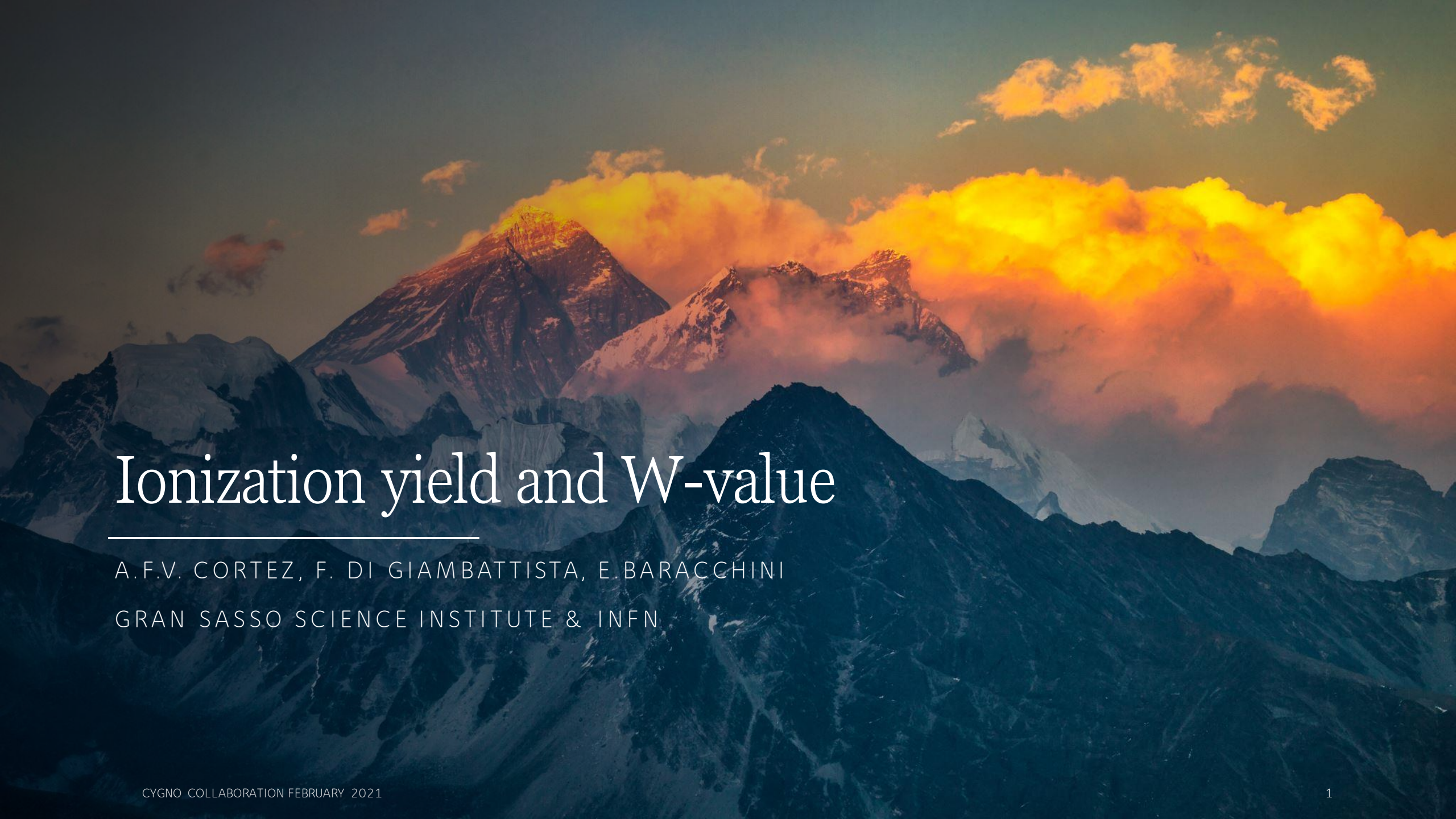




Ionization yield and W-value

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Objectives

- Determine the expected cross-sections for the Dark Matter searches within CYGNO Collaboration.
- Estimate the energy released from NR to electron ion-pairs to assess the detector performance.

