Study of the ionization efficiency for nuclear recoils

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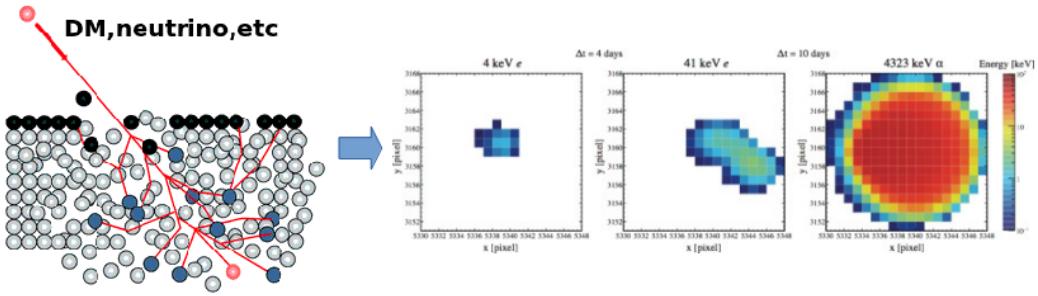
Contents

Introduction

- In experiments for direct dark matter searches or detection of (CENνS), the experimental signal entails the detection of the ionization produced by the recoiling target ions following a scattering event.



- The electronic excitation produced by a recoiling ion is typically smaller than that produced by an electron of the same energy, we name this as **quenching** ($[\mathrm{eV_{nr}}] \rightarrow [\mathrm{eV_{ee}}]$).

$$quenching = \frac{\text{total ionization energy}}{\text{total deposited energy}} = f_n = \frac{\bar{\eta}}{\varepsilon_R}$$

where $\bar{\eta}$ and ε_R are the ionization energy and the total recoil energy in adimensional units.

Introduction

- In 1963, Lindhard gave a parametrization for the quenching, but it is only acceptable for energy depositions ($\gtrsim$ 10 keV).
- Recent measurements of the QF for nuclear recoils in silicon (Si) reveal a clear deviation from Lindhard formula, below E_R <4 keV.
- Lindhard neglected the binding energy term. He end with a simplified integro-differential equation.
- In this work we incorporate correctly the binding energy term into the physical basic equation.
- This leads to a modify integro-differential equation that can be solved numerically.

Importance of Quenching Factor for DM and ν experiments.

Remark

Different quenching, e.g Lindhard and Chavarria, change significantly the rate for recent CONNIE results (*PhysRevD.100.092005*).

