Modeling of Light Production in Inorganic Scintillators

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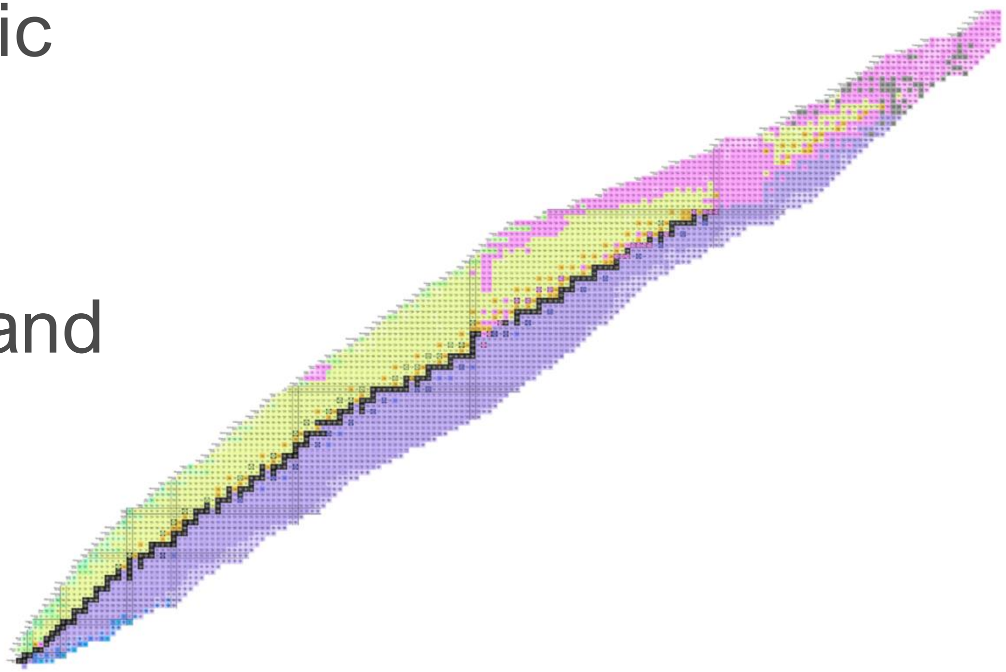
Motivation

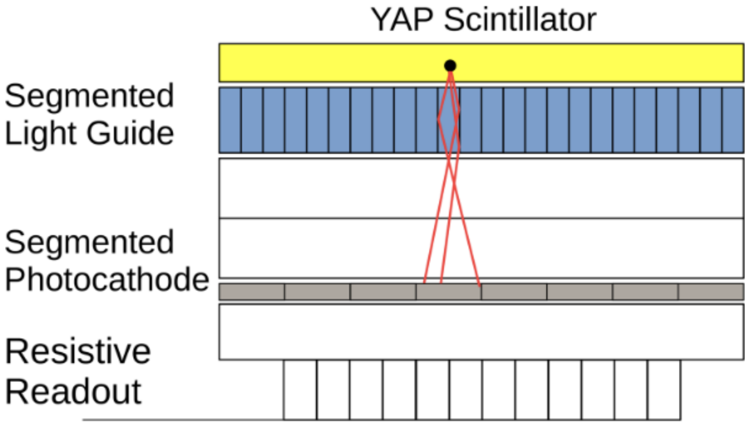
- Fragmentation facilities aim for more exotic nuclei.
- Fast detectors needed.
- Inorganic scintillators provide fast timing and have great stopping ability.



Borrowed from Australian National University, “Colourful Nuclide Chart.”

Implant Detectors

- Thin inorganic scintillator coupled to photomultiplier[1].
- Problem: signal range.
  - Implants: 1-10 GeV.
  - Decays: 100 keV to 10 MeV.
- Observed "light quenching" effect[2].



[1]

1. Y. Xiao et al., Phys. Rev. C **100**, 034315 (2019).
2. M. Singh et al., Nucl. Instr. and Meth. A 1073, 170239 (2025).

Light Quenching

- Quenching factor:

$$qf = E/L$$

Where:

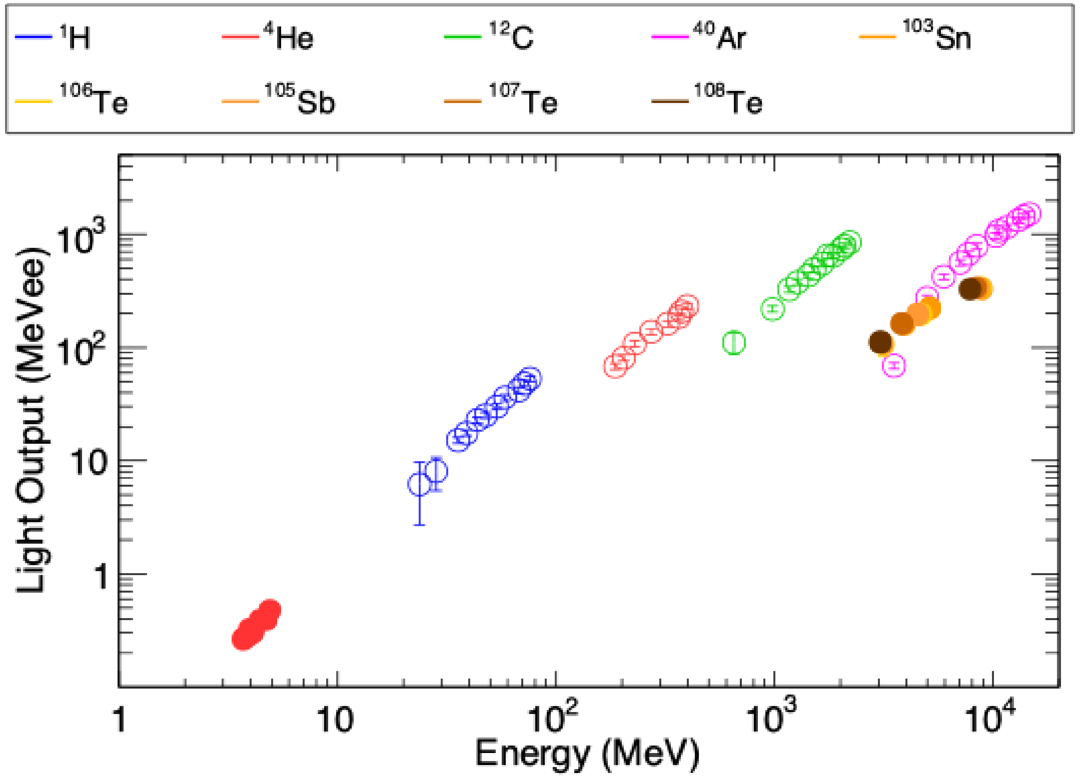
E: ion total kinetic energy.