Ionization Yield

The determination of the primary charge produced by an incident particle (neutral or charged) is not a issue for high energies.

- Number of electron-ion pairs is quite high;
- Fluctuations tend to be less important;
- No significant variation between ER and NR



- Problem arises for low energies, where a significant fraction of the energy of the NR is lost through collisions with the nuclei.

$$\Delta E = \frac{2mM}{(m+M)^2} E_i$$



- Usually no distinction is made between excitations and ionizations.

Table 5.1 Values of the Energy Dissipation per Ion Pair (the W-Value) for Different Gases^a

Gas	First Ionization Potential (eV)	W-Value (eV/ion pair)	
		Fast Electrons	Alpha Particles
Ar	15.7	26.4	26.3
He	24.5	41.3	42.7
H ₂	15.6	36.5	36.4
N ₂	15.5	34.8	36.4
Air		33.8	35.1
O ₂	12.5	30.8	32.2
CH ₄	14.5	27.3	29.1

^aValues for W from ICRU Report 31, "Average Energy Required to Produce an Ion Pair," International Commission on Radiation Units and Measurements, Washington, DC, 1979.

W-value depends:

- Particle
- Energy
- Medium

(Knoll, 2000)

Mixture	Fano factor			w-value (eV)		
	Previous experimental results	Simulation results	This work	Previous experimental results	Simulation results	This work
100% Ar	0.19 for 5.68 MeV α -particles [20]	0.17 [20]		26.4 for 5.3 MeV α -particles [26]		
	<0.40 $\pm$ 0.03 for 1.49 keV X-rays [21]					
	0.23 $\pm$ 0.05 (extrapolation to infinite pressures) [22]	0.16 for electrons [29]		25.8 $\pm$ 0.6 (at 1280 mbar) [13]		
	0.30 $\pm$ 0.04 [25]	0.15 [30]		26.2 $\pm$ 0.7 (at 1400 mbar) [14]		
	0.20 ^{+0.0} _{-0.02} [27]	0.16 [31]				
	0.22 for 6.0 MeV α -particles [28]					

As you can see values are quite close but if we look at the energies used for alpha particles these are quite high (MeV).

(do Carmo, 2008)

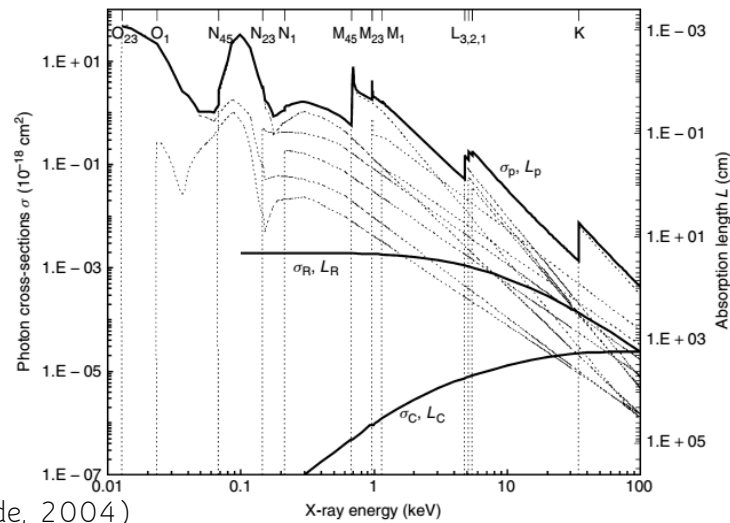
Ionization Yield

W-value is usually obtained experimentally. For low energies, it is possible to observe nonlinearity effects that result from the interaction mechanisms of the incident radiation (particle) used in the measurements.



