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Electronic LET for slow ions in dark matter detector media

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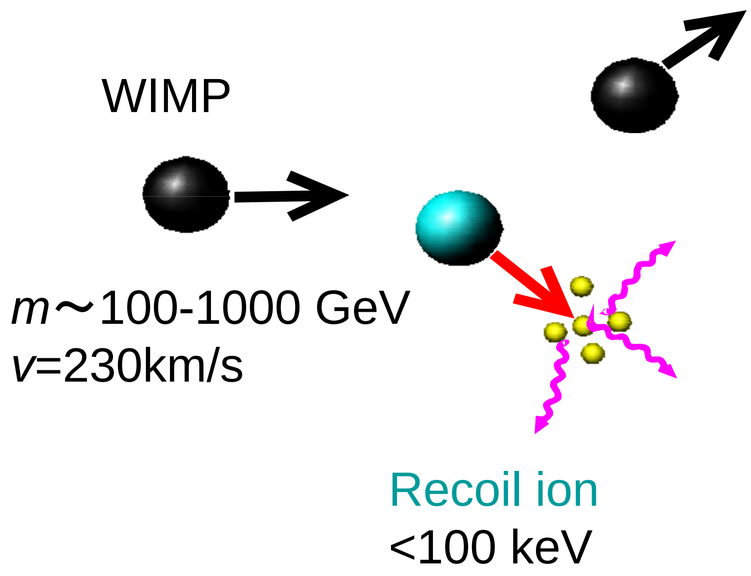
The leading candidates for Dark Matter :
  Weakly Interacting Massive Particles (WIMPs)
Low energy recoil ions may be detected.
  Scintillation and/or ionization
    Information on yield, decay shape, S/T ratio etc.
    are needed.

The electronic LET (linear energy transfer) is the specific electronic energy deposited along the charged particle track



Linear Energy Transfer (LET)

LET: The energy deposited per unit length

LET $\equiv$ -dE/dx for fast ions $S_T \approx S_e$

The electronic LET $LET_{el} = -d\eta / dx$ $S_T = S_e + S_n$

should be introduced for slow ions

The ionization density → The quenching calc., S/T ratio etc.

is given by LET_{el} in liquid and solid scintillators.

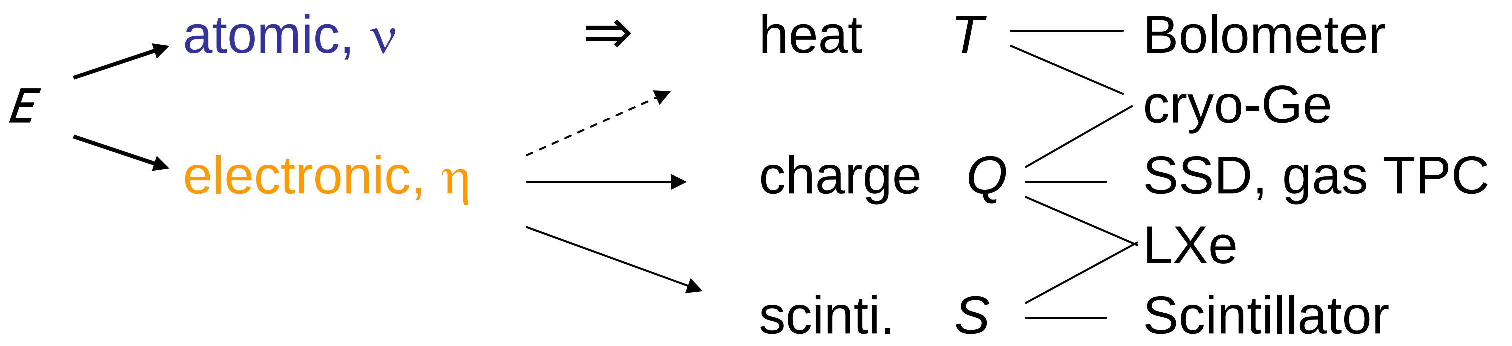
[not by the electronic SP, $(dE/dx)_{el}$]

The Bragg-like curve for TPC → The direction of recoil ions

practical & macroscopic

Energy shearing in low energy

For slow ions, $v < v_0 = e^2/\hbar$, S_e and S_n are similar in magnitude. The secondaries, recoil atoms and electrons, may again go to the collision process and transfer the energy to new particles and so on. After this cascade process completes, the energy of the incident particle E is given to atomic motion ν and electronic excitation η.



Nuclear quenching factor (Lindhard factor) $q_{nc} = \dfrac{\text{Electronic energy}}{\text{Ion energy}} = \eta / E$

integrated for individual recoil created in the cascade, the energy that went to electronic excitation.

RN/γ ratio $= (q_{nc} \cdot q_{el})/L_\gamma$

electronic Linear Energy Transfer (LET_{el})

Scintillation as well as its quenching are electronic processes. We introduce the electronic LET.

$LET_{el} \equiv -d\eta/dR = -\Delta\eta/\Delta R$ R: the range

$= -(\eta_1-\eta_0)/(R_1-R_0)$

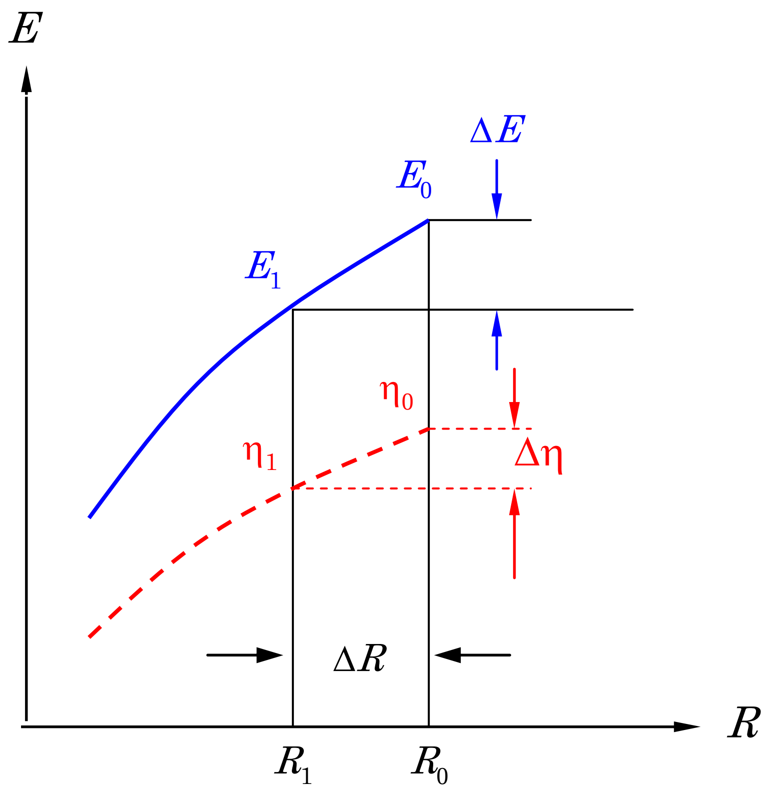
for quenching calc. etc.