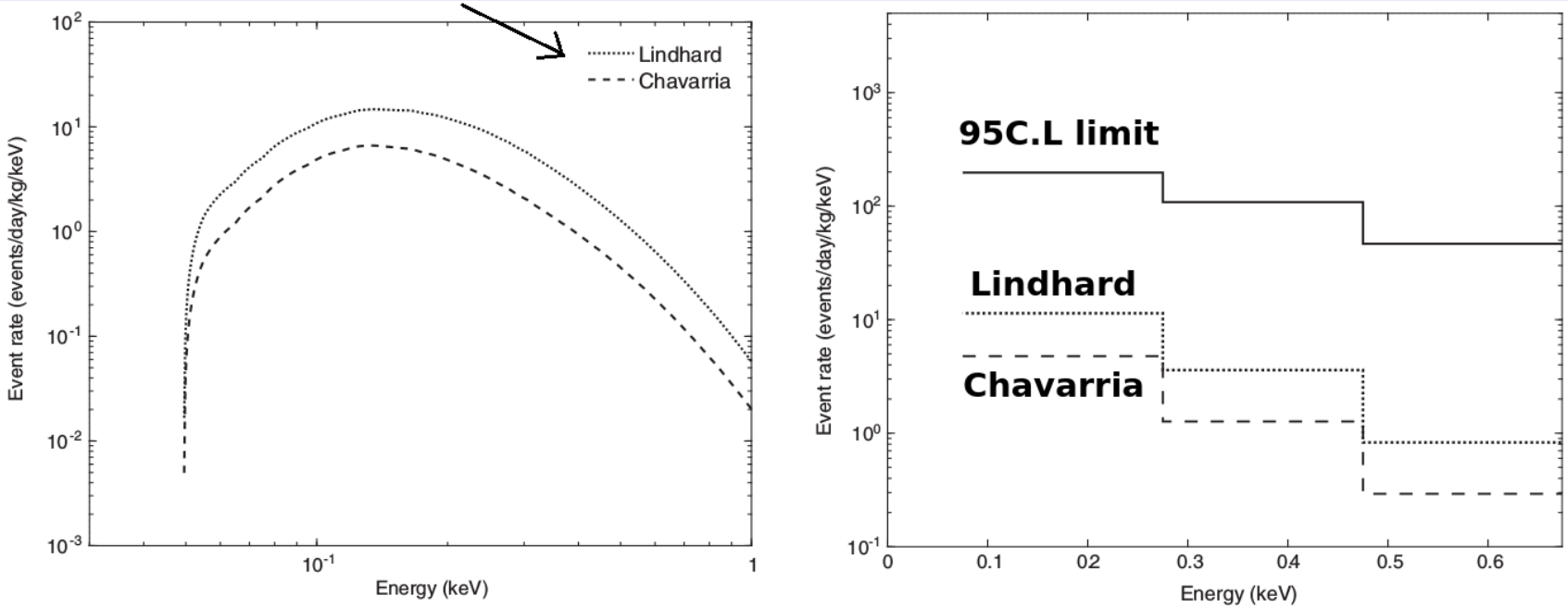


Figure: (left) Observable neutrino recoil spectrum in the CONNIE, (right) CEνNS event rate: 95% confidence level limit from the reactor on-off

Importance of Quenching Factor for DM and ν experiments.

For DM searches with pure crystals the quenching play an important role for calibration and efficiency.

The cutoff for the efficiency is about 60 $\mathrm{eV_{ee}}$ that correspont to $\sim (0.3 \pm 0.1)\mathrm{keV_{nr}}$.

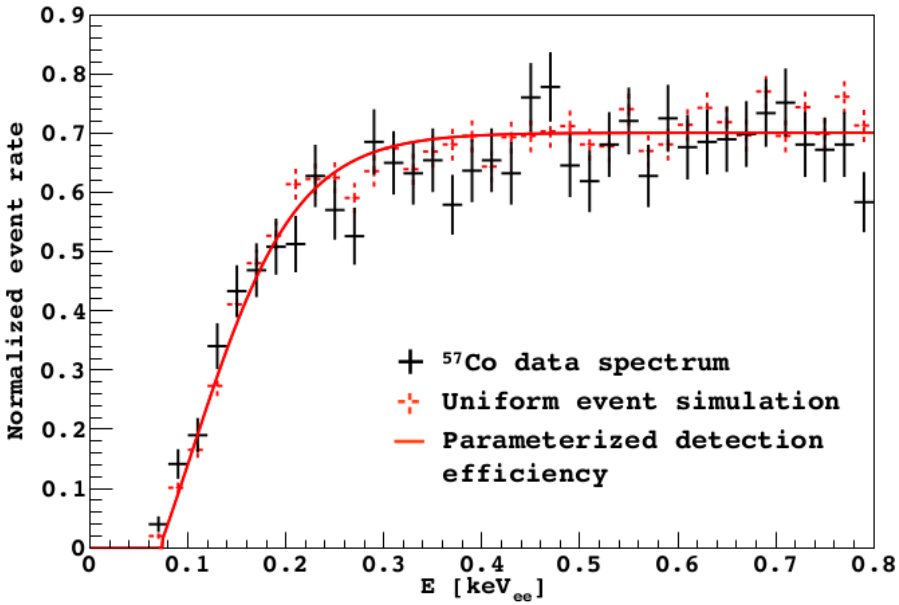


Figure: Detection efficiency, used for the WIMP search analysis (*Phys. Rev. D 94, 082006*).