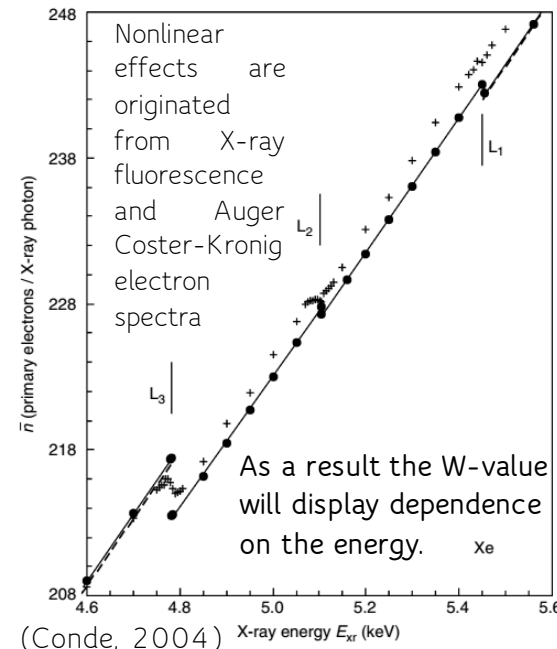
Still, the number of primary e- varies almost linearly with the energy (except for very low energies).

Example: X-rays – 5.86 keV (55Fe) in Xe

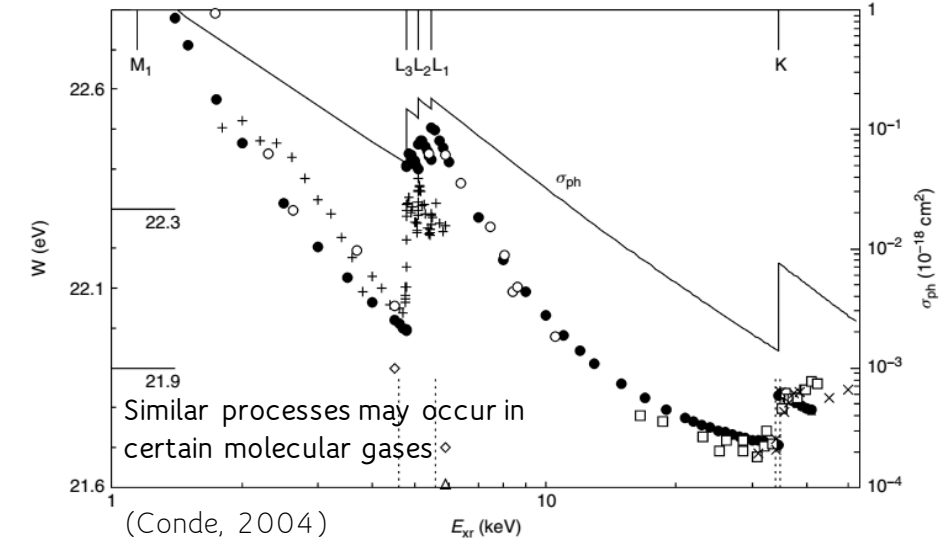


(Conde, 2004)

Figure 4.2.3 Photoelectric σ_p , Rayleigh σ_R and Compton σ_C cross-sections for X-rays in Xe. Corresponding absorption lengths L_p , L_R and L_C for Xe at 20°C and 760 Torr refer to the right-hand side axis. Partial shell and subshell cross-sections are plotted as dotted lines. (Based on Figure 1 of Dias *et al.*³ and references therein and in <http://www.photocoeff.com/212154.html> and http://physics.nist.gov/cgi-bin/Xcom/xcom3_1)



(Conde, 2004)



(Conde, 2004)

Figure 4.2.7 W value for X-rays in gaseous Xe as a function of energy (Figure 4 of Dias *et al.*⁵). Solid symbols are Monte Carlo values; other symbols are derived from experimental results or are absolute measurements ($\circ, \Delta$). Continuous line represents the Xe photoelectric cross-section. For details see Dias *et al.*⁵

Ionization Yield

Since most of the w-values found in literature were obtained experimentally, different processes come into play and their influence needs to be evaluated.

Penning effect

If the gas has a lower ionization energy than the excitation of the main one, both the w-value and Fano factor can be reduced

Energy that would go to excitation processes of the main gas can be converted into ionization.

Reduces W-value

Recombination

Takes place when electrons are thermalized very close to their parent ions (within Onsager radius)

$$\frac{dn^+}{dt} = \frac{dn^-}{dt} = -\alpha n^+ n^-$$

n^+ = number density of positive species
 n^- = number density of negative species
 α = recombination coefficient

Increases W-value

Depend on the reduced electric field.