The true range R is given by the total stopping power

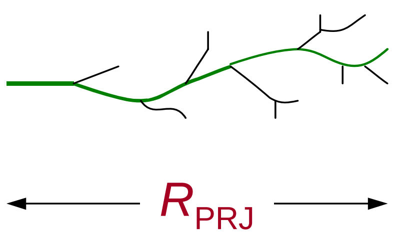
$$R_T = \int (dE/dx)_{total}^{-1}\, dE$$

The Bragg-like curve for TPC

The projected range, R_{PRJ}, may be used (depth)



b)



Lindhard factor η/ε

The stopping powers contain only a part of the necessary information to obtain the quenching factor, η/ε ratio. The differential cross section in nuclear collisions is needed for the integral equations.

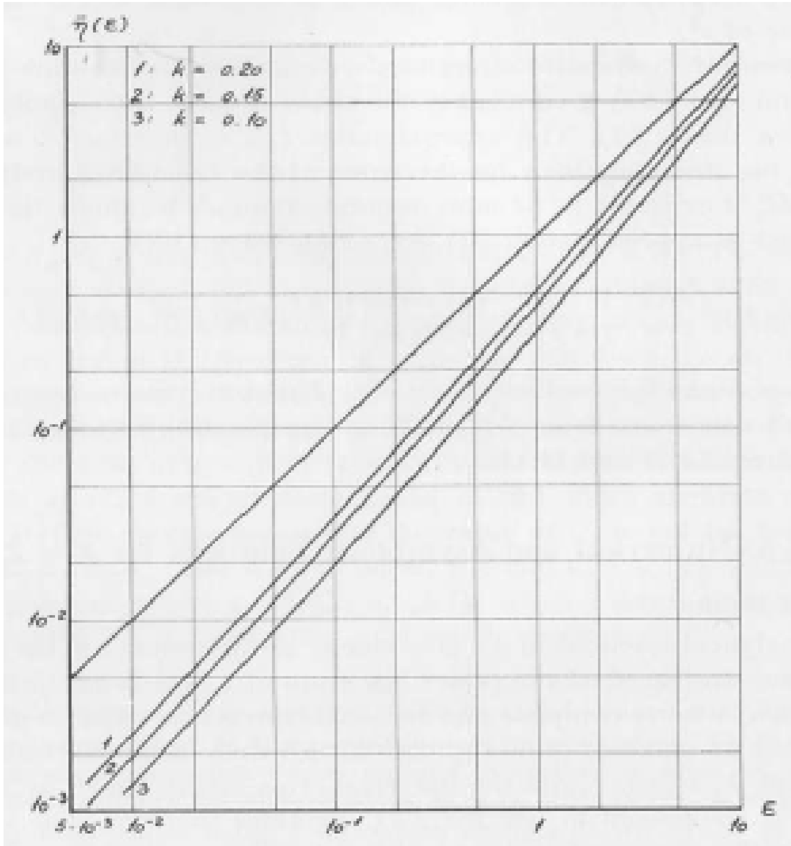
$$\left(\frac{d\varepsilon}{d\rho}\right)_e \cdot \nu'(\varepsilon) = \int_0^{\varepsilon^2} \frac{dt}{2t^{3/2}} \cdot f(t^{1/2}) \left\{ \nu\left(\varepsilon - \frac{t}{\varepsilon}\right) - \nu(\varepsilon) + \nu\left(\frac{t}{\varepsilon}\right) \right\}$$

$$\left(\frac{d\varepsilon}{d\rho}\right)_e = k\varepsilon^{1/2}$$

ε: the dimension less reduced energy

ρ: range

Lindhard



η as a fn of ε for k = 0.2, 0.15, 0.1

For $Z_1 = Z_2$, $\varepsilon > 0.01$

Stopping Power and electronic LET

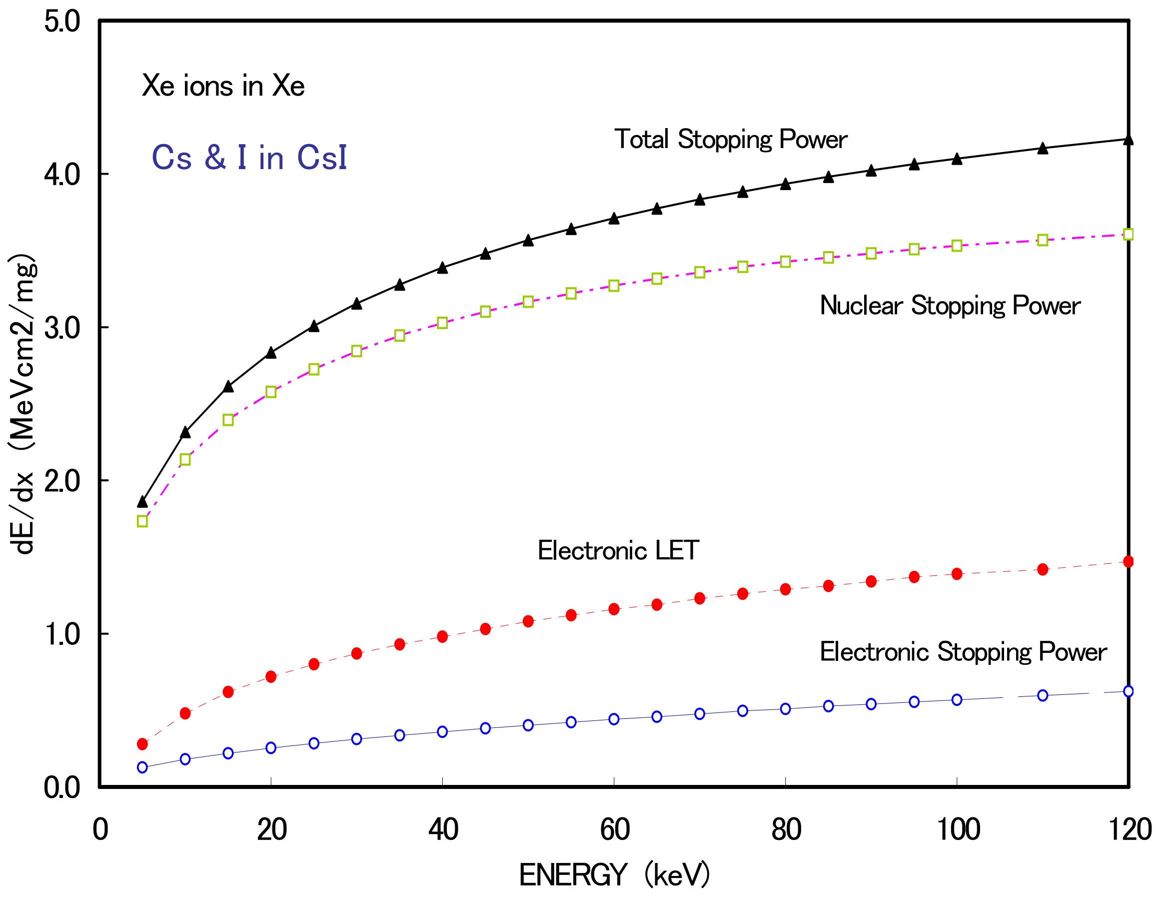


Fig. The stopping power and the electronic LET as a function of the recoil energy for Xe in Xe, and Cs and I ions in CsI.

