Alpha Quenching Factor in Liquid Argon

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2022 Canadian Association of Physicists (CAP) Congress
McMaster University, Hamilton, Canada

June 8, 2022

Outlines

- Introduction
- Objectives
- Relative measurement of alpha quenching factor
- Energy dependent quenching factor curve
- Summary and Outlook

Introduction

- A portion of deposited energy by incident particle within a scintillating material (e.g. liquid argon) leads to light. This effect is known as **"quenching"**.

- Quenching depends on incident particle's type and energy.

- $\mathbf{Quenching}\ \boldsymbol{Factor} = \dfrac{\boldsymbol{Measured\ Energy}}{\boldsymbol{Deposited\ Energy}} = \dfrac{\boldsymbol{Detectected\ Photoelectrons}}{\boldsymbol{Light\ Yield \times Deposited\ Energy}}$

- Light yield relates the energy deposited in the detector to the number of detected photoelectrons (PEs).
  - It can be measured from the calibration of energy response of detector.

Importance of Alpha Quenching Factor

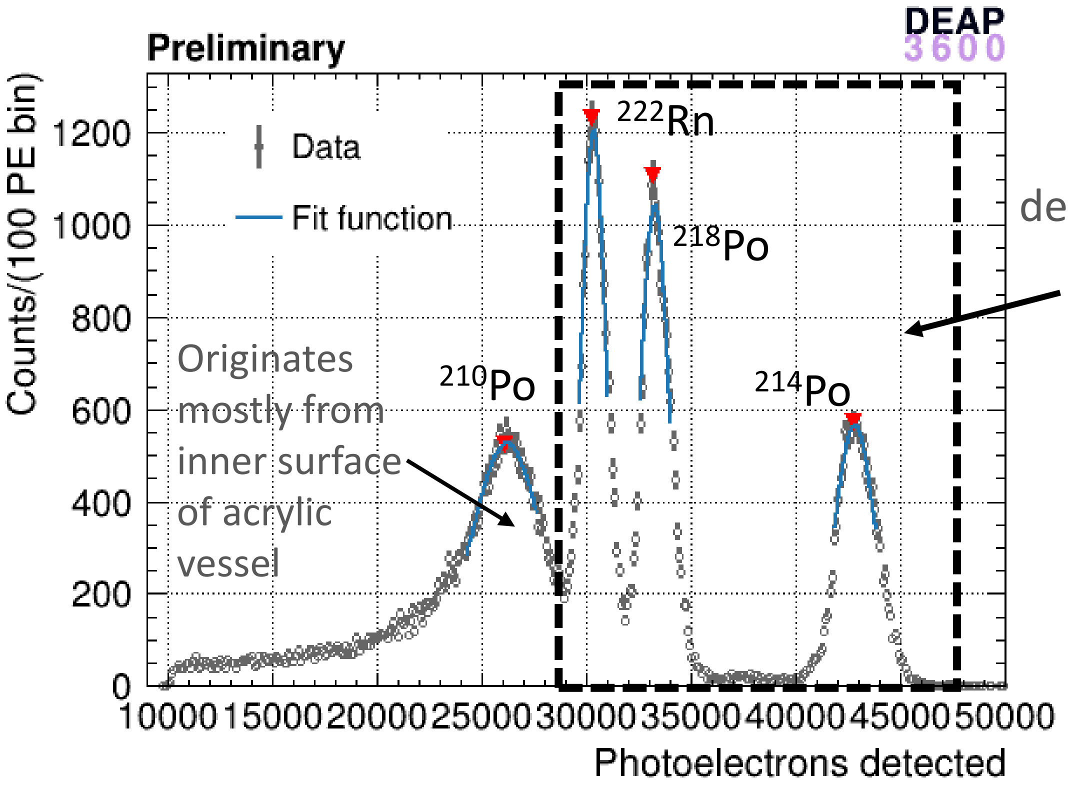
- **Alpha particle is one of the intrinsic backgrounds of DEAP-3600 dark matter search experiment.**
  - ❑Originates from alpha–decays from short- and long-lived radon (^{222}Rn) progeny.
- Liquid argon is used as target material for DEAP-3600 detector.
- Measurement of alpha quenching factor plays significant role in estimation of deposited energy.
  - ❑**Development of a well understood background model.**
  - ❑**Identification and mitigation of alpha background events.**