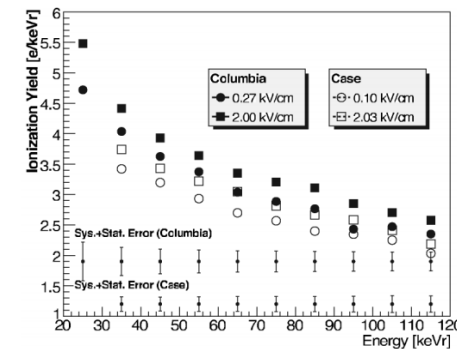


FIG. 4. Energy dependence of nuclear recoil ionization yield in LXe at different drift fields.

(Aprile, 2006)

Backscattering (tailing effects)

Very low energy X-rays (below 1 or 2 keV) are absorbed very near the detector window and since their absorption lengths are very small (about 20 μm for 100 eV x-rays and 200 μm for 1 keV X-rays), some electrons can be scattered back to the detector window.

Ionization Yield

Let's look at what happens in SRIM.
In the case of NR a cascade of atoms/ions is produced.



So the stopping power is used to determine the amount of energy that is transferred to ionization/excitation (first term) and the part of energy lost to heat (second term).

$$dE/dx = (dE/dx)_e + (dE/dx)_{\text{nucl}}$$

Which is what SRIM does...

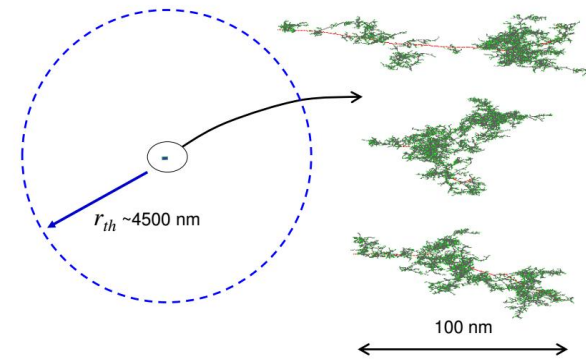


Figure 14. Xe recoil tracks in liquid xenon simulated with TRIM [62] compared with the thermalization distance (calculated in [134]). The projectile trajectory is shown in red; trajectories of secondary atoms/ions are in gray with end points in green (this shows the number of secondary atomic recoils in the cascade). No electron tracks are shown.

(Chepel, 2013)

So in order to compare ER and NR a QF was determined using SRIM. The use of the term "quenching factor" might be misleading. Since in semiconductors there are additional mechanisms through which the excitation energy is dissipated.



Where instead of emitting a deexcitation photon the energy is dissipated through the defects in the structure or through impurities.

Ionization Yield

For obvious reasons, in the case of ER we can assume:

$$dE/dx = (dE/dx)_e + \overset{\text{zero}}{\cancel{(dE/dx)_{\text{nucl}}}}$$

While in the case of NR this second term is not negligible

$$dE/dx = (dE/dx)_e + (dE/dx)_{\text{nucl}}$$



So in order to determine the number of excitations/ionizations) one should use only the electronic stopping power.

Which needs to be corrected (multiplying it by a correction factor...which some call "Ionization Quenching Factor".

So..how can we retrieve this value?

And how well can it describe the energy transferred to ionization?

Table 1. Energy expended per scintillation photon for different particles. (Chepel, 2013)