L: total light output (calibrated).

- "Electron equivalent" units: calibration with standard radioactive source, typically the 662 keV γ-ray line of ^{137}Cs.

LYSO

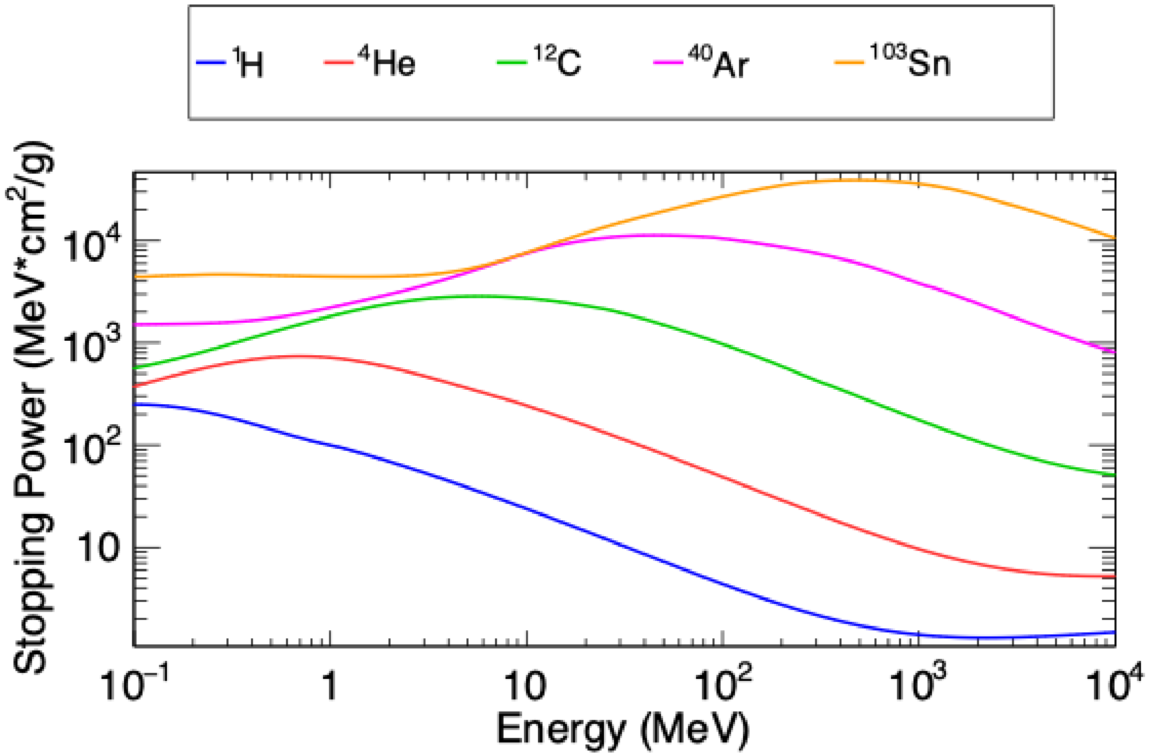
- Cerium-doped Lutetium Yttrium Orthosilicate ($Lu_{1.9}Y_{0.1}SiO_5$).
- Data:
  - Koba et al.[1]
  - RIKEN experiment.
    - I. Cox's talk.



1. Y. Koba et al, Progress in Nuclear Science and Technology **1**, 218 (2011).

Energy Loss/Stopping Power

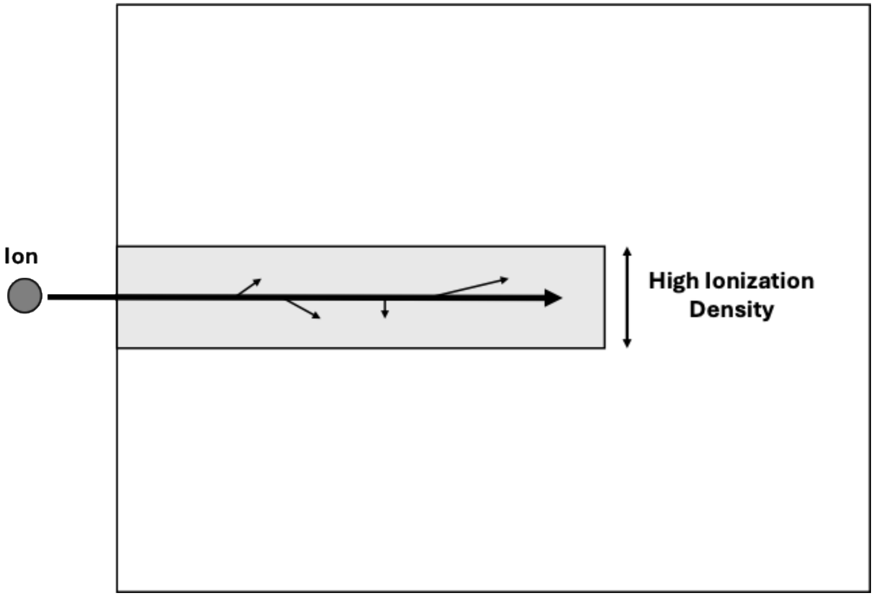
- dE/dx.
- Bethe-Bloch formula[1].
- We will use SRIM[2].



1. F. Salvat, Phys. Rev. A **106**, 032809 (2022).
2. J. Ziegler et al., Nucl. Instr. and Meth. B **268**, 1818 (2010).

Birks Model

- Ionization quenching[1].
- Both organic and inorganic scintillators.