Objectives: Analysis Method

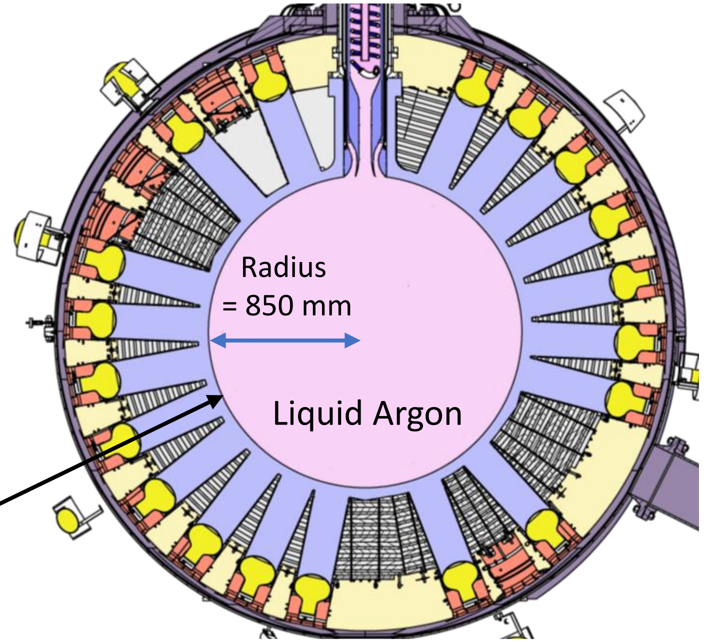
- Absolute uncertainty of alpha quenching factor is not known for DEAP-3600 experimental data.
- Present approach is to make the **relative measurement** of alpha quenching factor at high energy (∼MeV).
- **Relative uncertainties in quenching factor will provide the shape of the quenching factor vs energy curve.**
- Probing the uncertainty and shape of the energy dependent alpha quenching factor curve at low energy region (∼ few tens to few hundreds keV).

Measurement of Alpha Quenching Factor

Alpha Induced Events



Full energy deposition within liquid argon



Acrylic vessel surface

- Three years (November, 2016 – March, 2020) open dataset of DEAP-3600 experiment is used .
- Peaks are fitted by Gaussian distribution -- mean of Gaussian distribution is taken as the Photoelectron (PE) peak position.

^{238}U Chain Decay Modes

Parent Nuclei	Daughter Nuclei	Half-life, $t^{1/2}$	Q-value [MeV]	Decay Mode [MeV]
^{222}Rn	^{218}Po	3.823 d	5.590	α[5.489]
^{218}Po	^{214}Pb	3.10 min.	6.114	α[6.002]
^{214}Pb	^{214}Bi	26.8 d	1.024	β[1.024]
^{214}Bi	^{214}Po	19.9 min	3.272	β[3.272]
^{214}Po	^{210}Pb	164.3 μs	7.833	α[7.686]
^{210}Pb	^{210}Po	22.3 yr	0.0635	β[0.0635]
^{210}Po	^{206}Pb	138.376 d	5.407	α[5.304]

Relative Measurement of Quenching Factor

- DEAP-3600 detector is calibrated at low energy (keV) region whereas alphas have energies of the order of MeV.
- Non-linearity in the measurement of light yield can lead to incorrect evaluation of quenching factor.
- **Step I : Estimation of relative light yield using :**
  - **Alpha quenching factor for ^{210}Po isotope = $Q_{^{210}Po}^{Doke\ et\ al.}$ = 0.71 $\pm$ 0.028 . [*Ref: T. Doke et al. NIMA 269 (1988) 291*]**
  - Photoelectron (PE) value for alphas from ^{222}Rn in DEAP-3600 data.
  - $Q_{^{222}Rn}^{Calib}$ = **0.71 $\pm$ 0.028**

    [Assumption: Negligible difference in quenching factor of alphas originated from ^{210}Po and ^{222}Rn isotopes because energies of alphas are nearly same (5.304 MeV and 5.489 MeV respectively).]
  - $PE_{^{222}Rn} = Q_{^{222}Rn}^{Calib} \times E_{^{222}Rn} \times LY_{Relative}$
- **Step II : Calculation of quenching factor**
  - $Q_{^{218}Po} = \dfrac{PE_{^{218}Po}}{E_{^{218}Po} \times LY_{Relative}} = \dfrac{PE_{^{218}Po}}{PE_{^{222}Rn}} \times \dfrac{E_{^{222}Rn}}{E_{^{218}Po}} \times Q_{^{222}Rn}^{Calib}$
  - $Q_{^{214}Po} = \dfrac{PE_{^{214}Po}}{E_{^{214}Po} \times LY_{Relative}} = \dfrac{PE_{^{214}Po}}{PE_{^{222}Rn}} \times \dfrac{E_{^{222}Rn}}{E_{^{214}Po}} \times Q_{^{222}Rn}^{calib}$

Using ratios of peak energies makes the analysis insensitive to the absolute energy calibration at high energy in DEAP-3600 experiment.