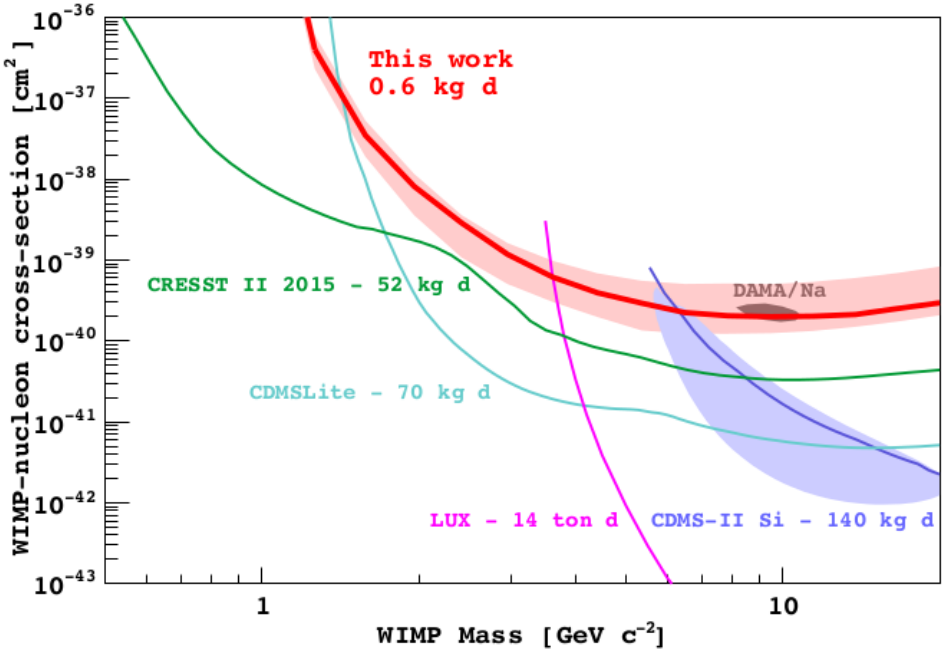
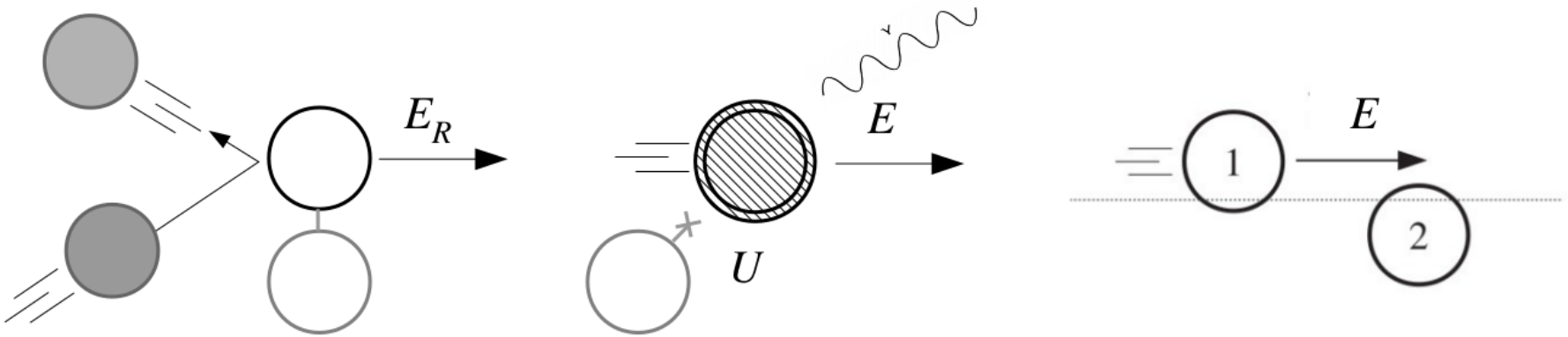


Figure: DAMIC 0.6 kg limit.

The model

- Consider an ion in a homogeneous substance moving with a kinetic energy E, after recoiling off an interaction with an incident particle (e.g., a DM particle).
- Suppose that the ion recoils from the interaction with an energy E_R , and that an energy U is lost to some disruption of the atomic bonding, then $E_R = E + U$
- The moving ion sets off a cascade of slowing-down processes that dissipate the energy E throughout the medium.



The model

Lindhard considered the atomic movement $\bar{\nu}$ an additive quantity over the individual slowing-down processes generated by the initial scattering, for $\bar{\nu}$ the equation is