HMI & Lindhard

RN/γ ratios for LXe and CsI(Tl)

I, Xe and Cs are adjacent to each other in the periodic table.

SP(I) ≈ SP(Cs) ≈ SP(Xe)

q_{nc}(I) ≈ q_{nc}(Cs) ≈ q_{nc}(Xe)

Different energy dependences on RN/γ for recoil ions for CsI and LXe are due to q_{el}.

RN/γ

$$= (q_{nc} \cdot q_{el})/L_{\gamma}$$

Lindhard

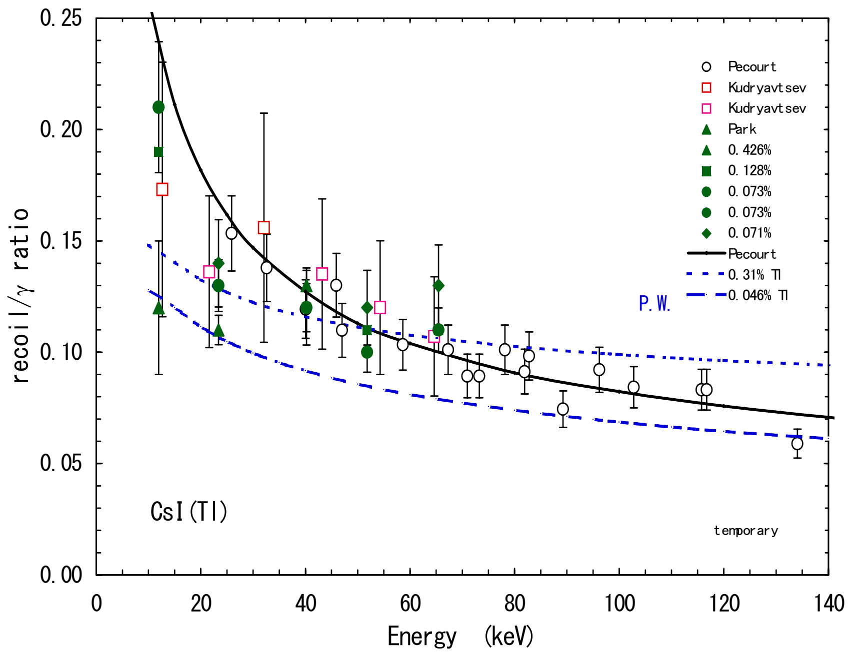
q_{el} ~ 1 for Gas, Si, Ge

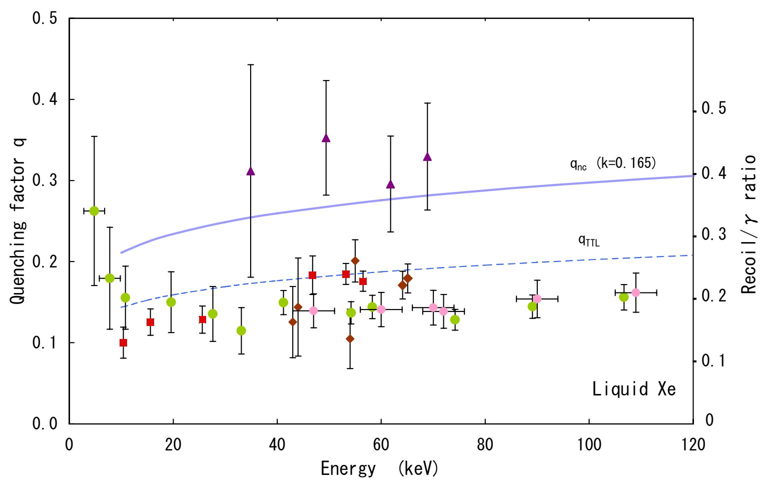
q_{el} < 1 for CsI, NaI, LAr, LXe

LET_{el}

Exciton-exciton collisions

Diffusion

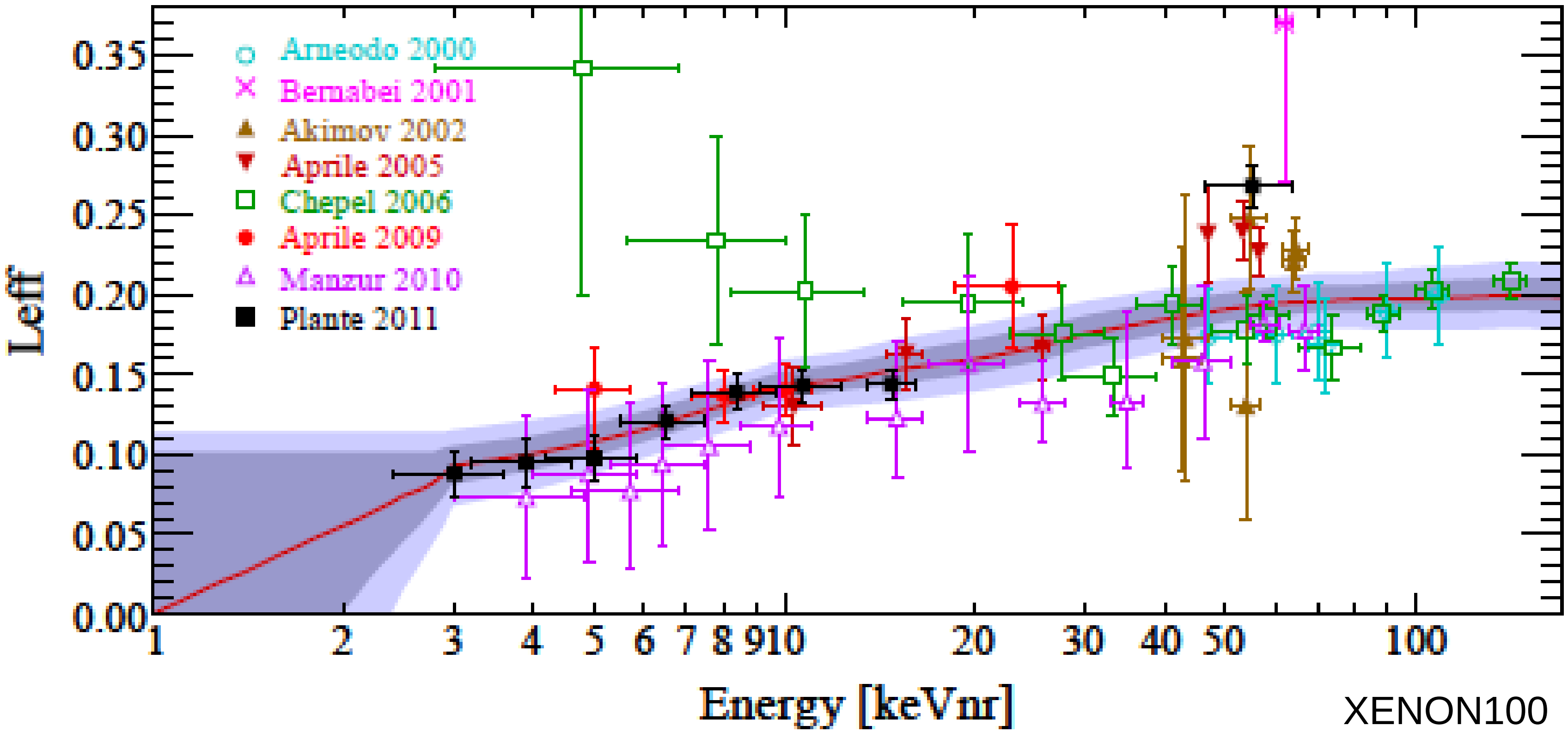




Hitachi, Astropart. Phys. 24, 247 (2005)

実験値: DAMA, ICARUS, ZEPLIN, XENON, Coimbra.

Liquid Xe



XENON100

α/γ ratio
Stopping power theory is not very good for E < 10 keV for Xe-Xe
Needs MO-theory which is quite complicated.
The energy partition between ionization, excitation and sub-excitation e^- may be changed.