Ratio of PE can be obtained from DEAP-3600 data

Uncertainties in Quenching Factor

Isotope	Alpha Energy in MeV	$\frac{PE_{isotope}}{PE_{^{222}Rn}}$	Uncertainty in $\frac{PE_{isotope}}{PE_{^{222}Rn}}$	Quenching Factor	Relative Uncertainty in Quenching Factor	Uncertainty in Quenching Factor	Comments
^{210}Po	5.305	-	-	0.710	-	0.028	*Ref : T. Doke et al., NIMA 269 (1988) 291*
^{222}Rn	5.489	-	-	0.710	-	0.028	***Calibration data*** *[QF is assumed to be same as* ^{210}Po *data]*
^{218}Po	6.002	1.096	0.002	0.712	0.001	0.028	From relative measurement
^{214}Po	7.686	1.410	0.006	0.715	0.003	0.028	From relative measurement

Development of Energy Dependent Quenching Factor Curve

Quenching Factor Model

Birks' Law

- Local concentration of quenching agent (damage molecule) at any point on the track is proportional to stopping power of incident particle.

- Describes measured light per unit length (dL/dr) as a function of the electronic energy loss per length (dE/dr).

$$\frac{dL}{dr} = \frac{A\frac{dE}{dr}}{1+kB\frac{dE}{dr}} \Longrightarrow \frac{dL}{dE} = \frac{A}{1+kB\,\frac{dE}{dr}}$$

A, kB are treated as fitted constants and can be estimated from experimental data.

- **Quenching factor :**

$$QF_{Birks}(E) = \frac{1}{N_{step}}\sum\frac{dL}{dE} = \frac{1}{N_{step}}\sum\frac{A}{1+kB\,\frac{dE}{dr}}$$

[*Ref: J. B. Birks, Proc. Phys. Soc. A 64 (1951) 874*]

Lindhard's Approach

- Total energy loss by an incident particle within a substance can be divided into two parts :

  - ❑ Produces electronic excitation or ionization (electronic collision).
  - ❑ Produces translational motion of whole atom, excluding internal excitation of the atom (nuclear collision).

  [Assumption: electronic and nuclear collision are unconnected]