Particle	Energy	LET, MeV/(g·cm ²)	W _s , eV (LAr)	W _s , eV (LXe)
No quenching; W _s ^{min}	–	–	19.5 ± 1.0 ^{a)} 19.8 ^{b)} 18.4 ^{b)}	13.8 ± 0.9 ^{a)} 13.0 ^{b)} 14.7 ± 1.5 ^{c)} 13.45 ± 0.29 ^{d)} 13.7 ± 0.2 ^{e)}
Relativistic electrons	1 MeV	≈ 1	25.1 ± 2.5 ^{c)} 24.4 ^{a)}	23.7 ± 2.4 ^{c)} 21.6 ^{a)} 22.5 ± 2.5 ^{f)} < 35 ^{g)} 42 ± 6 ^{h)} 67 ± 22 ⁱ⁾
Low energy electrons	20 – 100 keV	~7 to 2	–	18.3 ± 1.5 ^{f)} 14.2 ^{j)} 12.7 ± 1.3 ^{k)} 29.6 ± 1.8 ^{l)}
α-particles	≈ 5 MeV	~ 4 × 10 ²	27.1 ^{a)} 27.5 ± 2.8 ^{c)}	17.9 ^{a)} 19.6 ± 2.0 ^{c)} 16.3 ± 0.3 ^{m)} 17.1 ± 1.4 ^{f)} 39.2 ⁿ⁾
Relativistic heavy ions	~ 1 GeV/amu	~ 10 ² to 10 ³	19.4 ± 2.05 ^{c)}	14.7 ± 1.5 ^{c)}
Nuclear recoils*	60 keV	2.9/4.0 × 10 ³	~ 100 ^{p)} (exp) ~ 90 ^{q)} (theor)	95 ± 20 ^{r)} (exp) ~ 77 ^{s)} (theor)
	20 keV	2.6/2.7 × 10 ³	~ 100 ^{p)} (exp) ~ 105 ^{q)} (theor)	110 ± 20 ^{r)} (exp) ~ 86 ^{s)} (theor)
	5 keV	1.9/1.5 × 10 ³	~ 100 ^{p)} (exp) ~ 140 ^{q)} (theor)	160 ± 40 ^{r)} (exp) –
Fission fragments	~ 1 MeV/amu	~ 10 ⁴	~ 110 ^{t)}	60 ^{u)}

Ionization Yield

First problem to understand the conversion of the energy deposited to the observed primary charge is nonlinear for low energies (due to fluctuations in the ionization processes) .. This is especially relevant for energies below 10 keV

Naively I would think that these aspects play a crucial role:

- Recombination (leading to the loss of primary charge);