W-value measurements in gas gives information on q_{nc}.

Inorganic Scintillatiors

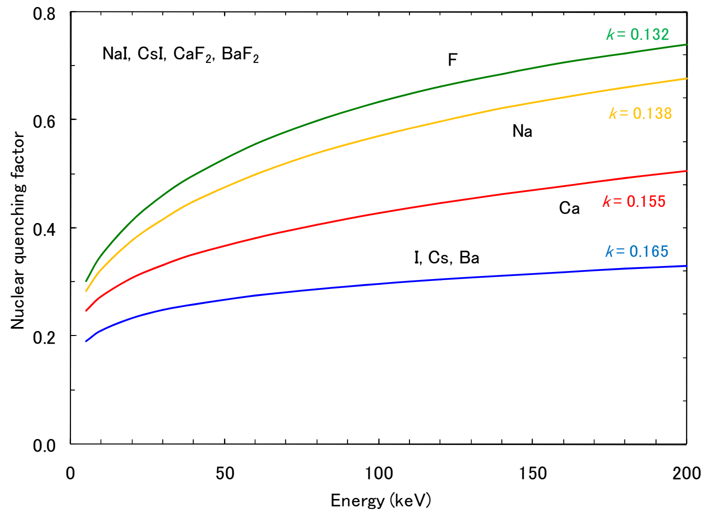


Fig. Nuclear quenching factor q_{nc} for recoil ions in NaI, CsI, CaF_2 and BaF_2 as a function of recoil ion energy.

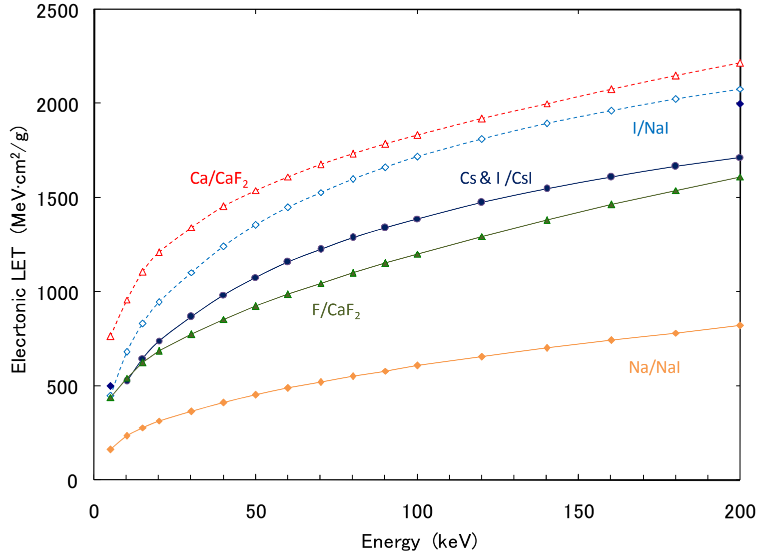


Fig. Electronic LET for recoil ions in NaI, CsI and CaF_2 as a function of energy.

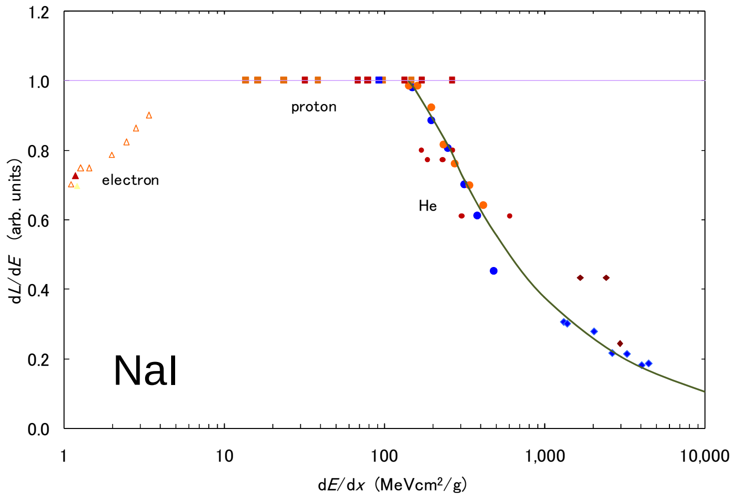


Fig. Scintillation efficiency for various particles as a function of LET in NaI(Tl). The horizontal bars show regions of electronic LET for recoil ions. Murray & Meyer, PR 122, 815 (1961).

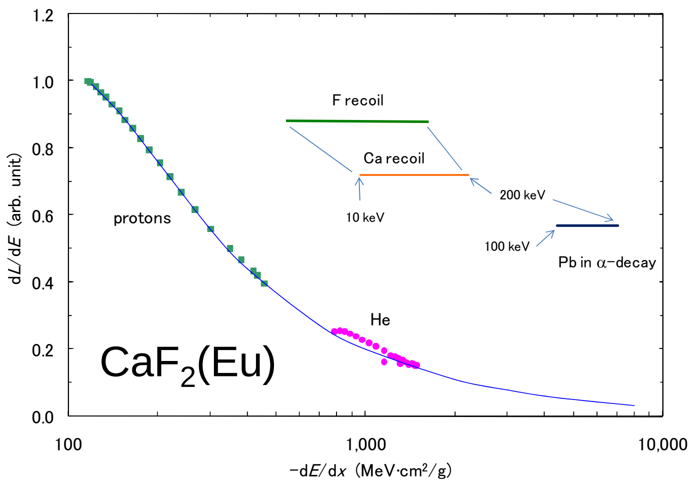


Fig. Scintillation efficiency for protons and He ions (Zhang,2008) as a function of differential LET in CaF_2(Eu). Horizontal bars show electronic LET (=-dη/d*x*) for recoil ions.