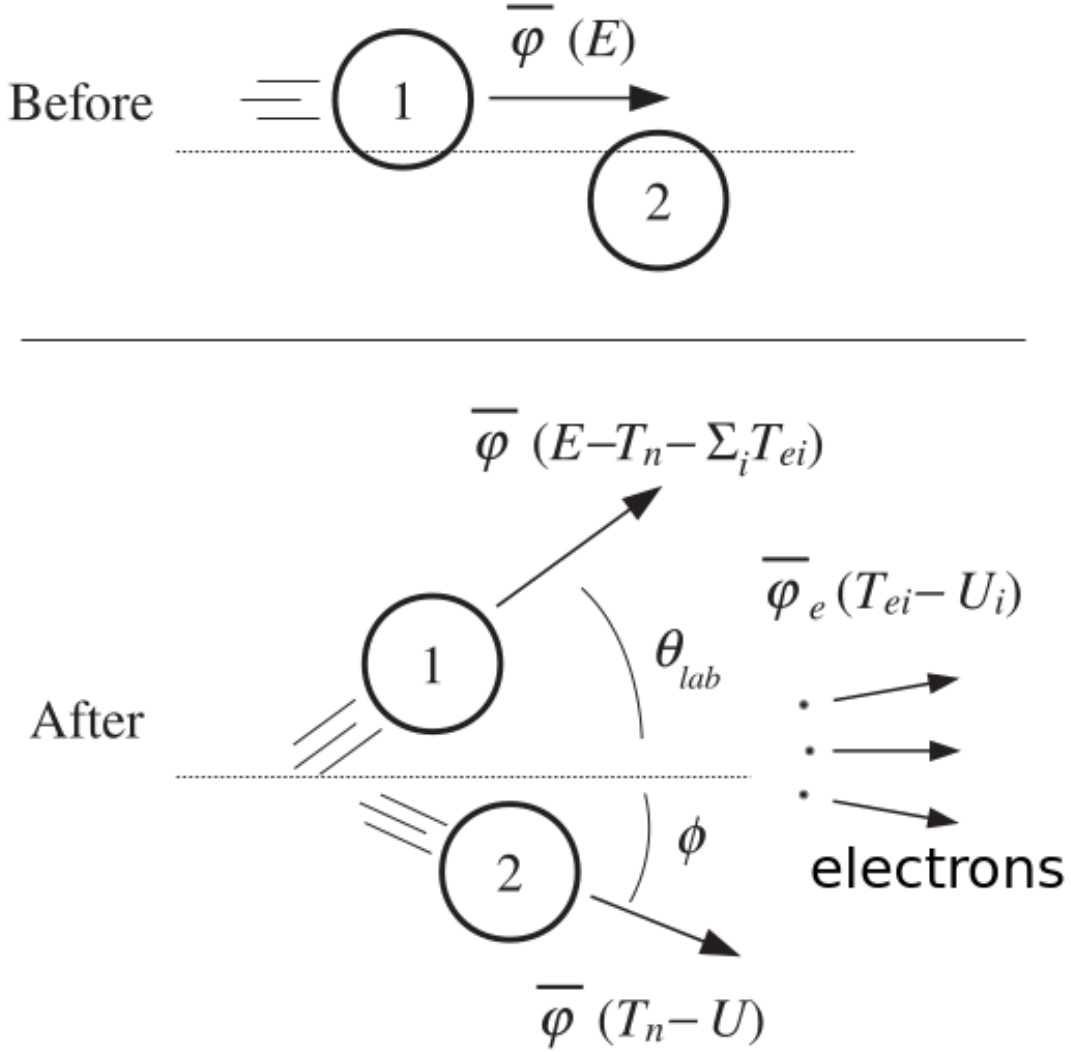
$$\int d\sigma_{n,e} \left[\bar{\nu}\left(E - T_n - \Sigma_i T_{ei}\right) + \bar{\nu}\left(T_n - U\right) - \bar{\nu}(E) + \Sigma_i \bar{\nu}_e \left(T_{ei} - U_{ei}\right)\right] = 0 \tag{1}$$

where T_n and T_{ei} are the energies transferred to nuclei and electrons in the CM frame.

Lindhard originally neglects the binding energy in all his computations.

The model

Here $\bar{\phi} = \bar{\nu}$, can be any aditive physical quantity.



The model

In order to compute a solution for $\bar{\nu}$, we have to made five approximations.

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; $\varepsilon_R = \bar{\eta} + \bar{\nu}$.
iv. T_n is also small compared to the energy E.
v. Expand the terms in Eq. 1 up to **second order including binding energy**.

Simplified integral equation with binding energy

With the above remarks and with the use of the electronic stopping power $S_e = k\varepsilon^{1/2}$ (with k a constant) and the nuclear stopping $d\sigma_n(t)$ with $t = \varepsilon^2 \sin^2(\theta/2)$, we can transform Eq.1 to:

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

This equation can be solved numerically from $\varepsilon \geqslant u$. So the equation predicts a threshold energy of u ($\varepsilon_R^{threshold} = 2u$). The function $f(t)$ is related to the interatomic potential (e.g Thomas-Fermi).

The equation admits a solution featuring a "kink" at $\varepsilon = u$ (discontinuous 1st derivative).