1. J. Birks, Proc. Phys. Soc. A **64**, 874 (1951).

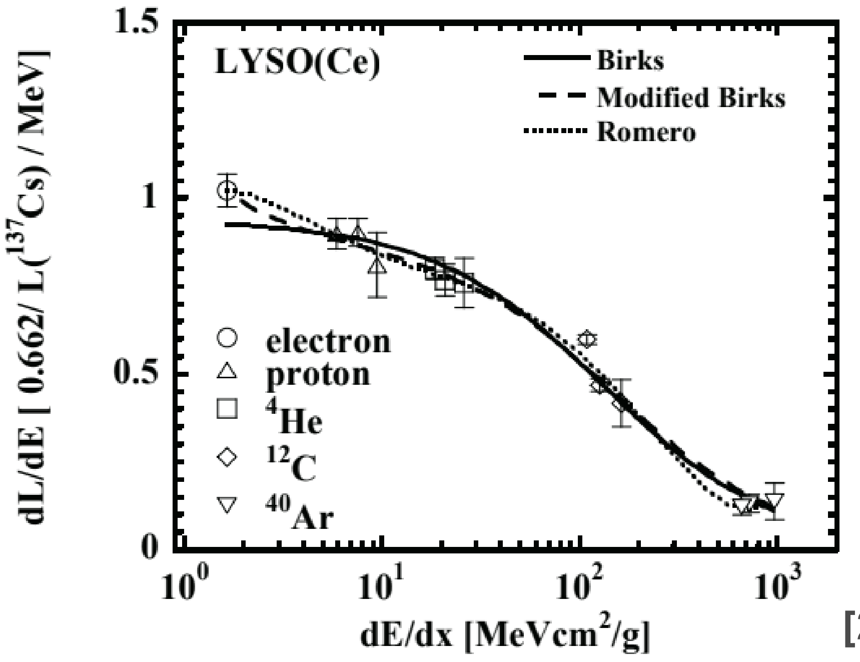
Birks Formula

- Specific fluorescence[1]:

$$\frac{dL}{dx} = \frac{a\frac{dE}{dx}}{1 + b\frac{dE}{dx}}$$

- Scintillation efficiency[2]:

$$\frac{dL}{dE} = \frac{a}{1 + b\frac{dE}{dx}}$$



[2]

1. J. Birks, Proc. Phys. Soc. A **64**, 874 (1951).
2. Y. Koba et al, Progress in Nuclear Science and Technology **1**, 218 (2011).

Birks Formula

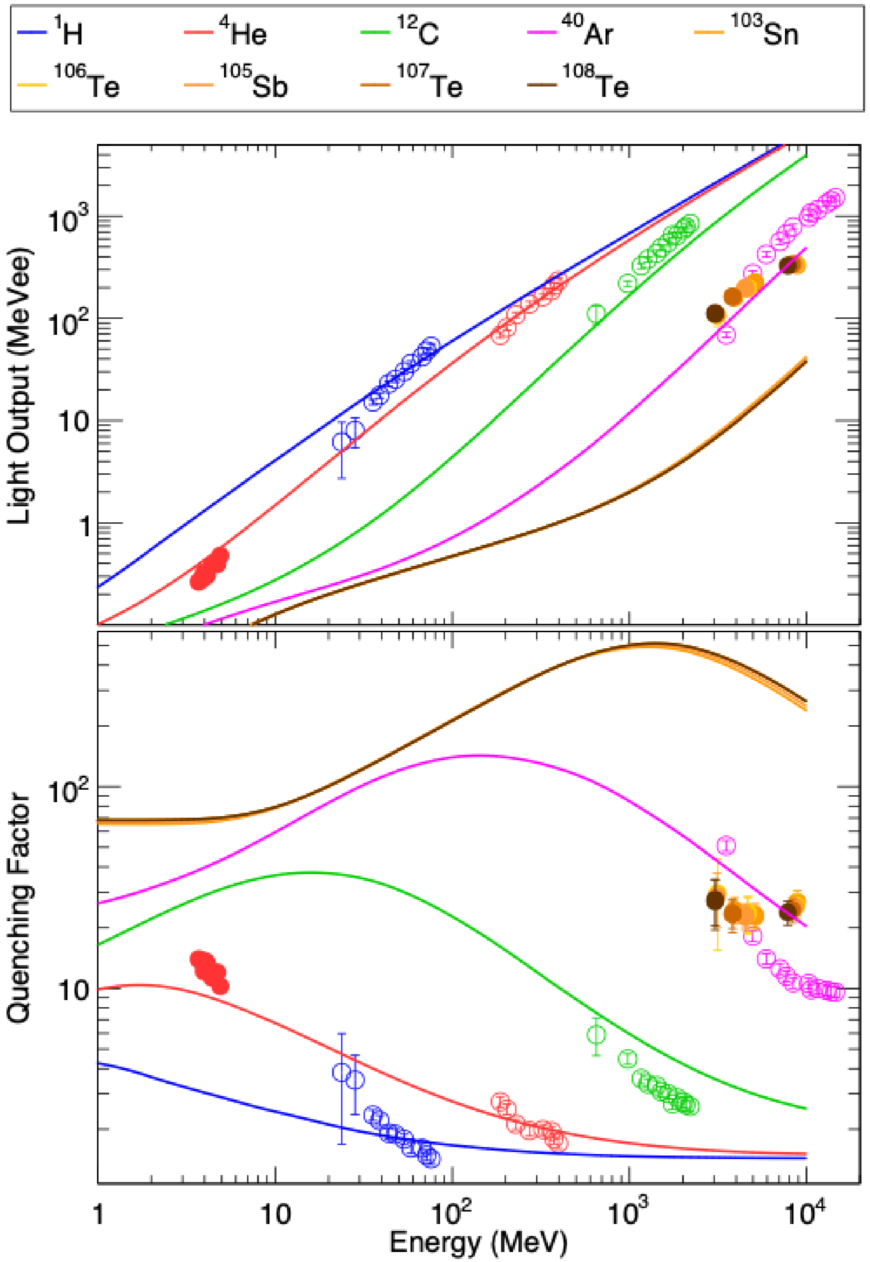
- We eliminate the need for $\frac{dL}{dE}$ measurements by fitting the *integral* of the Birks formula:

$$L = \int_0^E \frac{a}{1 + b\frac{dE'}{dx}} dE'$$

a (unitless)	b (g/(MeV*cm^2))
0.712	0.0101

Results

- Poor agreement for very heavy ions.
- Problem: failure to account for second mechanism.



