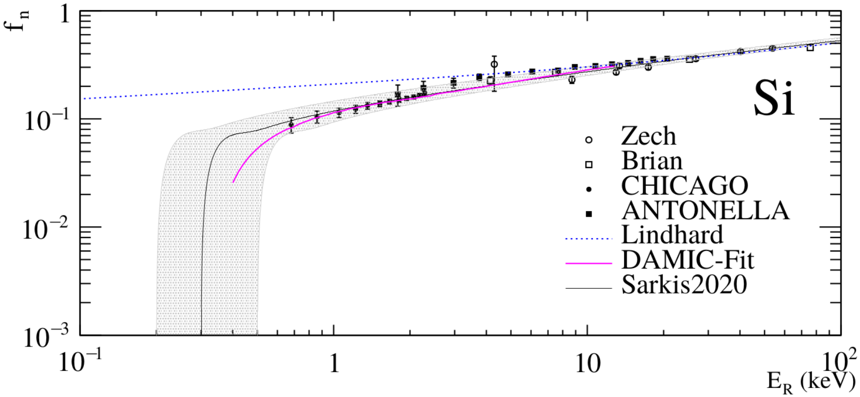


Figure: QF measurements for Si, compared with Lindhard model, the ansatz, and the numerical solution; U = 0.15 keV y k = 0.161.

Ge with recent data.

Results (Band is build to cover data)

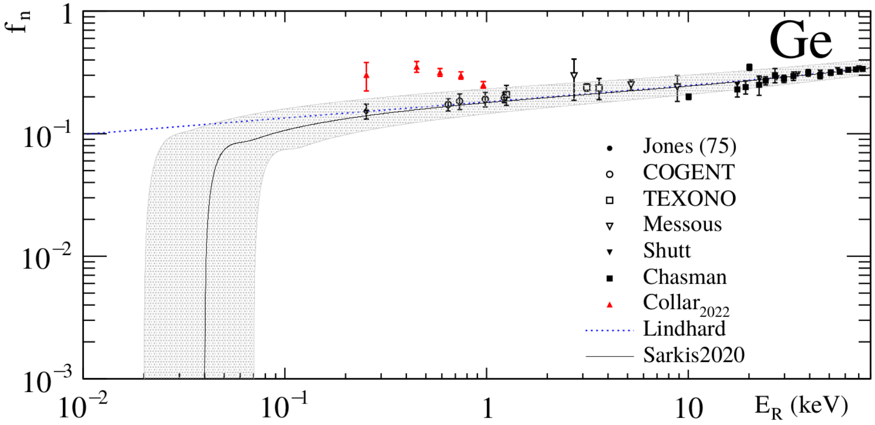


Figure: QF measurements for Ge, compared with Lindhard model, the ansatz, and the numerical solution; U = 0.02 keV y k = 0.162.

Improvements of the Model

- **For Si, constant U, gives a cut off too high compared to the expected threshold given by the energy to create a Frenkel-pair (≈ 30 eV).**
- A varying binding energy model is proposed;
  - Low energies just considered the Frenkel energy.
  - High energy considers electron inner excitations, using T.F theory.
- **Lindhard electronic stopping is not valid at low energies.**
- It doesn't consider Coulomb repulsion effects and electron stripping.
- We can also add electronic straggling $\Omega^2 = \langle \delta E - \langle \delta E \rangle \rangle^2$ ($\frac{d\Omega^2}{d\rho} \equiv W$) effects to the model.

$$\boxed{\begin{aligned} -\frac{1}{2}\varepsilon S_e(\varepsilon)\left(1+\frac{W(\varepsilon)}{S_e(\varepsilon)\varepsilon}\right)\bar{\nu}''(\varepsilon) + S_e(\varepsilon)\bar{\nu}'(\varepsilon) = \\ \int_{\varepsilon u}^{\varepsilon^2} dt \frac{f\left(t^{1/2}\right)}{2t^{3/2}}\left[\bar{\nu}(\varepsilon - t/\varepsilon) + \bar{\nu}(t/\varepsilon - u) - \bar{\nu}(\varepsilon)\right], \end{aligned}} \tag{5}$$

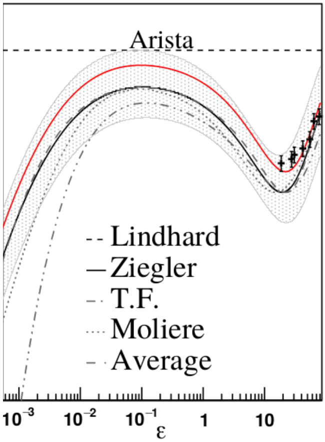
High Energy Effects (> 10 keV) for $S_e(\varepsilon)$

§ *Bohr Stripping*

- Electrons can be lost according to momentum transferred.
- The effective number of electrons obeys $Z^{\dagger} \approx Z e^{-v/Z^{2/3} v_0}$.
- $S_e \propto Z^{\dagger}$, this leads to damping.