Numerical solution

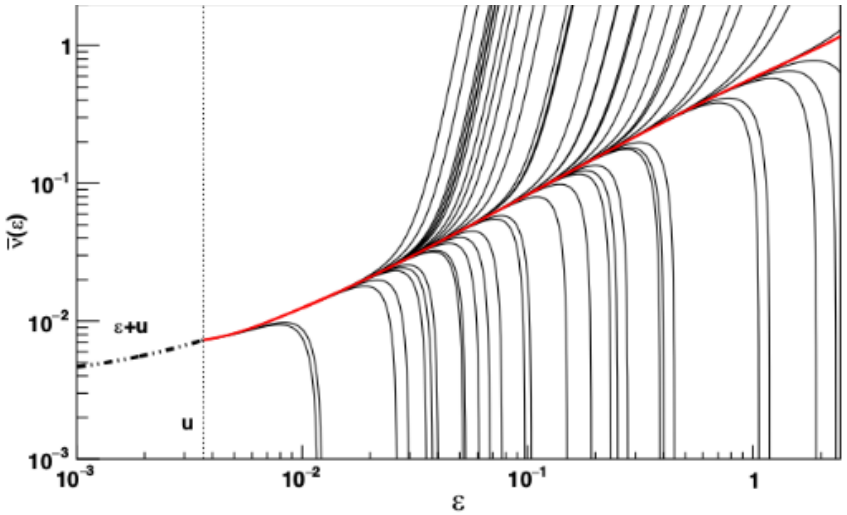
Shooting method

We have the boundary condition $\bar{\nu}''(\varepsilon \to \infty) \to 0$.

Now, since the R.H.S of Eq. 2 is zero at $\varepsilon = u$ and lower, we impose that the L.H.S to be zero at this point, this gives the relation

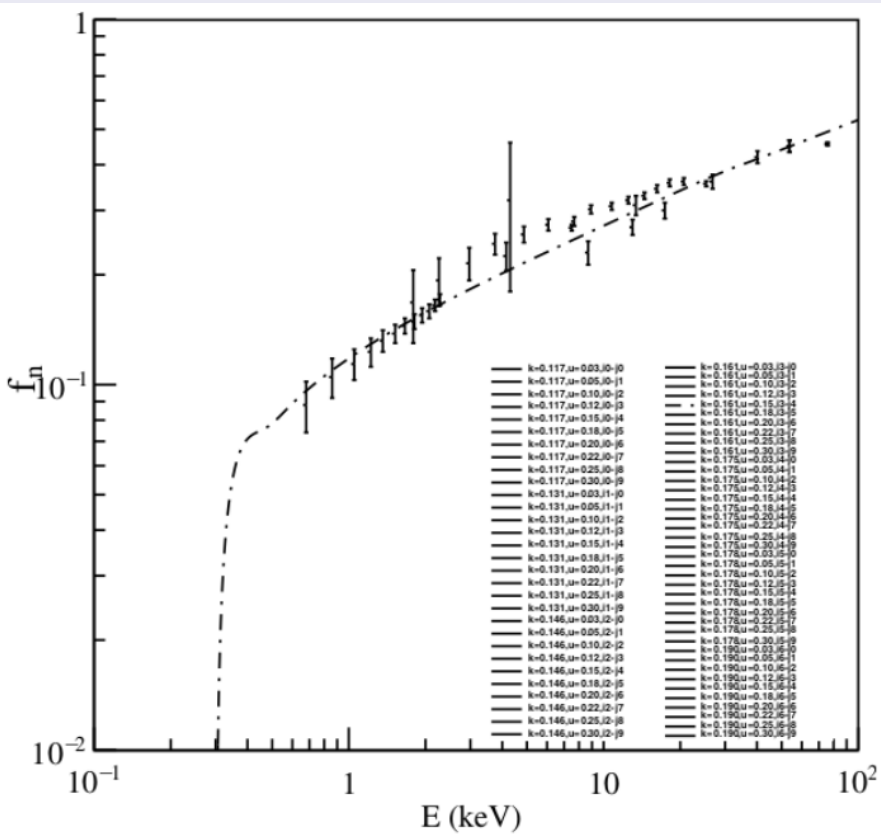
$$\bar{\nu}'(u) = \frac{u}{2}\bar{\nu}''(u)$$