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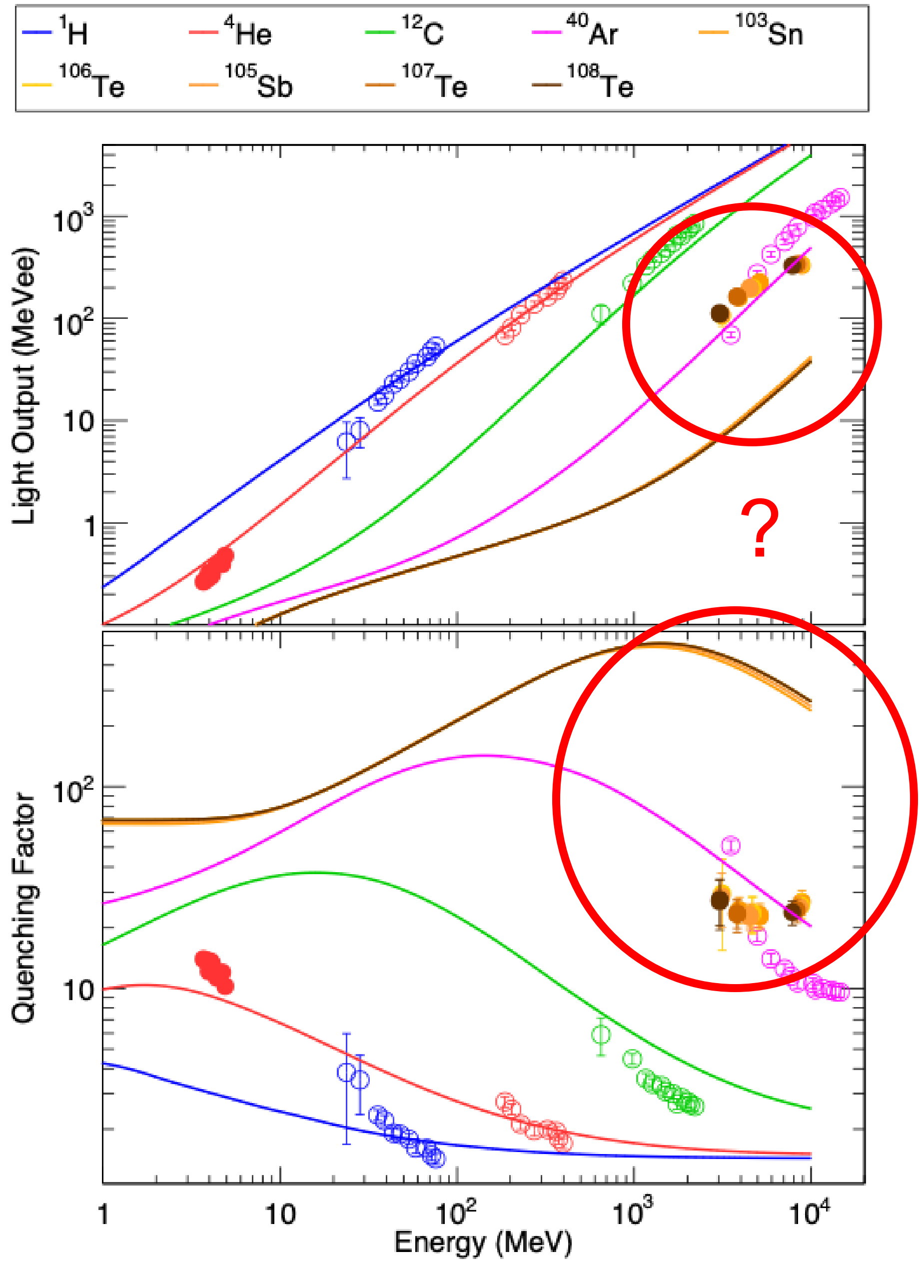
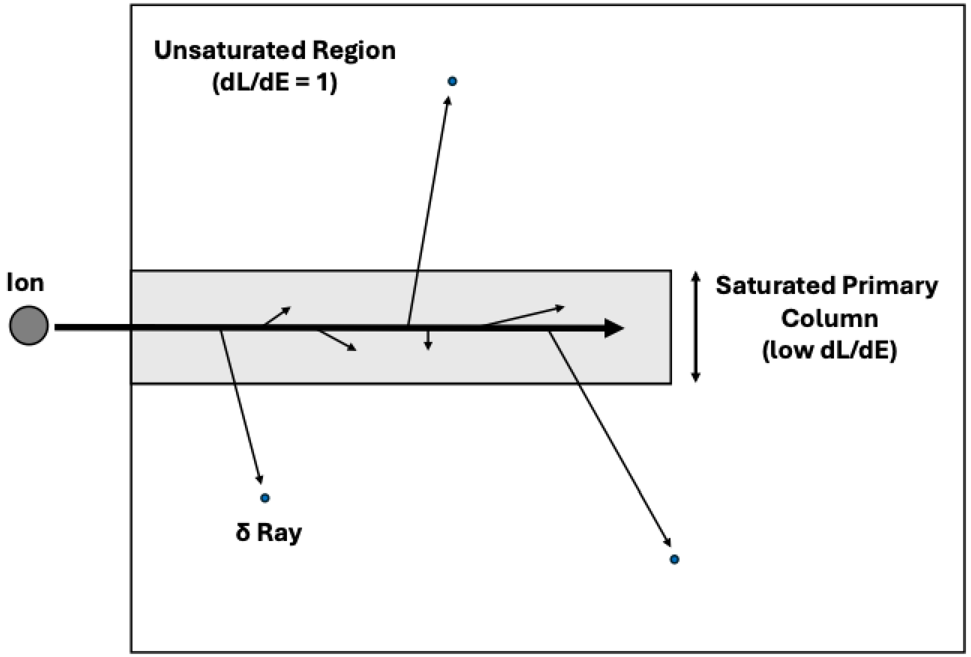


δ Rays

- First suggested by Meyer and Murray[1].
- Light comes from two sources:
  - Saturated "primary column."
  - High-energy secondary electrons a.k.a. δ rays.



1. A. Meyer and R.B. Murray, Phys. Rev. **128**, 98 (1962).

The Meyer-Murray Model[1]

- Total scintillation efficiency:

$$\left(\frac{dL}{dE}\right)_t = (1 - F)\left(\frac{dL}{dE}\right)_p + F\left(\frac{dL}{dE}\right)_\delta$$

- δ ray fraction:

$$F \equiv \frac{\left(\frac{dE}{dx}\right)_\delta}{\left(\frac{dE}{dx}\right)_t}$$

1. A. Meyer and R.B. Murray, Phys. Rev. **128**, 98 (1962).

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$$\left(\frac{dL}{dE}\right)_\delta \approx 1$$

- δ ray fraction:

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Estimating F

- Isotropic emission approximation:

$$\left(\frac{dE}{dx}\right)_\delta = \frac{3.08\cdot 10^5}{(E/A)} z^{*2} \int_{\epsilon_0^{min}}^{\epsilon_0^{max}} \frac{d\epsilon_0}{R_p^3 \epsilon_0} \int_{r_c}^{R_p} \left(1 - \frac{r}{R_p}\right) r^2 dr \int_{\sin^{-1}\left(\frac{r_c}{r}\right)}^{\frac{\pi}{2}} \left(1 - \frac{r_c}{r\sin\theta}\right)^{\frac{1}{n}} \sin\theta\, d\theta$$

- Normalize by $\left(\frac{dE}{dx}\right)_t$ to get F.
- Note that $\left(\frac{dE}{dx}\right)_t \propto z^{*2}/(E/A)$, so F is primarily a function of E/A.