Quenching factor for Inorganic Scintillatiors

$RN/\gamma = q_T/L_g = (q_{nc} \cdot q_{el})/L_\gamma$

$q_{nc} \Rightarrow LET_{el} \Rightarrow q_{el}$

Scintillation efficiency L_γ in NaI depends on LET and the velocity. We take values for slow ions

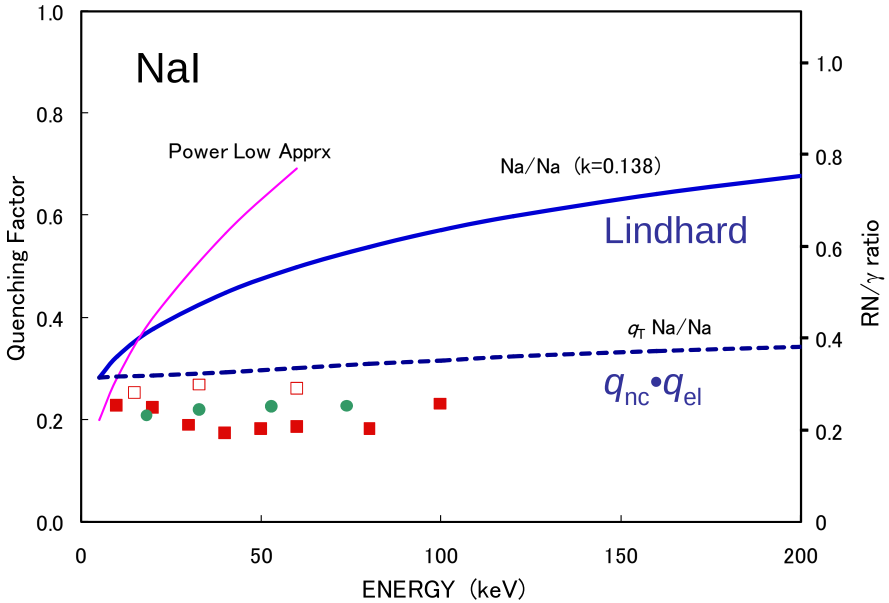


Fig. q_{nc} for recoil Na ions in NaI(Tl).
■ □:Sheffield, ●:Gerbier

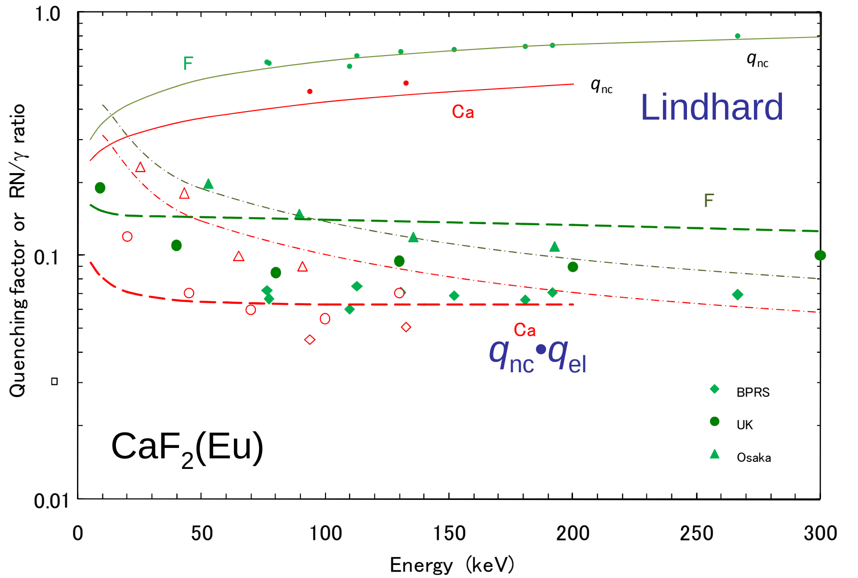
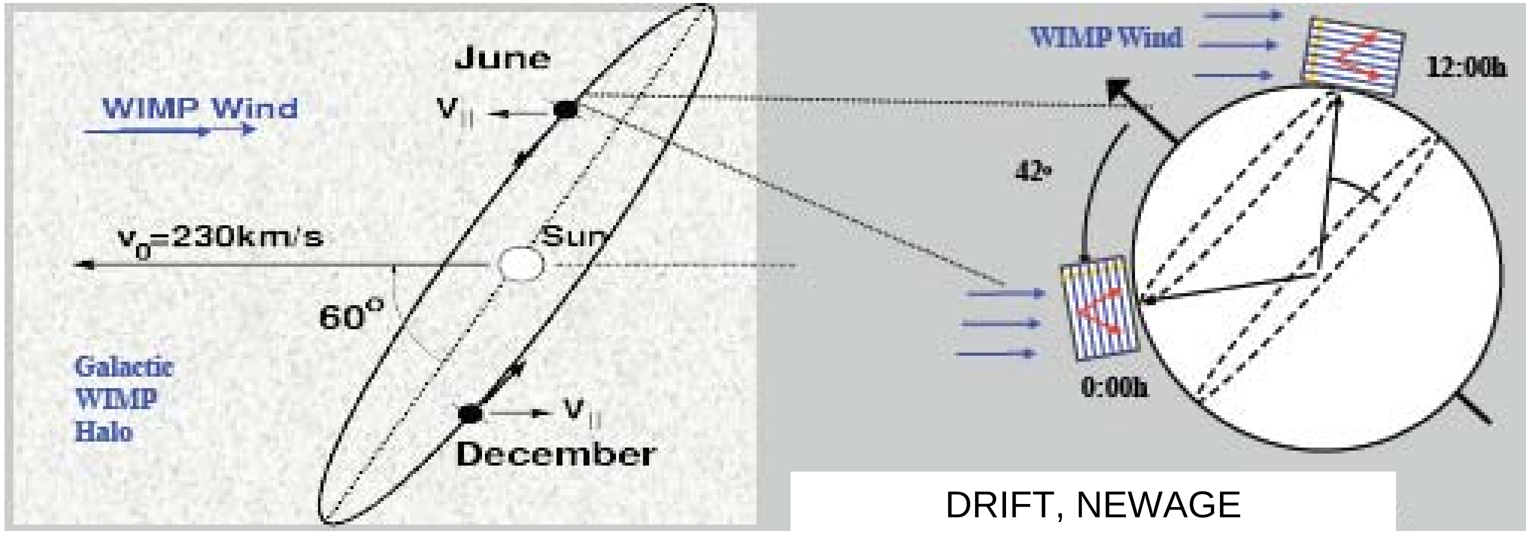


Fig. The nuclear quenching factor, q_{nc}, and RN/γ ratios for Ca and F ions in CaF_2(Eu) as a function of recoil ion energy.
Solid curves are q_{nc} (p.w.).
Broken curves are RN/g ratio (p.w.).
Small dots represents q_{nc} using TRIM code (BPRS).
The dot-dashed curves are RN/γ ratio, fitting and extrapolated to the low energy region assuming that the q-value depends inversely on S_T (Osaka).