§ *Z Oscillations*

- When the ion charge changes, the transport cross section σ_T changes.
- Phase shift is appear to maintain neutrality of electron Fermi gas.
- S_e may be affected by this effect at energies $v \ll v_0 Z^{2/3}$.Since $S_e \propto \sigma_T$.



S_e vs data

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.

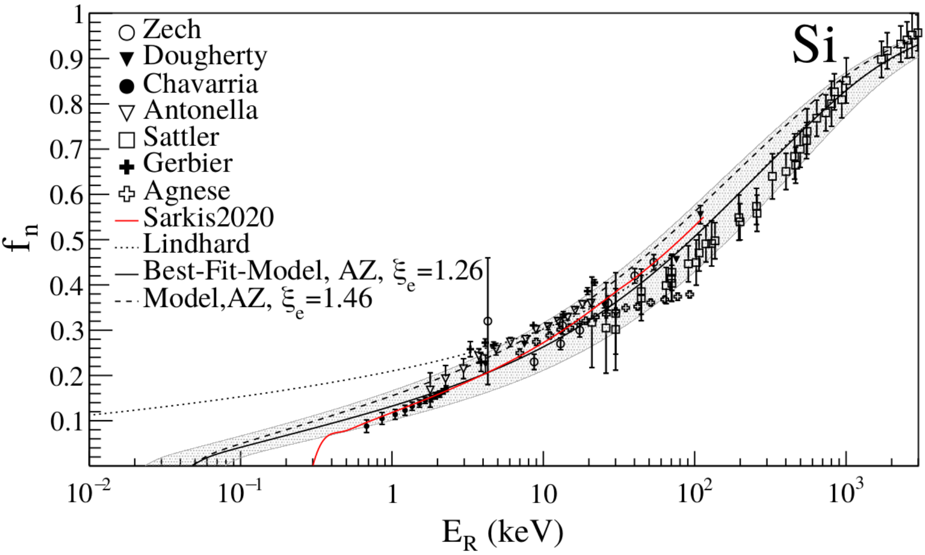
$$S_e = \xi_e(\Xi) N m v \int_R^\infty v_F \sigma_{tr}(v_F) N_e dV$$

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.
- **We introduce and scaling parameter ξ_e for S_e.**

[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. Fernández-Varea, N.R. Arista, Rad. Phy. and C.,V 96, 88-91, (2014),

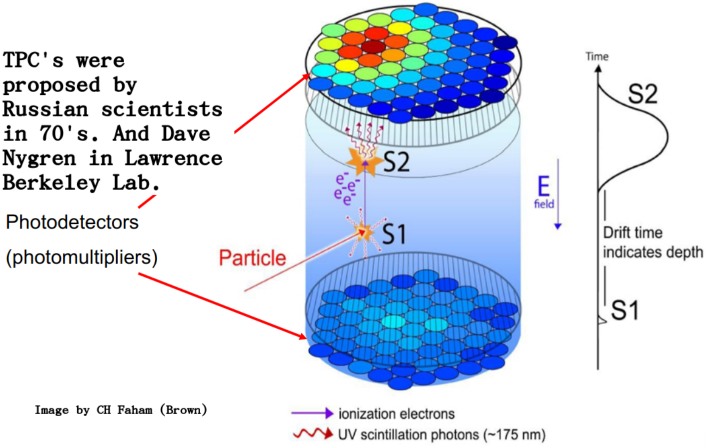
QF Results (Si) up to 3 MeV.