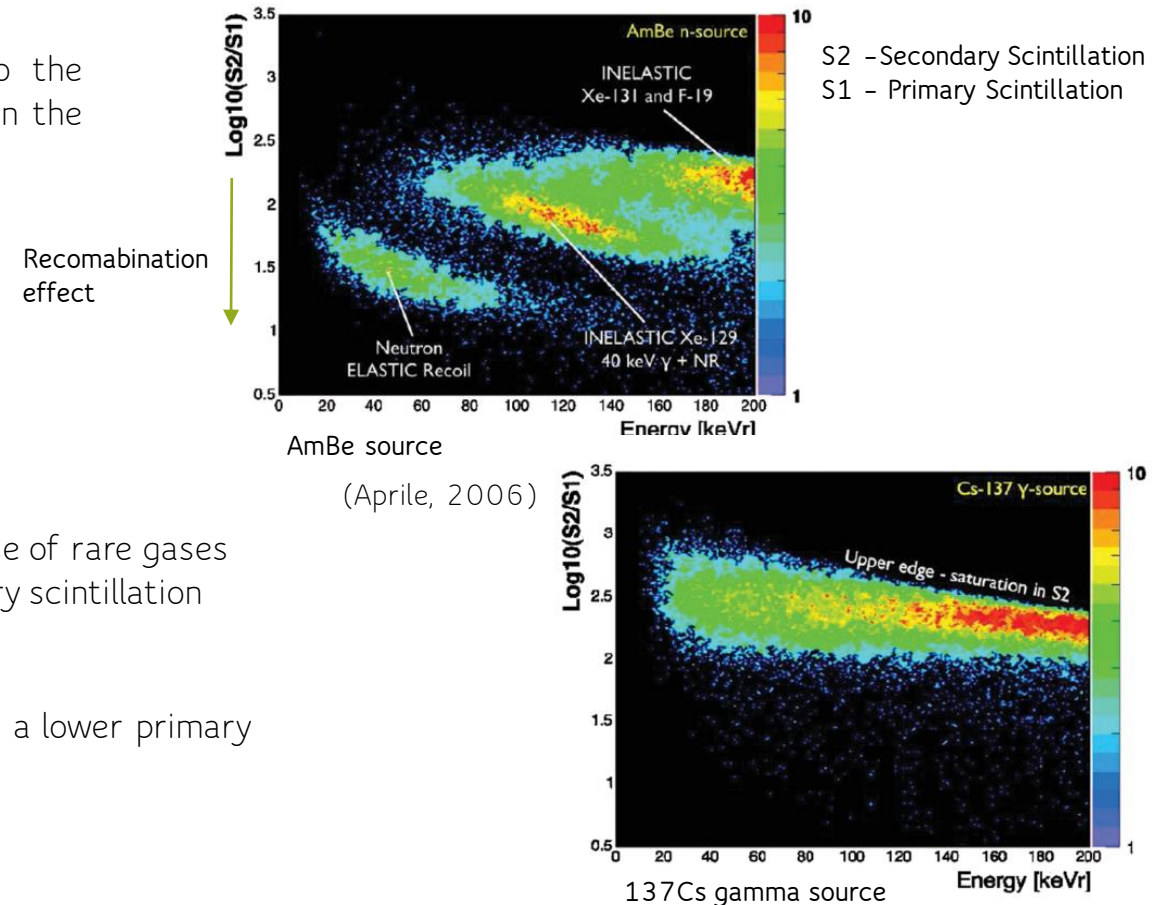


- Charge density is higher for NR and so electrons produced will thermalize very close to their parent ions (within Onsager radius)



Leading in the case of rare gases to a higher primary scintillation yield (gas-phase)

But at the cost of a lower primary charge.



Ionization Yield

How to determine the influence of the incident particle in terms of ionization yield?

First issue, is that the majority of experiments regarding low energy NR are based on scintillation and so the effect of NR is better understood for scintillation than for ionization. Still, we can learn a great deal from them...

XENON1T example

Ionization yield

For gammas and alpha particles:

$$Q_0 = E_e/W_e$$

$\mathcal{L}$ - Lindhard factor
(Aprile, 2006)

Lindhard's theory describes the energy loss due to nuclear collisions.

For nuclear recoils:

$$Q_0 = E_r \mathcal{L} / W_e$$

How can we get the Lindhard factor for our gas mixture?

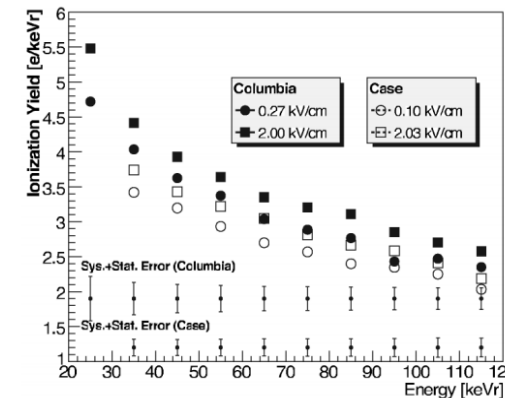


FIG. 4. Energy dependence of nuclear recoil ionization yield in LXe at different drift fields. (Aprile, 2006)

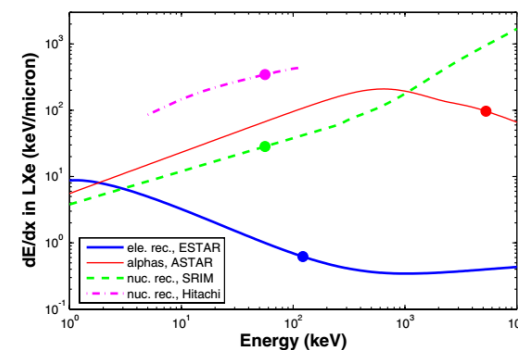


FIG. 5 (color online). Predicted electronic stopping power, dE/dx , for different particles in LXe. The circles indicate the particle energies discussed in the text. (Aprile, 2006)

Important: NR ionization yield exhibit a slight dependence with the drift field and NR energy.

Lindhard predicts a slight decrease in the charge yield for lower NR energies (oppose to what is observed here) this might be due to the non linearity of the tracks for low energy (track structure).

According to Lindhard the suppression observed in the ionization yield should be independent of the drift field.

Ionization Yield

Questions to be answered...

- Is the Lindhard factor similar to the QF obtained by SRIM?

Naively I wouldn't expect..

But this might not be as relevant, depending on the difference between both.