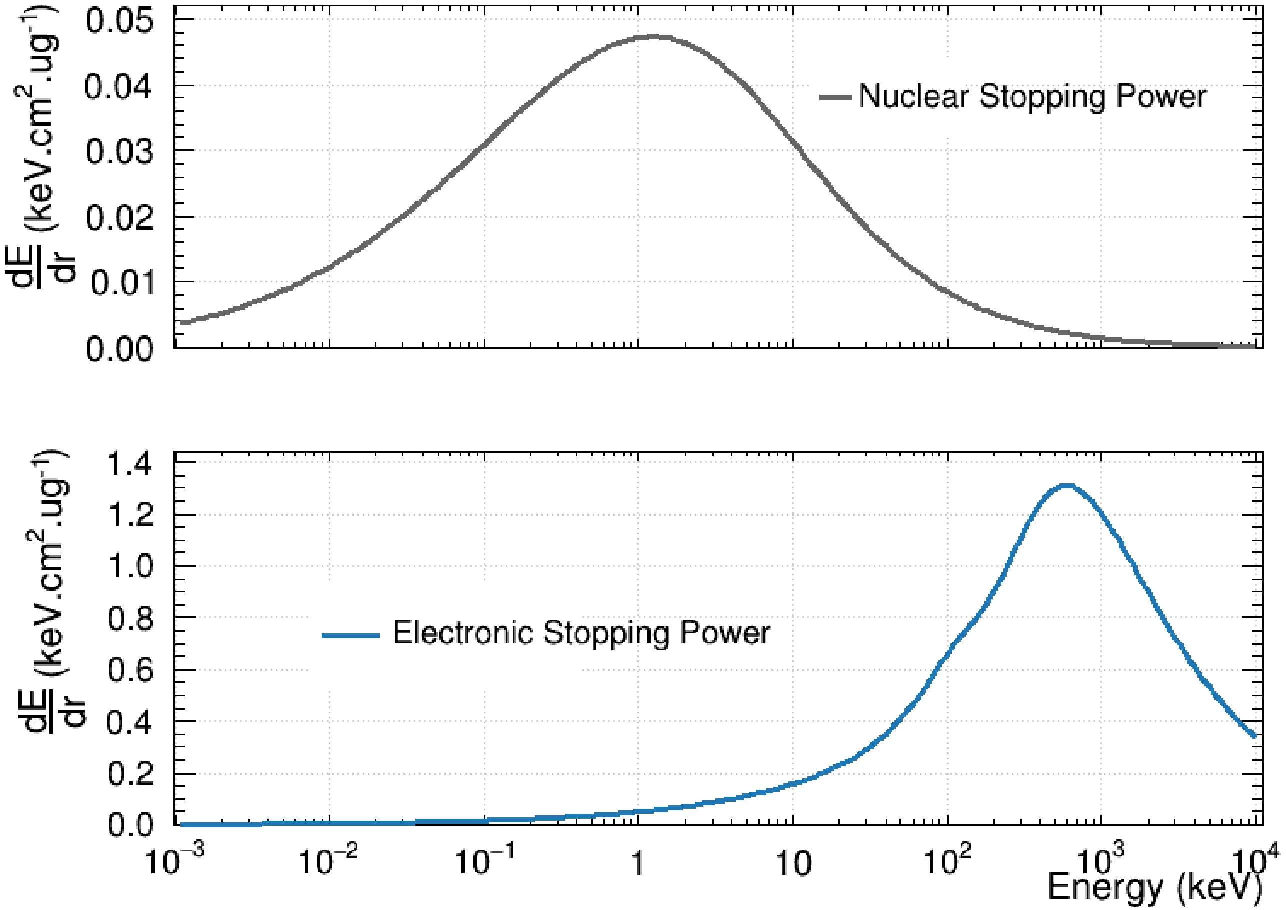
- **Energy lost in ionization** plays significant role in producing scintillation light.

- **Quenching factor :**

$$QF_{Lindhard}(E) = \frac{E_{dep,electronic}}{E_{dep,electronic} + E_{dep,nuclear}}$$

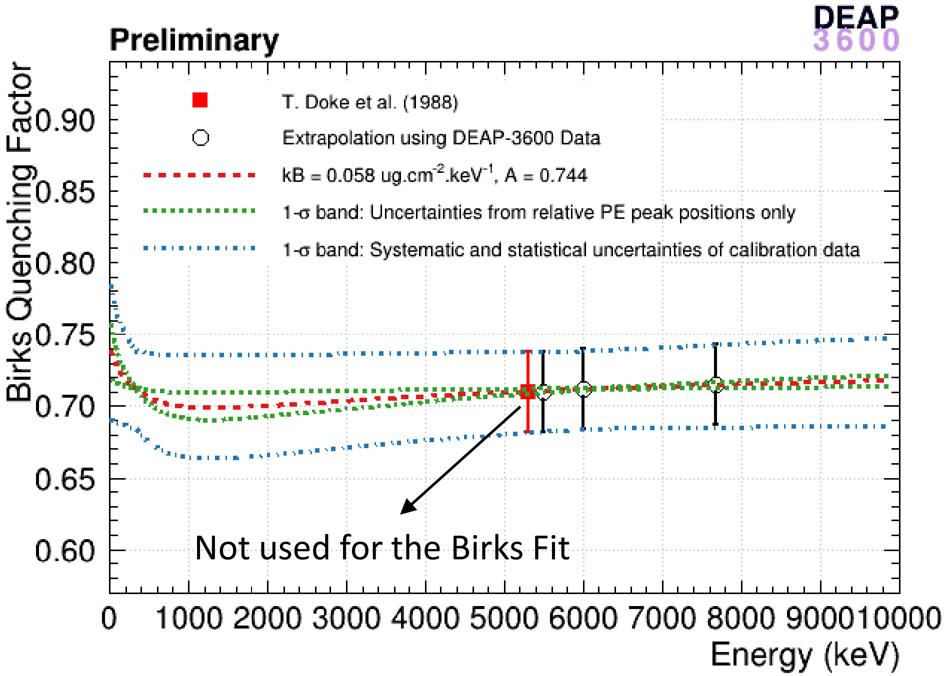
[*Ref: J . Lindhard et al., Mat. Fys. Medd. Dan . Vid. Selsk . 33, no . 10 (1963)*]