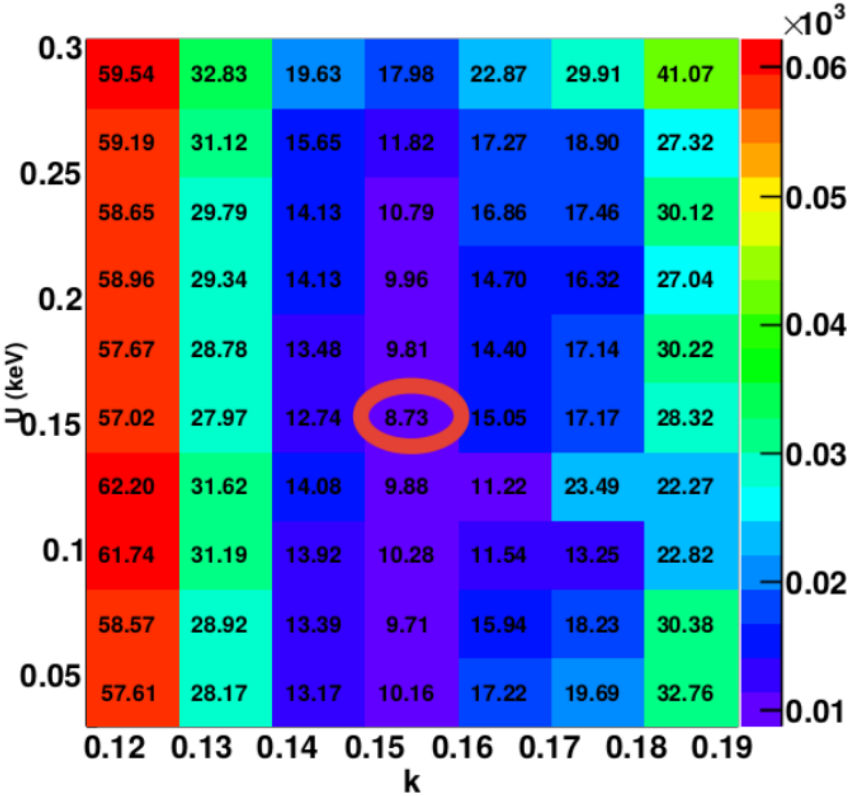
So we give an initial try of $\bar{\nu}'$ to get the boundary condition, we shoot in this way until the boundary condition is satisfy.



Fits to data

We set a grid of 7x7 points in U and k region, in an acceptable ranges, and compute the χ^2/ndf of each (U,k) point to determine the optimal value, we do this for Si and Ge.





Fits to data

In general, U includes both the energy needed to remove the ion from its site and contributions to excitation of bound atomic electrons, therefore incorporates the Migdal effect.

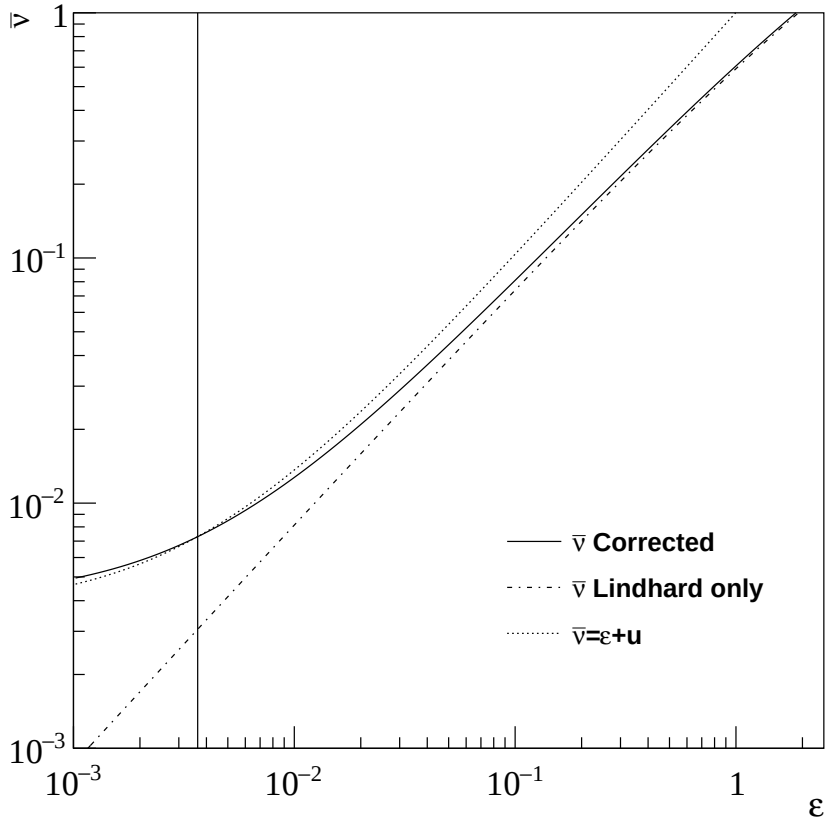
	Silicon*			Germanium*	
Shell	$U(\mathrm{eV})$	$\#e$	Shell	$U(\mathrm{eV})$	$\#e$
$[\mathrm{Ne}]^4$		4	$[\mathrm{Ar}]^{18}$		18
$2p$	100	6	$3d$	30	10
Average $e-h$	3.7	4	Average $e-h$	3.0	4
Dislocation	36		Dislocation	23	

(3)

* E. Clementi and D.L.Raimondi, J. Chem. Phys. 1963, 38, 2686.