- Is it possible to determine the Lindhard factor for He-CF₄?
How do we plan to cross-check it?

Measurement of Scintillation and Ionization Yield and Scintillation Pulse Shape from Nuclear Recoils in Liquid Argon

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(The SCENE Collaboration)

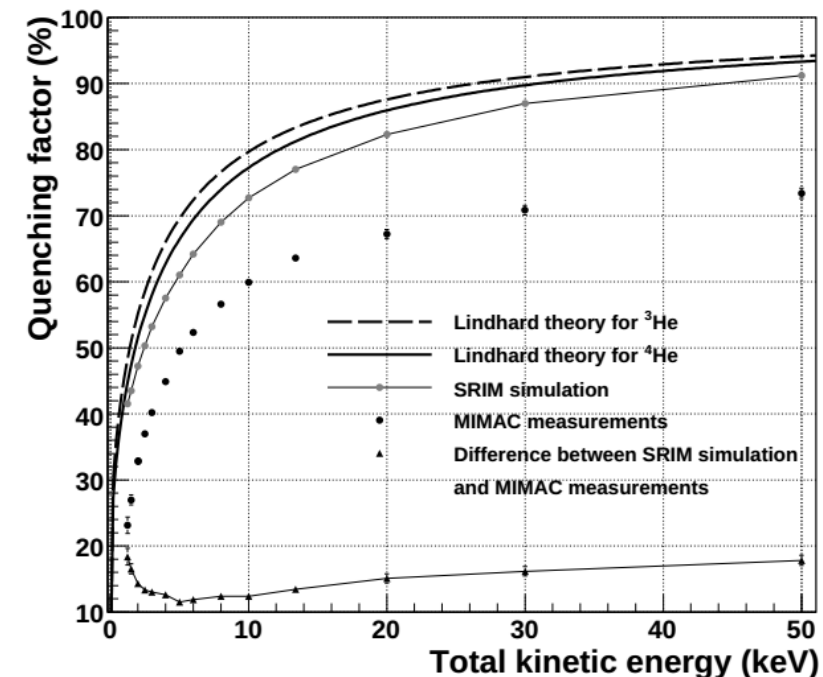


Fig. 7. Comparison between Lindhard theory, SRIM simulation and Quenching measurements in ⁴He + 5% C₄H₁₀ gas mixture at 700 mbar (from Santos *et al.* 2008)

(Guillaudin, 2012)

Ionization Yield

What can we do?

- We know from LZ and XENON experiments that it is possible to measure it.
- Alternatively we could use an estimate for the efficiency in the production of the ionization yield.

As we know, QF is defined (from our point of view) as being the efficiency of converting the energy of an incident particle into ionization (and consequently to pairs of electrons and ions) which we can measure.

From the definition of the W-value we know that this is already included in its determination (as it accounts for all mechanisms present for the dissipation of the excess energy – either elastic or inelastic)

$$Q_0 = E_r \mathcal{L} / W_e$$

with $\mathcal{L} = Q_{nr} / Q_{er}$

Which we can cross check with the Lindhard factor presented in last slide.

In this case the different mechanisms would be considered, enabling us to retrieve the primary charge produced by NR (Q_{er} should be different from 1).

As we've seen one possibility might be the use of a IQF (which is the fraction of the energy of a NR transferred to ionization) and if we assume that this value is good we can simply divide the w-value of ER to obtain the primary charge.

Still, as we've seen the value of IQF obtained from SRIM might be far from the Lindhard factor (used by other experiments to estimate the ionization yield). Alternatively, we could use (Q_{nr} / Q_{er}) as a correction factor for the difference in the conversion of the particle energy between the NR and ER.

Conclusions

The possibility of using the IQF (ionization quenching factor) as defined by Santos (thanks Davide for pointing that out to us), seems to be an initial **adequate approach**.

Still, there are some aspects that need to be considered while evaluating the primary charge expected (number of electron-ion pairs).

The effect of recombination needs to be evaluated (as it **depends** on the **type** and **energy of the incident particle**, but also on the **pressure and electric field** – reduced electric field)

When considering the IQF provided by SRIM, one should try to understand what are the mechanisms used for the energy dissipation.

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