1. A. Meyer and R.B. Murray, Phys. Rev. **128**, 98 (1962).

The Complete Model

- Combine the Birks formula with the Meyer-Murray formulation:

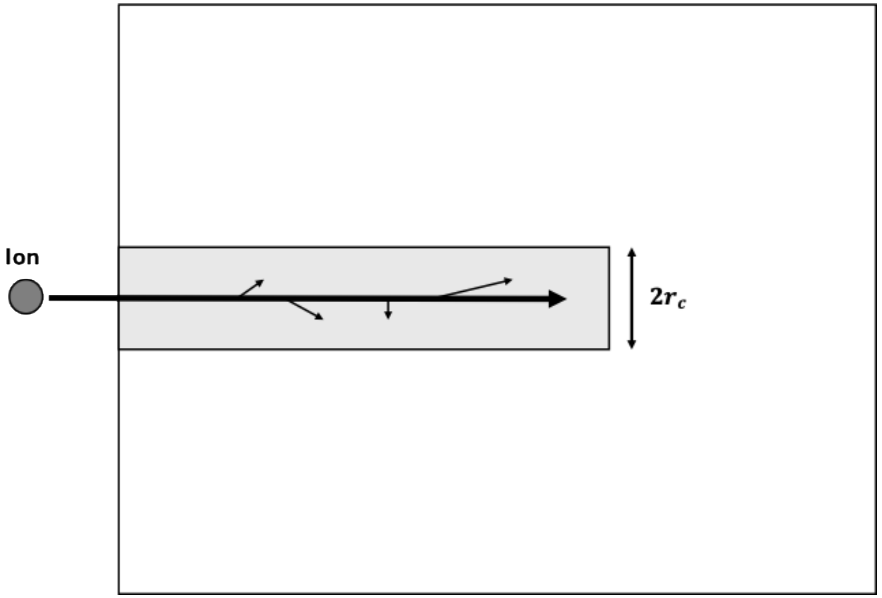
$$L = \int_0^E \left[\left(1 - F'(r_c)\right) \frac{a}{1 + b\left(1 - F'(r_c)\right)\frac{dE'}{dx}} + F'(r_c) \right] dE'$$

Where:

$$F'(r_c) = cF(r_c)$$

Fitting Parameters

- 4 fitting parameters:
  - a and b: from the Birks formula term.
  - c: scales F.
  - r_c: primary column radius, in μm



	a (unitless)	b (g/(MeV*cm^2))	c (unitless)	r_c (μm)
Value	0.795	0.0153	0.190	1.41

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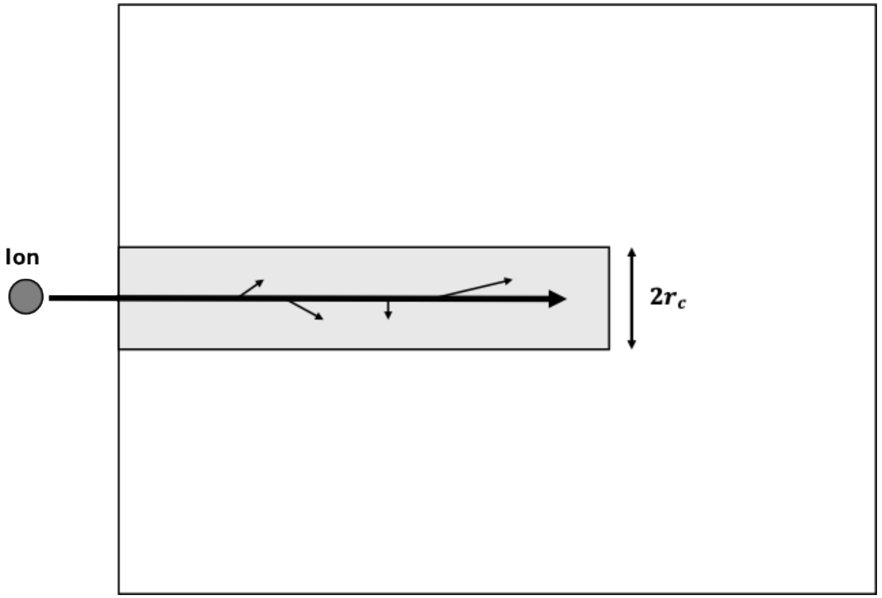


New Model:

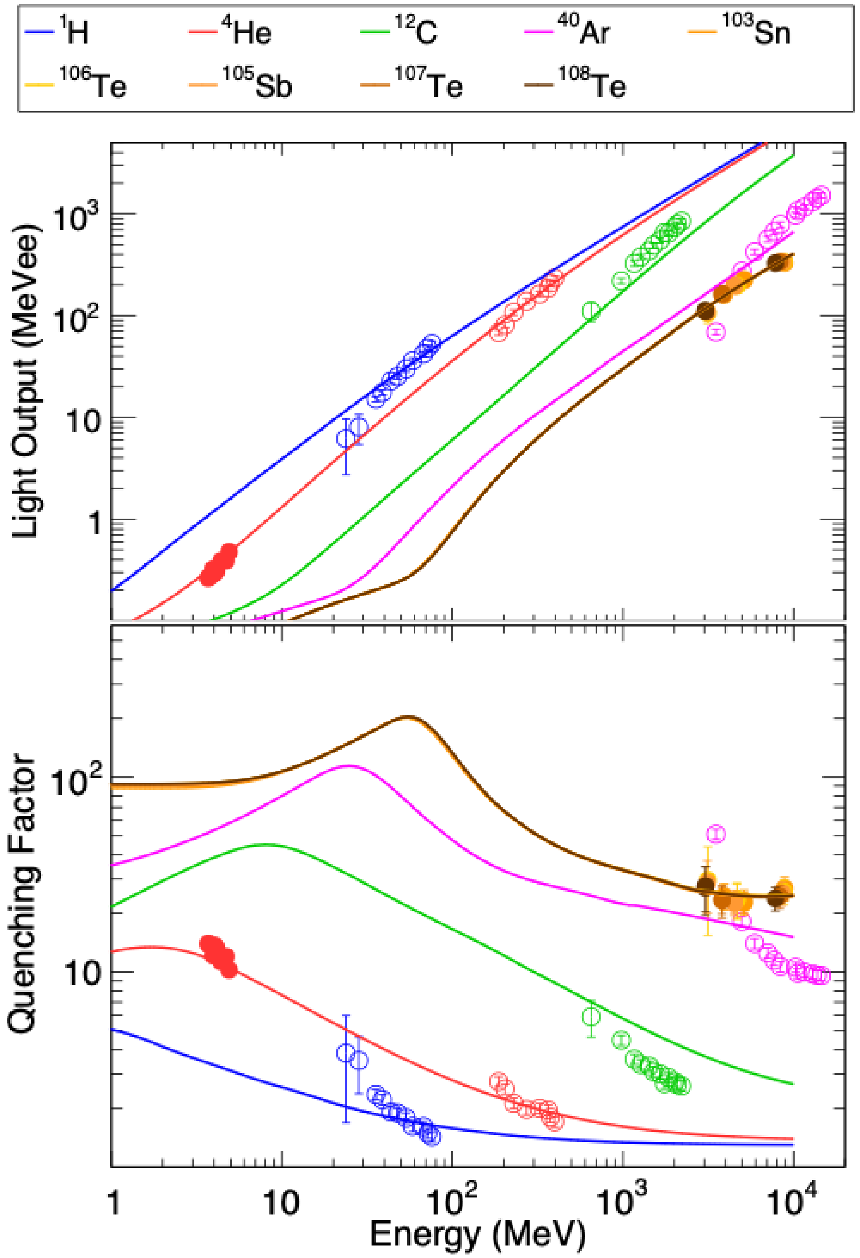
	a (unitless)	b (g/(MeV*cm^2))	c (unitless)	r_c (μm)
Value	0.795	0.0153	0.190	1.41

Birks:

	a (unitless)	b (g/(MeV*cm^2))
Value	0.712	0.0101

Results

- Much better agreement than Birks.



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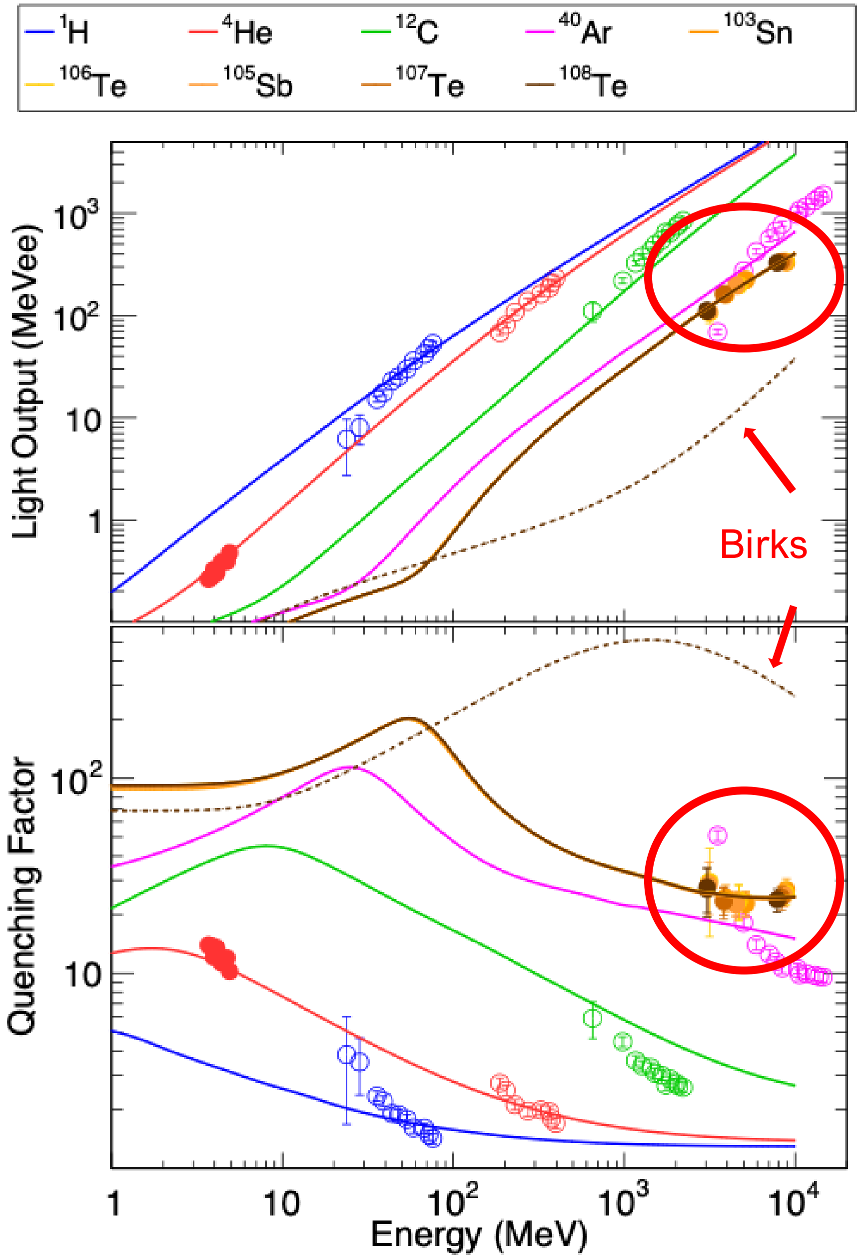
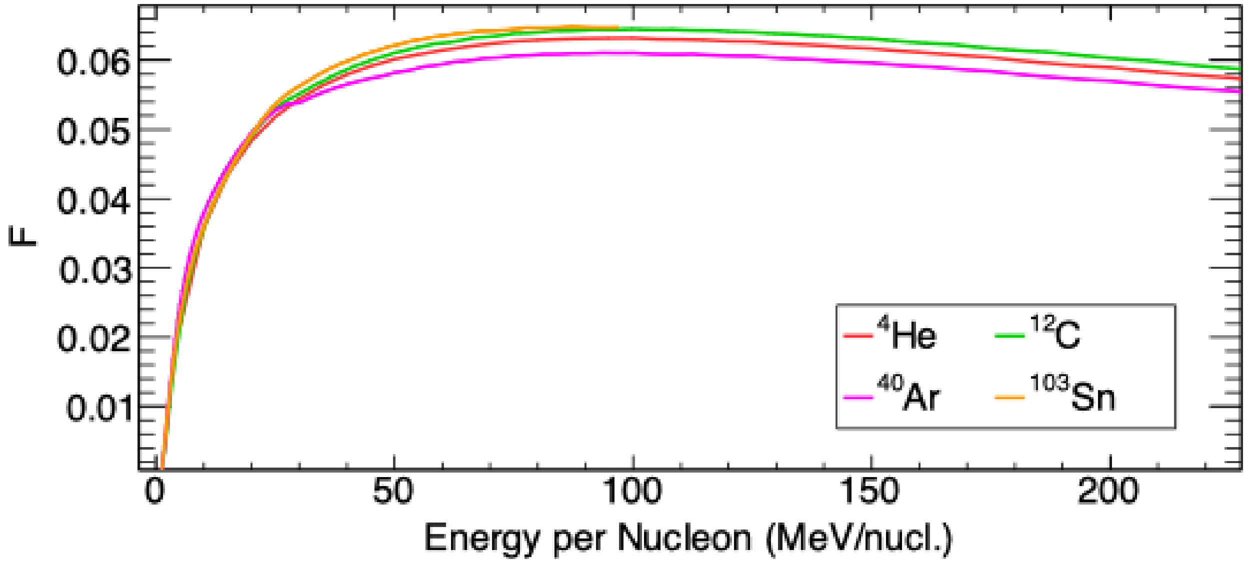