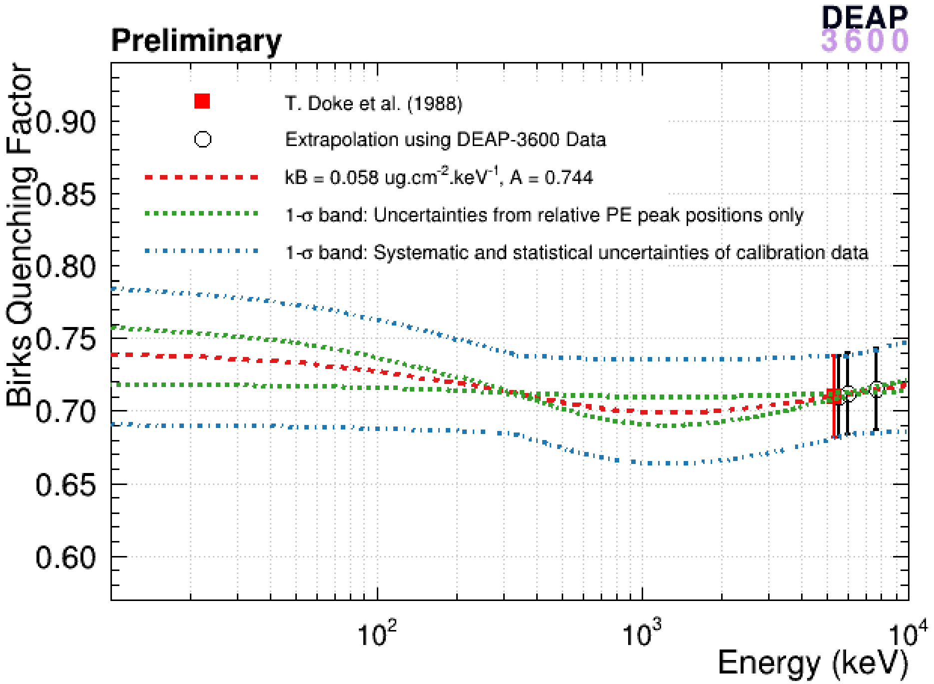
Stopping Power of Alpha in Liquid Argon



SRIM-2013 (The Stopping and Range of Ions in Matter)