Noble Liquids Ionization Detectors; TPC's

TPC's

Combines the advantages of gas detectors: the possibility of proportional or EL amplification, XYZ positioning, and the possibility to have the large mass



Noble Gases Ionization Response

- Dual-phase noble liquid time projection chambers (TPCs) have yielded, a competitive sensitivity for the search for WIMP's.
- Reconstruction is done by exploiting the full anticorrelation between the S1 (scintillation photons n_γ) and S2 (ionized electrons n_e).

$$E_{\mathrm{er}} = W \left(\frac{S1}{g_1} + \frac{S2}{g_2} \right), \quad \to E_R = W \underbrace{(n_\gamma + n_e)}_{\textbf{Total Quanta}} / f_n,$$

- With $W_{Ar} = 19.5$ eV and $W_{Xe} = 13.7$ eV, is the average energy required to produce an excitation or ionization for Ar and Xe.
- A usual assumption is that each excited atom leads to one scintillation photon.

Total Quanta for LXe and LAr (Constant Binding Model)

Y. Sarkis et al 2023 JINST 18 C03006

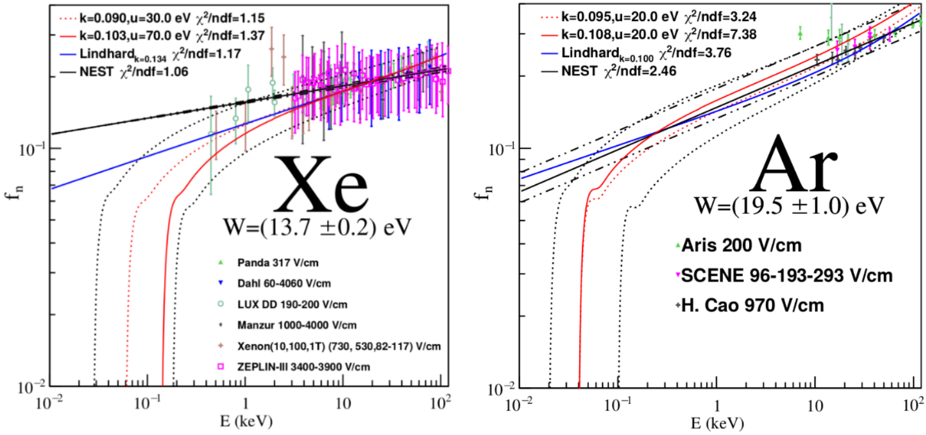


Figure: Total quanta for LXe and LAr as a function of the recoil energy.

Conclusions

Conclusions

1. *We have presented the importance of the challenge for understanding ionization efficiency at low energies.*
2. *We present a general model based on integral equations for ionization in pure crystals and noble liquids.*
3. *For silicon low and high energy effects allow us to fit the data up to 3 MeV and have a threshold near Frenkel-pair creation energy.*
4. *We have shown charge and light yields for Xe and Ar consistent with actual data.*
5. *For heavier elements a detailed study of electronic and nuclear stopping is needed.*

Thanks!

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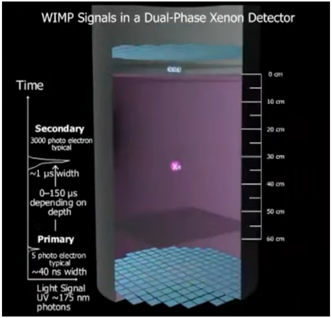
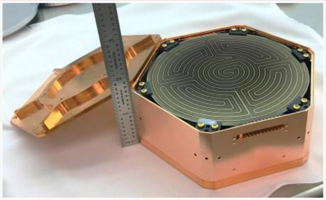
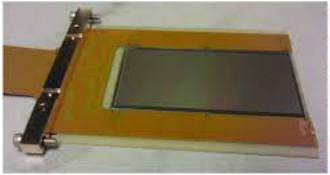
BackUp

Relevant DM Experiments



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



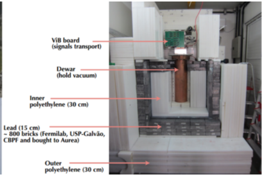


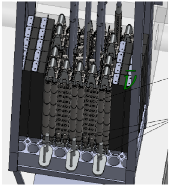
These detectors detect signals by ionization due to WIMP's that produce NR's in the material.

Figure: 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.





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

Lindhard Approximations With Binding Energy.

In order to compute a solution for $\bar{\nu}$ that includes the binding energy, we make the following

i. Neglect atomic movement from electrons, since is negligible at low energies $\bar{\nu}_e = 0$.
ii. Energy transferred to ionized electrons is small compared to that transferred to recoiling ions.
iii. Effects of electronic and atomic collisions can be treated separately.
iv. T_n is also small compared to the energy E.
v. Expand the terms in Eq. 2 up to **second order** in $\boxed{\Sigma_i T_{ei}/(E - T_n)}$.