Ansatz

- We can implement a good analytical approximation to solve the integral equation.
- The idea is to lessen the ionization contribution, subtracting a fraction of the electronic stopping power.
- $\bar{\eta} = \bar{\eta}_{lind} - c\varepsilon^{1/2} - c'$ where c, c' and u are estimated from a fit to the available data.
- Where $\bar{\eta} = \varepsilon - \bar{\nu}$.



Results (Error band approximate cover the data fluctuation)

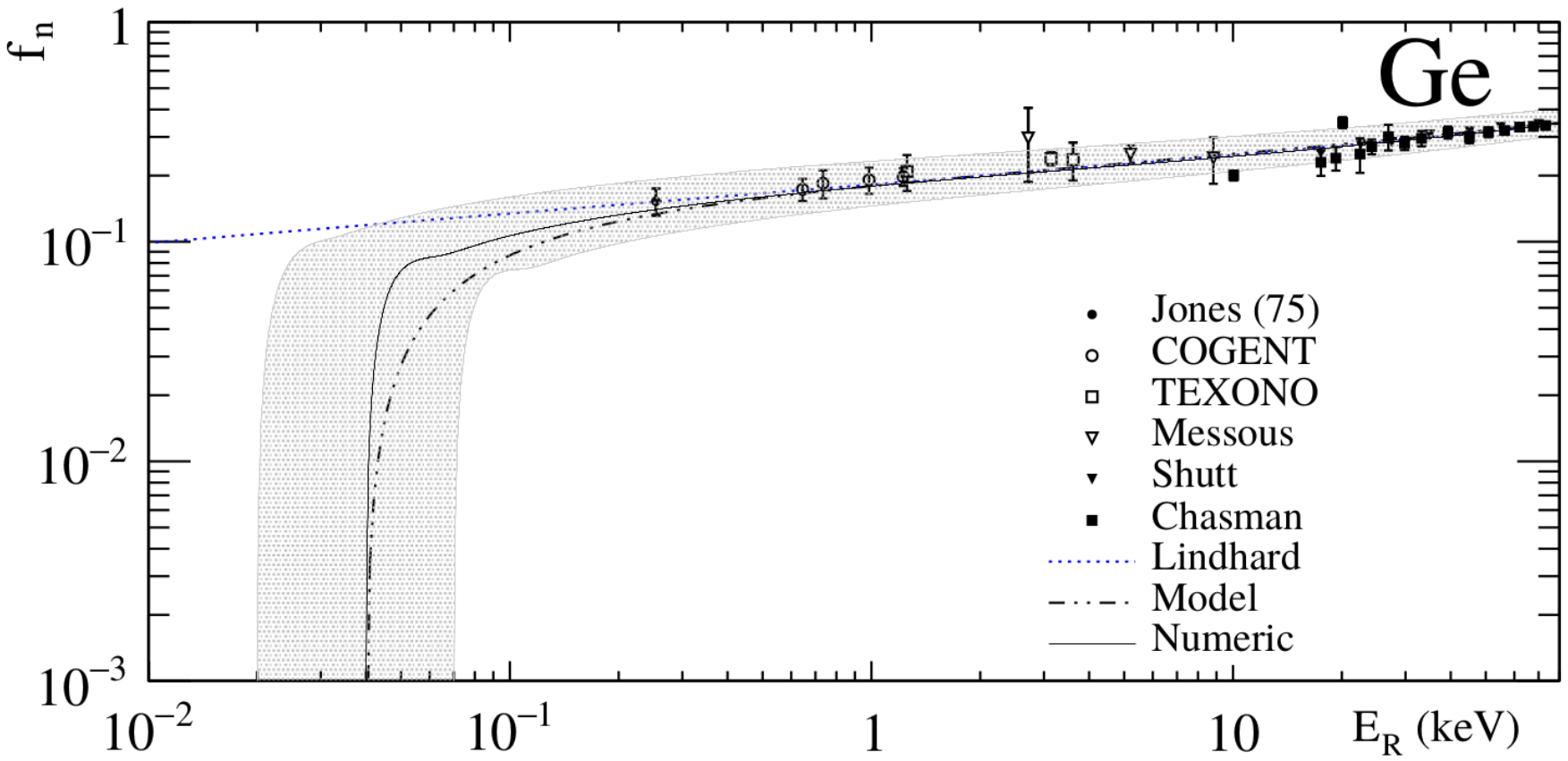


Figure: Measurements of the QF in Ge (points with error bars) compared to the Lindhard model (dot-dashed line), the fitted ansatz, and the numerical solution with U = 0.02 keV and k = 0.162.