Fit using Birks' Law

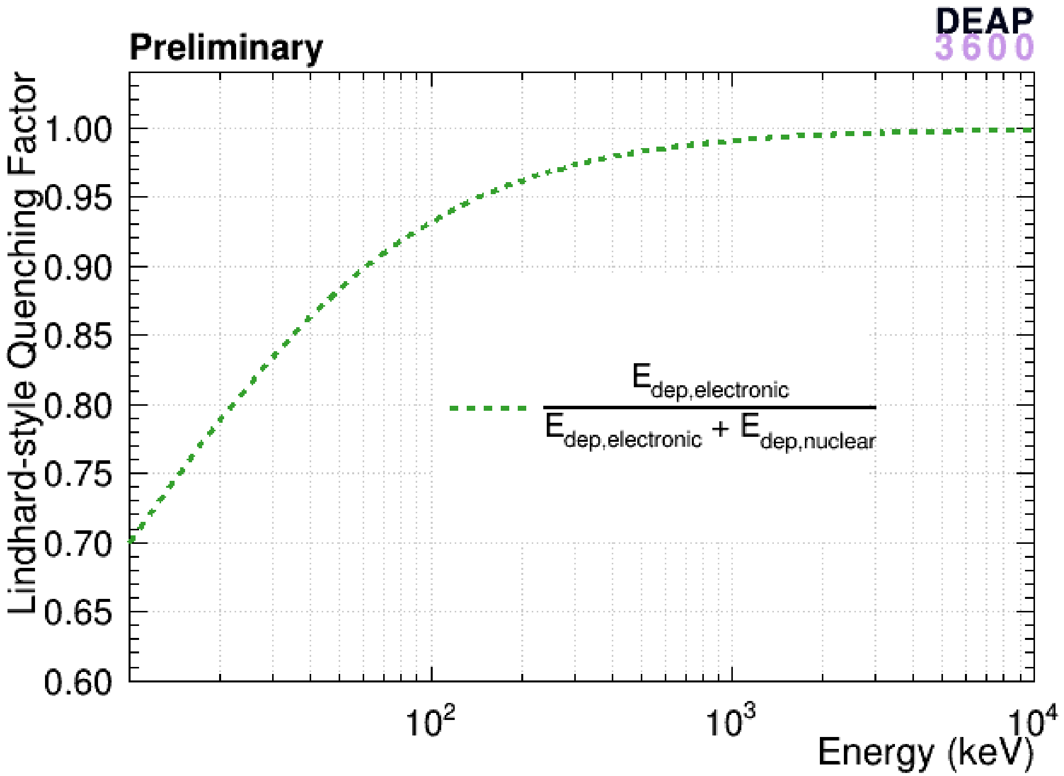




- 1-sigma contour (χ^2_{min}+ 1.0) is drawn in (kB, A) parameter space.
- **Shape of the 1-sigma band (green curve) depends on relative uncertainties of the DEAP-3600 data.**
- At MeV energy, the relative uncertainty in quenching factor is quite small (0.2 - 0.4 %) ⇒ leads to constraint the energy dependence of quenching factor well ⇒ nearly flat.

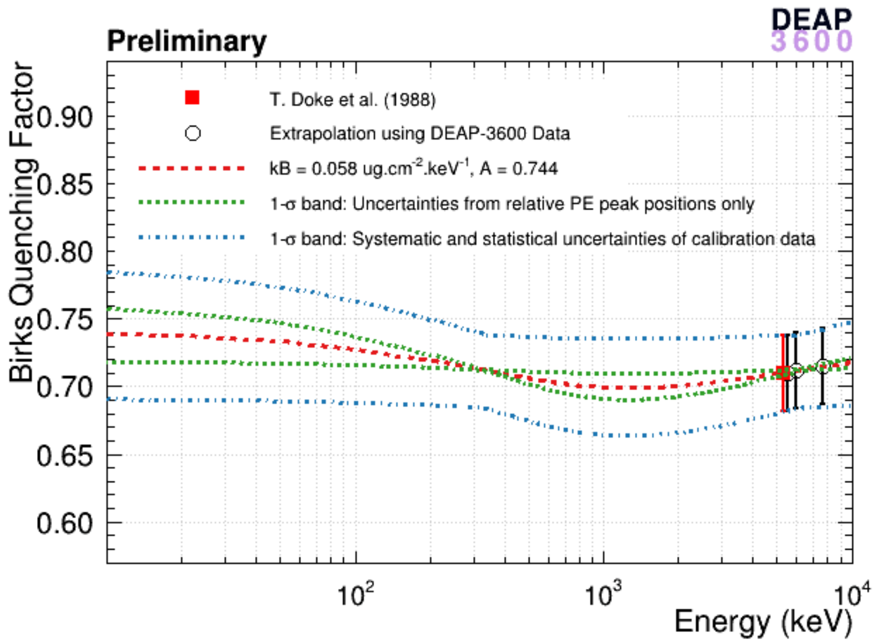
- 1-σ upper and lower bands (green curve) are multiplied by $R_1 = \frac{Q_{max}^{Calib}}{Q_{max}^{222Rn}}$ and $R_2 = \frac{Q_{min}^{Calib}}{Q_{min}^{222Rn}}$, respectively. **[$Q_{min}^{222Rn}$ and Q_{max}^{222Rn} are extracted from green curve]**
- **Shape (blue curve) is determined by 1-σ error band** using **relative uncertainties** and consider absolute uncertainty of calibration data.
- Provides maximum and minimum values of quenching factor for each energy.