The first four approximations are still the same that Lindhard used.

Recoil Spectrum

As experiments have lowered their detection thresholds well below 1 keV, understanding the quenching at those low energies have become important.

$E_v = f_n(E_R)E_R$ be the visible energy.

The visible energy spectrum is shifted to lower energies, due to the QF,

$$\frac{dR}{dE_R} = \frac{dR}{dE_v}\frac{dE_v}{dE_R} = \frac{dR}{dE_v}\left(f_n + E_R\frac{df_n}{dE_R}\right)^{-}$$

*QF moves events below the threshold.

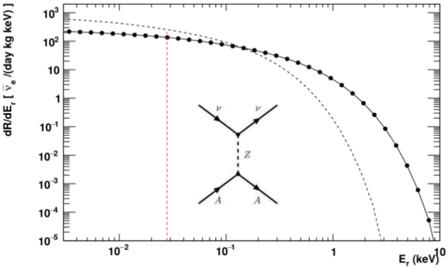


Figure: CEνNS spectrum $\frac{dR}{dE_v}$ (dotted) and $\frac{dR}{dE_R}$ (solid).

Numerical Solution

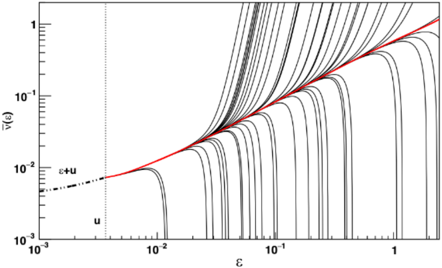
We first notice that the QF depends only of $\boldsymbol{k}$ and $\boldsymbol{u}$.

Shooting method

We have the boundary condition (BC) $\bar{\nu}''(\varepsilon \to \infty) \to 0$.
Now, since the R.H.S of Eq. 4 is zero at $\varepsilon = u$ and lower, we impose that the L.H.S to be zero at this point, this gives the relation

$$\alpha_1 = 1 + \frac{1}{2} u_0 \alpha_2$$

So we give an initial try of α_2 to hit the BC, we shoot in this way until the BC is satisfied.

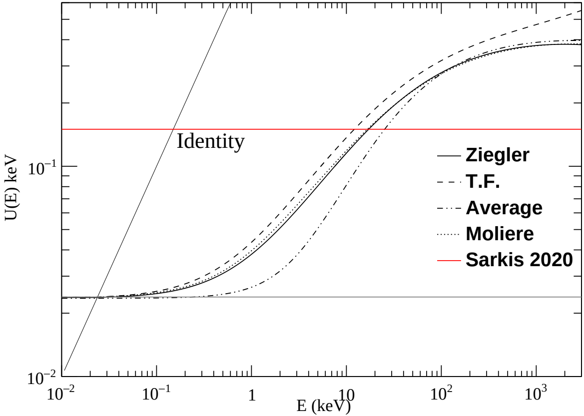


Binding energy model

The model consider:

- Frenkel pair creation energy, U_{FP}.
- Atomic binding with DFT theory, $U_{TF}(E)$.
- $U(E) = U_{FP} + U_{TF}(E)$

$$U_{FP} = 23.54^{+9.63}_{-12.04} \text{ eV}$$



The DFT depends on the screening function used in the inter-atomic potential.

The Model in the Experimental Community

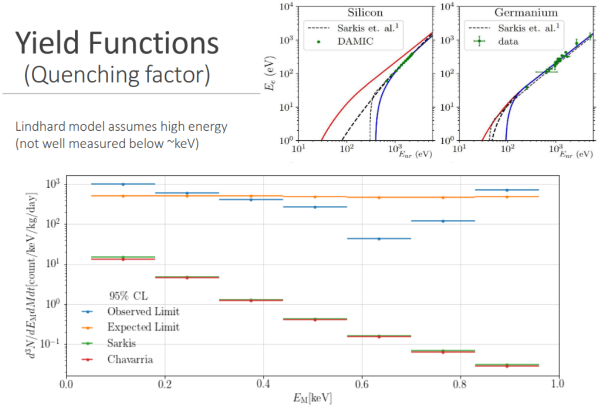


Figure: (Up) Tom Schwemberger (Univ. Oregon) talk at Mag.CEVNS2021. (Down) Reactor ON-OFF for CONNIE (1x5) 2022.