Can depends on sensitizer [Tl] concentration.

Head-Tail Detection

The directional detection of low-energy recoil ions can provide strong possibility for observation of dark matter in the Galaxy.

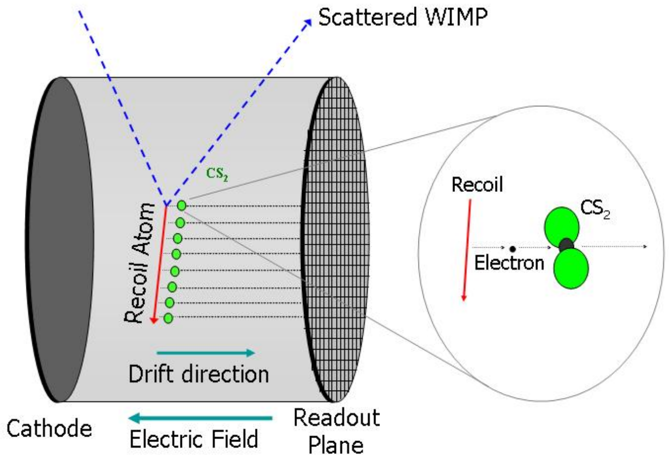


DRIFT, NEWAGE

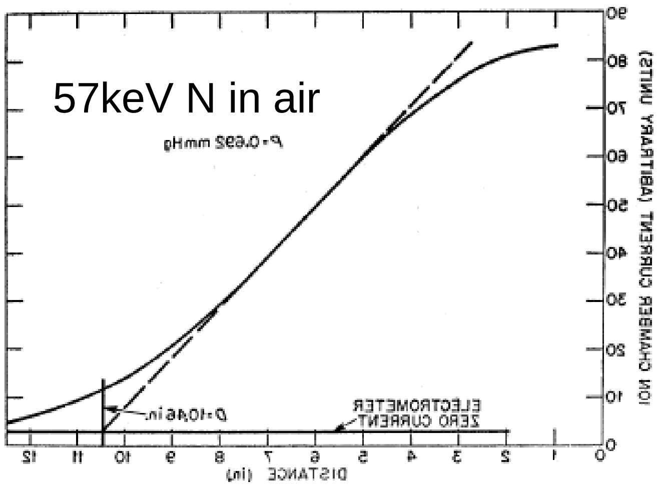
Detectors with directional capabilities can observe daily fluctuations.

gas TPC (Time Projection Chamber)

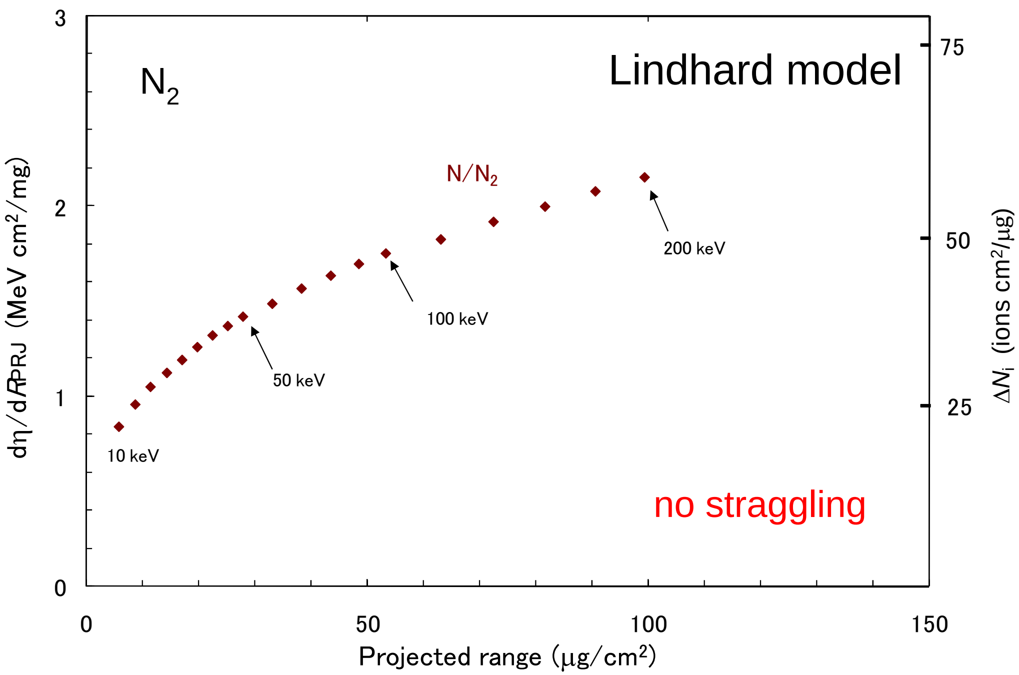
The Bragg-like curve



Bragg-like curve $d\eta/dR_{PRJ}$

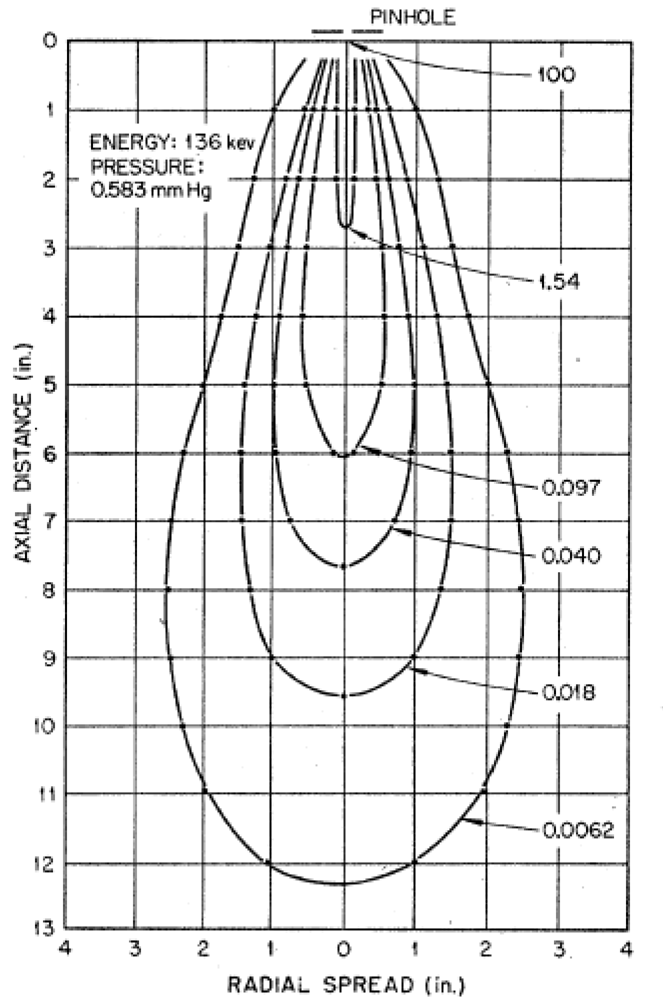


ions



Hitachi, Rad. Phys. Chem. 77, 1311-1317 (2008)