δ Ray Fraction F

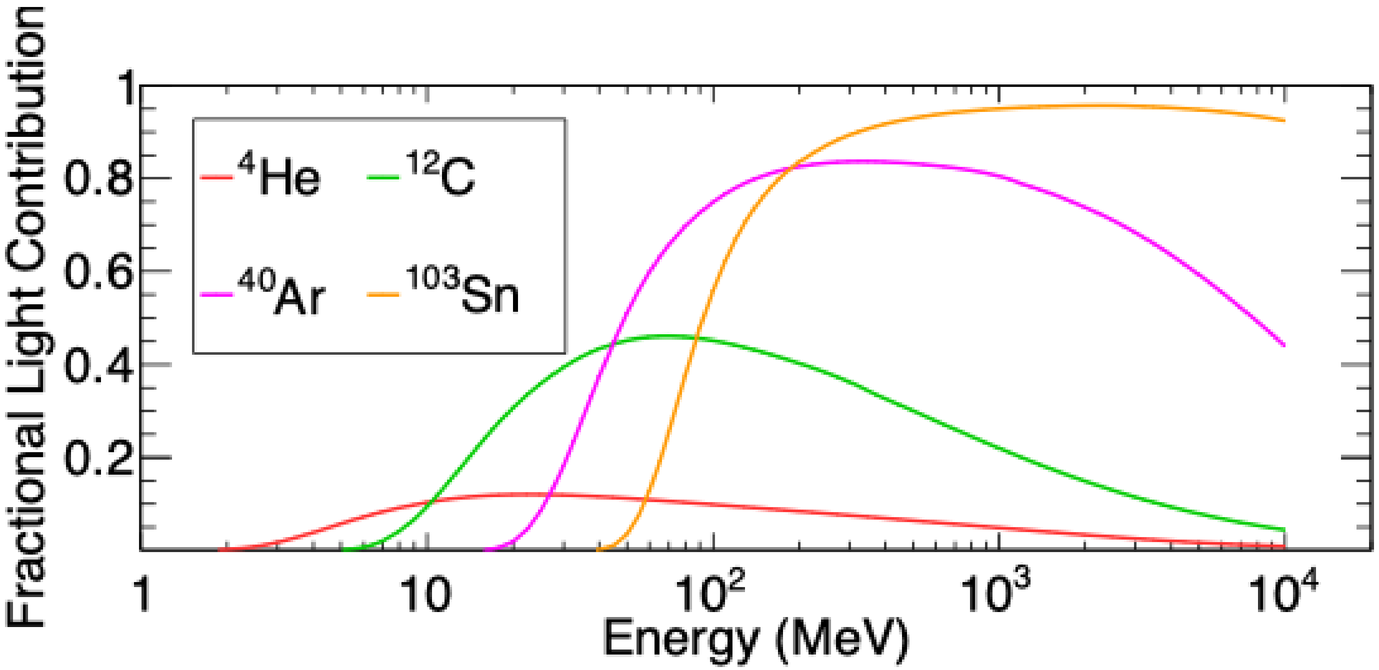
- According to Meyer-Murray model:
  - Function of E/A.
  - Doesn't change with mass or charge.



Relative Contribution of δ Rays

- Light output mostly due to δ rays for ions heavier than ^{40}Ar.