Lindhard-style Quenching Factor

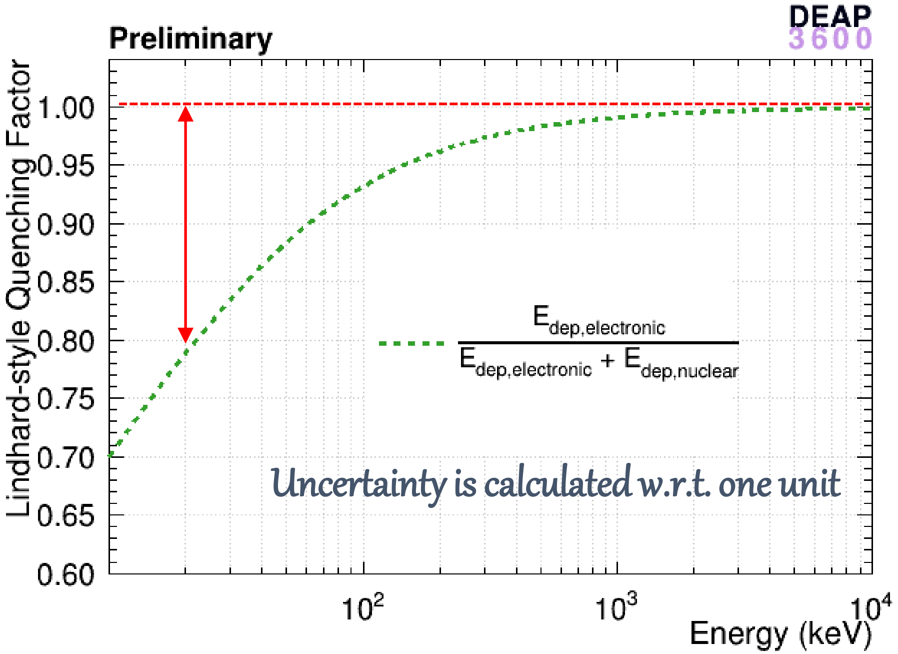


Lindhard-style Quenching Factor for 10 keV - 10 MeV using SRIM stopping power curves.