136keV Ar in Ar



Evans, PR 90, 825 (1953)

$\Delta R_{\perp}$ ⇒ bell shape

$\Delta R_{\perp}$ & $\Delta R_{//}$ ⇒ drop-shape

Lindhard factor in compounds

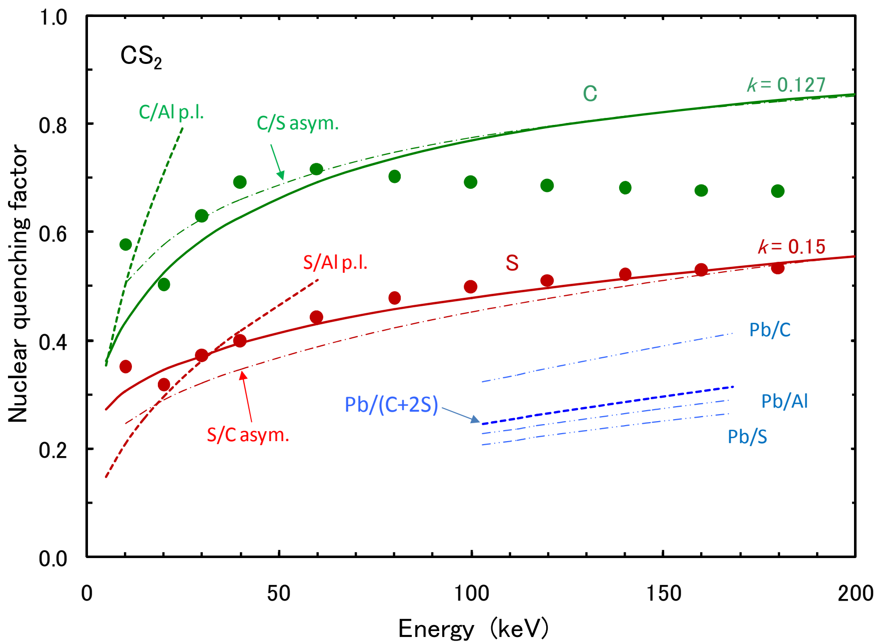
No expressions for q_{nc} in compounds are available. We use a simple approximation.

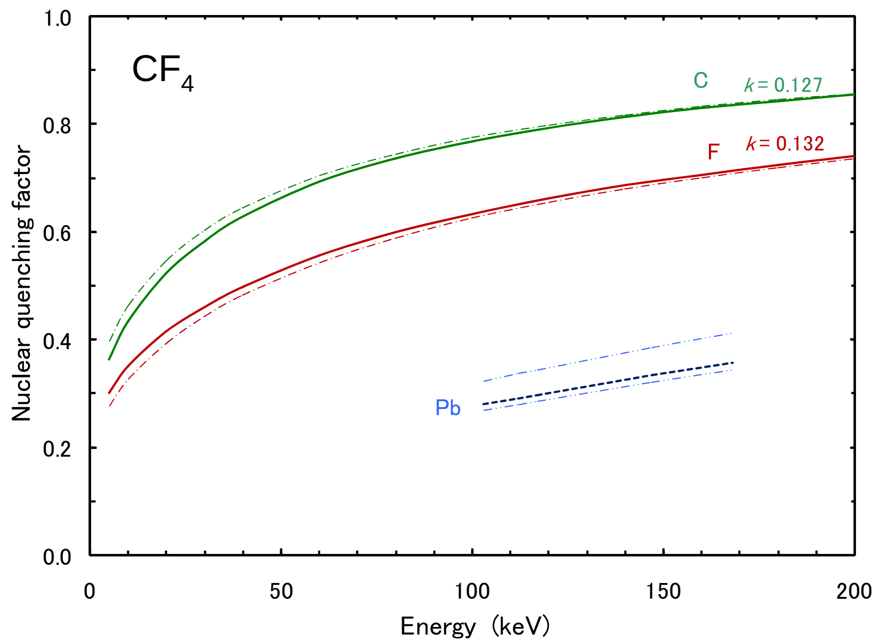
An independent element approach

$$q_{nc}(C/CS_2) \approx q_{nc}(C/C)$$

$$q_{nc}(S/CS_2) \approx q_{nc}(S/S)$$

The model should be tested in ionization measurements in gas.
The simple approach is possible since S_e/S_T ratios for collisions with homo- and hetero-atoms are close to each other





●,●; expt. & part simulation by Snowden-Ifft

NIMA 498, 155 (2003)

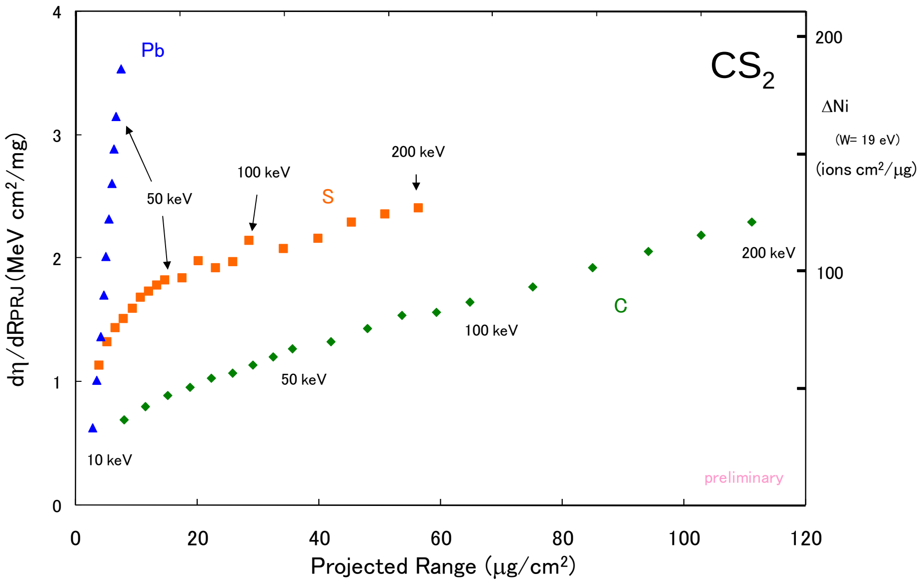
Solid curves; the independent element approach