$$\text{Fractional Contribution} = \frac{L_\delta}{L_t}$$



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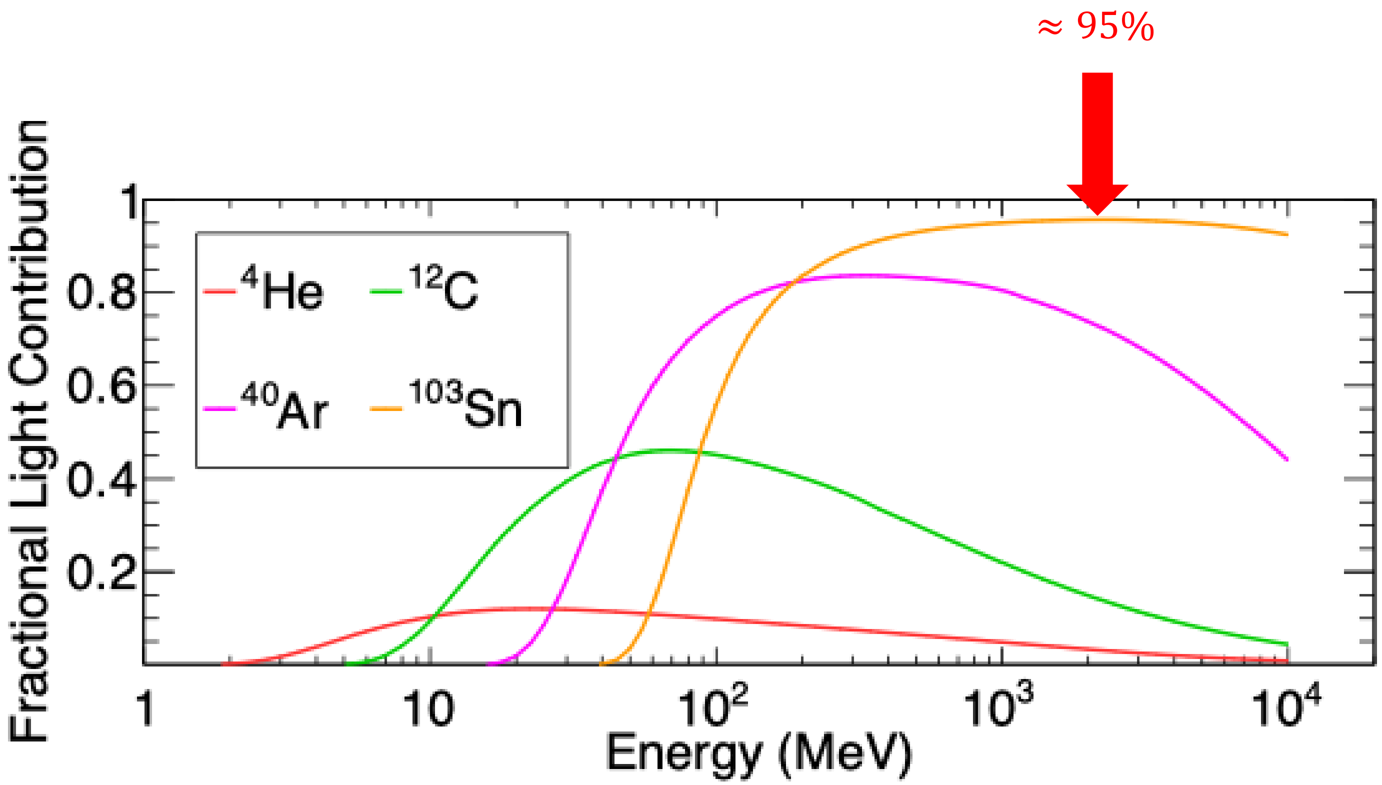
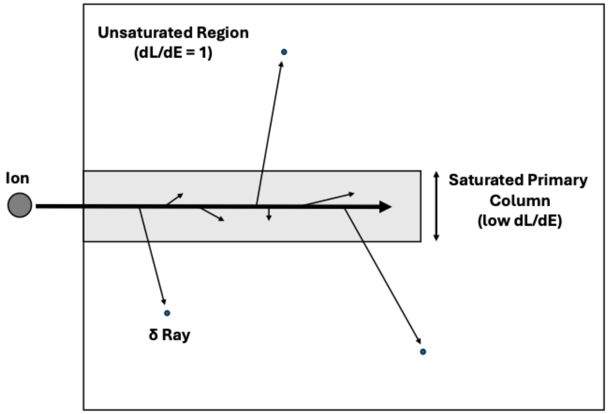
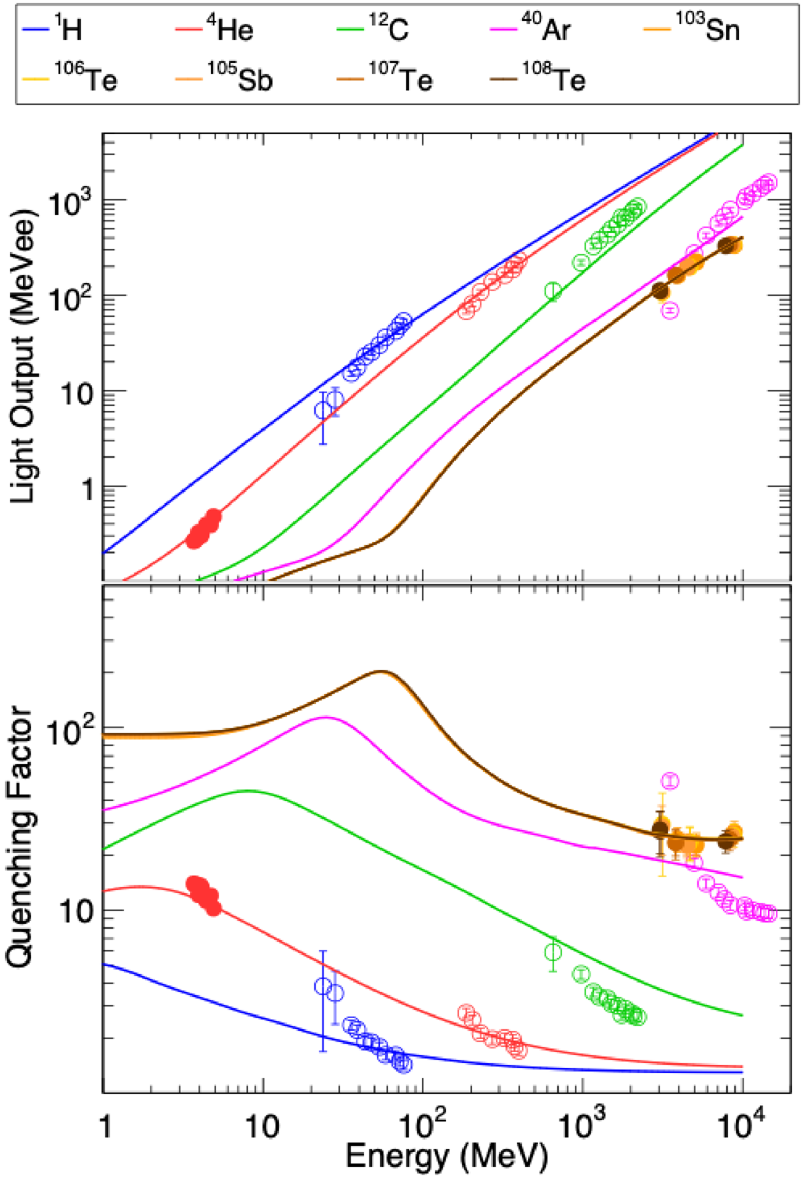


Summary

- Scintillator response to heavy ions determined by:
  - Ionization quenching.
  - δ ray effects.
- Simple model based on the work of Birks, Meyer, and Murray.





Collaborators

- UTK – I. Cox, R. Grzywacz, Z. Y. Xu, D. Hoskins, N. Braukman
- ORNL – T. T. King, K. Rykaczewski
- RIKEN – S. Nishimura, V. Phong, S. Go
- CNS – R. Yokoyama, N. Kitamura