Results

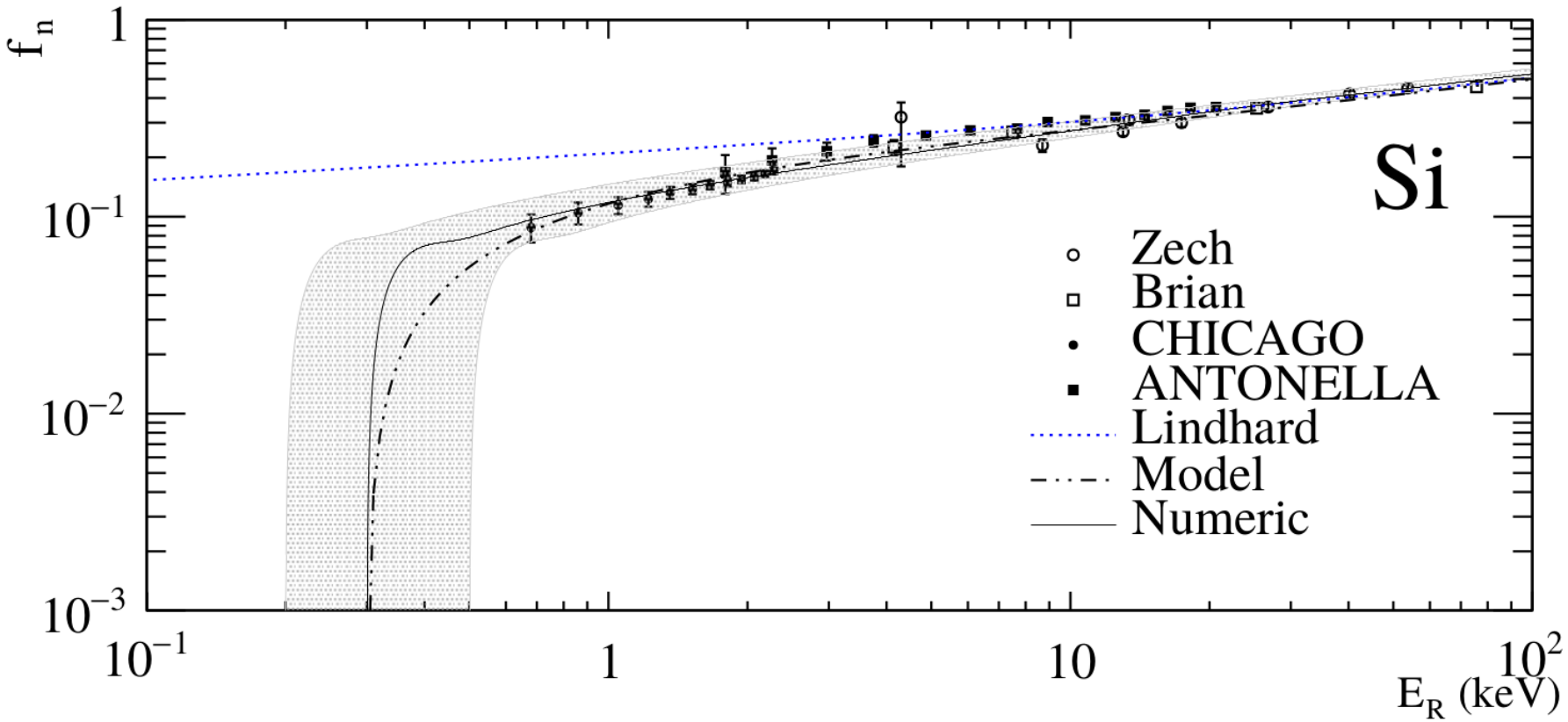


Figure: Measurements of the QF in Si (points with error bars) compared to the Lindhard model (dot-dashed line), the fitted ansatz, and the numerical solution with U = 0.15 keV and k = 0.161.

Conclusions

1. We found an appropriate form for the basic integro-differential equation describing the energy given to atomic motion by nuclear recoils in pure crystals, when a constant binding energy is considered.
2. Measurements of QF in Ge detectors are well described by our model.
3. In the case of Si, the QF measurements are well described by our model if the binding energy is in the range 100-250 eV, where this is consistent with DAMIC data estimate (cutoff of ≈ 0.3 keV).
4. The predicted cutoff for Si is much larger than the Frenkel (dislocation) energy of about 36 eV, and therefore also greater than the physical cutoff.
5. This model can be extended considering energy variable binding energy and modify expression for S_e for low energies. Work in progress.