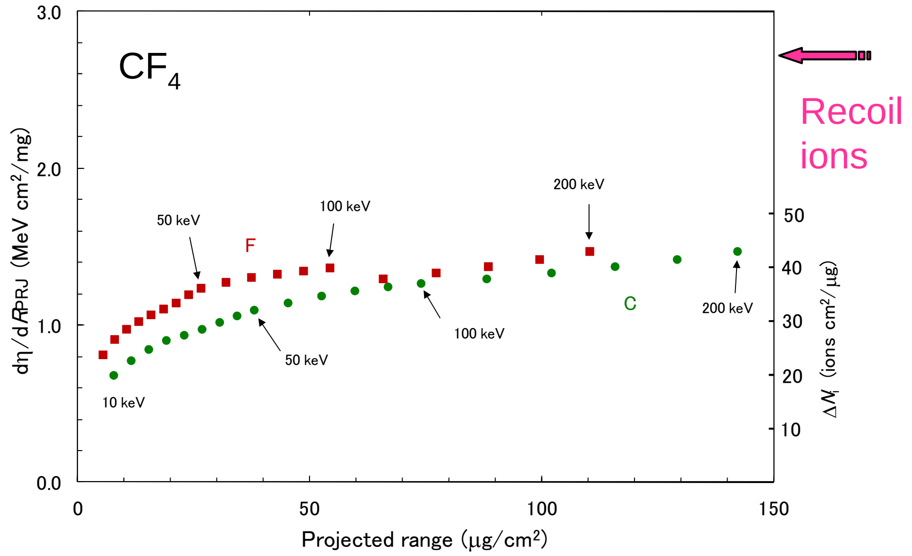
Head-Tail CS_2 CF_4

Bragg-like curve $d\eta/dR_{PRJ}$ charge distribution in recoil direction

CS_2
low diffusion CS^- ions
release e^- at the anode and
get electron multiplication

CF_4
charge carrier is electron
F is effective for WIMP search
via spin-dependent interaction





$\eta = CE^{3/2}$

Recoil ions in α-decay

A power law approximation for $Z1 \neq Z2$ at very low energy (Lindhard 1963),

$$\eta = CE^{3/2} \qquad E < E_{1c}, E_{2c}$$

$$C = \tfrac{2}{3}\{E_{1c}^{-1/2} + \tfrac{1}{2}\gamma^{1/2}E_c^{-1/2}\},$$
$$\gamma = 4A_1 A_2 /(A_1 + A_2)^2$$
$$E_c = \gamma E_{2c}.$$

Energy Straggling

Power law approximation

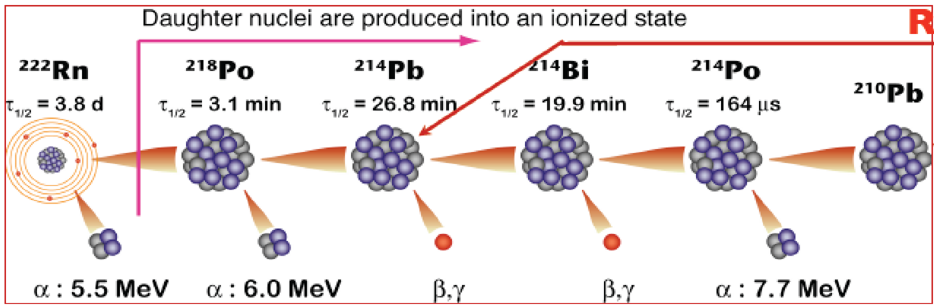
$\sigma^2 = \Omega^2/\eta^2$

σ ~ 14% LAr

Recoil Pb ions in α-decay in LAr

110 keV σ ~ 12%

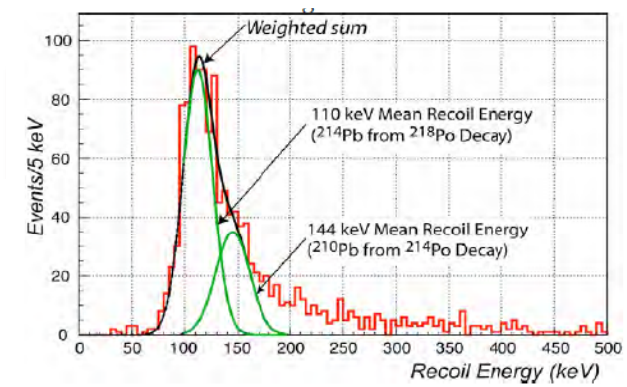
144 keV σ ~ 11%



Recoil energy = 110 keV

Recoil energy = 144 keV

WARP 2007



Lindhard factor for recoil ions in α-decay

Recoil ion	206Pb		208Tl		208Pb		*E*2c
Energy keV	103		117		168		
gas	expt	calc	expt	calc	expt	calc	keV
Ar	0.221a	0.196	0.263	0.205	0.294	0.249	665
Xe	0.139 a	0.124		0.132		0.158	3730
H2		0.73	0.457	0.78	0.544	0.93	26
He		0.53	0.500b	0.56	0.546 b	0.68	53
CH4	0.250		0.265		0.307		
C2H4	0.236		0.269		0.321		
C3H6			0.272		0.281		
CO2			0.336		0.347		
C + 2O		0.297		0.316		0.378	174
C		0.323		0.344		0.411	174
O		0.284		0.302		0.361	241
N2	0.319	0.302		0.320		0.384	207
Dry air	0.296						
4N + O		0.298		0.317		0.379	207
CS2							
C + 2S		0.246		0.262		0.314	174
S	0.208						550
Al (for CS2)	0.228						428

Recoil ion	214Pb		210Pb			
Energy keV	112	calc	147	calc		
CS2		0.346		0.397	SRIM by P.J.	
C + 2S		0.253		0.292		174
Al (for CS2)		0.237		0.272		430

calc : the power law approximation by Lindhard which is only good at E<E2c.

expt : W(alpha)/W(recoil) from:

[a] G.L.Cano, Phys. Rev. 169, 227 (1968). [b] W.G. Stone & L.W. Cochran, Phys. Rev. 107, 702 (1957).

Summary

a) The Lindhard model looks inconsistent with experimental results in inorganic crystals in the first sight. However, the inclusion of electronic (scintillation) quenching, the model still gives the best results.

b) The electronic LET (=-dη/dx) plays important role in the evaluation of scintillation quenching.

c) The electronic LET for recoil ions is close to LET for α-particles. Therefore, the scintillation characteristics, such as decay shape, S/T ratio and the ionization yield due to recoil ions are expected to be similar to those due to α-particles.

d) The Bragg-like curve is useful for estimation of head-tail detection.

The scintillation efficiency for γ-rays, protons, α-particles and fission fragments are needed to evaluate the quenching factor for recoil ions.

Refinement of stopping theory for low energy ions is required.

Refs.
1) A. Hitachi, Rad. Phys. Chem. 77, 1311-1317 (2008).
2) S. Suzuki and A. Hitachi, "Application of Rare Gas Liquids to Radiation Detectors" in *Charged Particle and Photon Interactions with Matter: Recent Advances, applications, and Interfaces*. ed. Y. Hatano *et al*. (Taylor & Francis, Boca Raton. 2010). Chap. 31.