Quenching Factor Curve from Relative Measurement

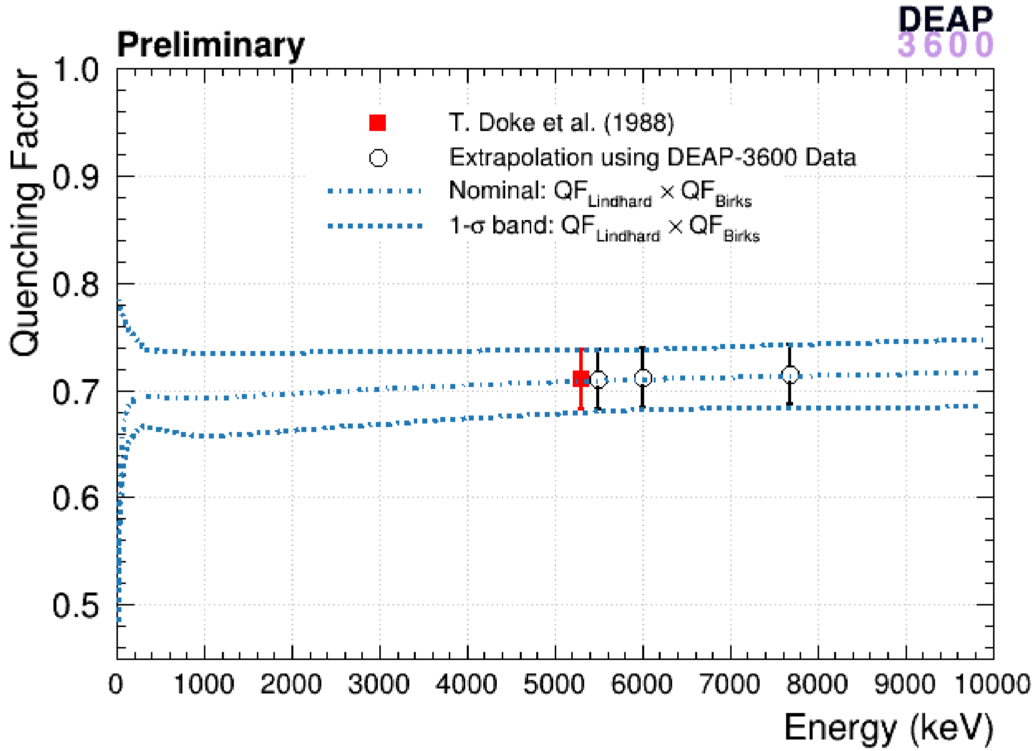


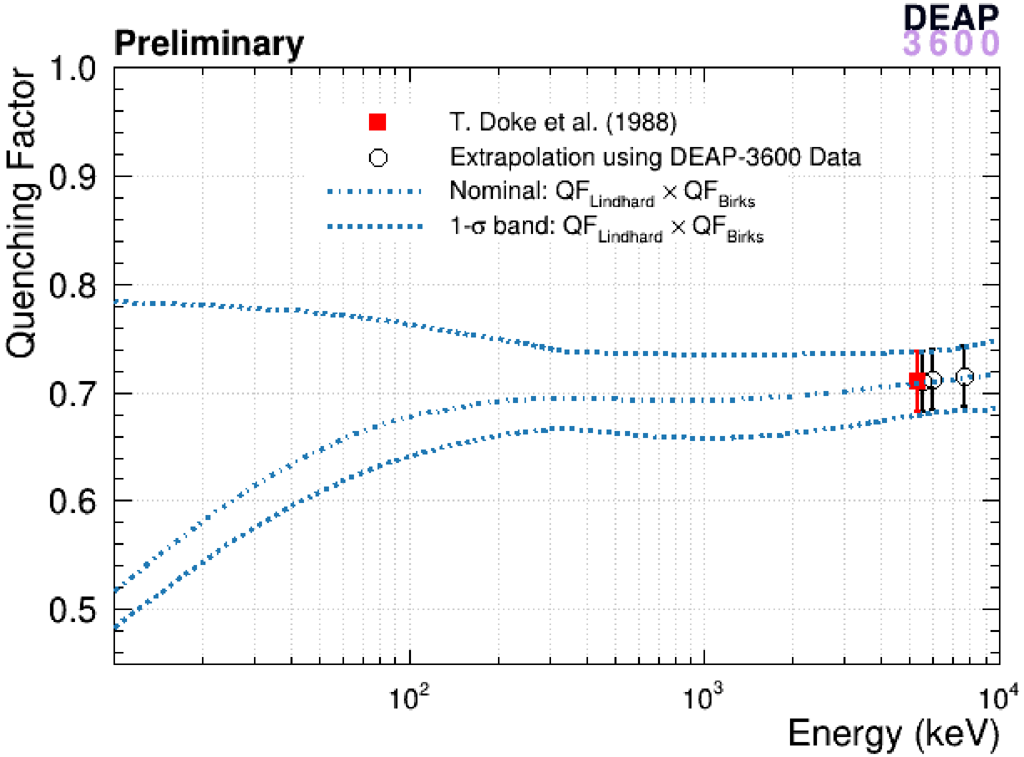
- **Method is adopted** from **D.-M.** Mei et al. approach [Ref: Astroparticle Physics 30 (2008) 12] which was used for nuclear recoils of few tens to few hundred keV:
  - ❑ Quenching Factor = Lindhard-style Quenching Factor × Birks' Quenching Factor.
  - ❑ Birks' Quenching Factor is dominant at higher energy region, whereas Lindhard-style quenching plays important role in lower energy region.



In (30 – 600) keV energy region,

- Electronic stopping power is dominant for alphas whereas in case of ^{40}Ar nuclear recoil, electronic and nuclear stopping power are comparable.
- For alphas, greater than 80% of total energy loss is due to electronic collision whereas nuclear recoils this is about (30 – 70)%.





- Shape of the 1-σ error band for quenching factor can be validated by the measurement of quenching factor.
- Measurements of alpha quenching factors for few hundreds of keV – few MeV region using Argon-1 (a modular single phase liquid argon cryostat) at Carleton University are underway. ***[see Michael Perry's presentation, M3-8 session, June 6 at 4:30 PM]***

Summary and Outlook

- Relative measurement of alpha quenching factor is performed considering T. Doke et al.'s alpha quenching data for ^{210}Po as calibration data.

- We can well-constrain the energy dependence of quenching factor by using relative uncertainties.

- 1-sigma uncertainty bands for energy dependent quenching factor curve are developed.

  - ❑ To validate the uncertainty bands, measurement of alpha quenching factors using Argon-1 at Carleton University are underway.

Thank you for your kind attention

Extra Slides

Estimation of Relative Uncertainties

- Arises due to uncertainty in measurement of ratio of photoelectrons (PEs) at different energies.
  - Central region of the spherical volume is divided into 4 regions: (0-200) mm, (200-400) mm, (400-600) mm , (600 - 800)mm
  - Three years (November, 2016 – March, 2020) open dataset is divided into 21 time windows.

Isotope	**Ratio of PE**		**Standard Deviation of Ratio**	
	Position of source	Time of occurrence	Position	Time
^{218}Po	1.0957	1.0962	0.0010	0.0015
^{214}Po	1.4080	1.4117	0.0047	0.0032

^{218}Po ⇒ 1.096 ± 0.002 (uncertainty ~ 0.16 %)

^{214}Po ⇒ 1.410 ± 0.006 (uncertainty ~0.4 %)

Activity of alpha –decays within liquid argon

Component	Activity
^{222}Rn LAr	(0.153 ± 0.005) μBq/kg
^{218}PoLAr	(0.159 ± 0.005) μBq/kg
^{214}Po LAr	(0.153 ± 0.005) μBq/kg