SAND2022-12091C

Ionization quenching in organic scintillators

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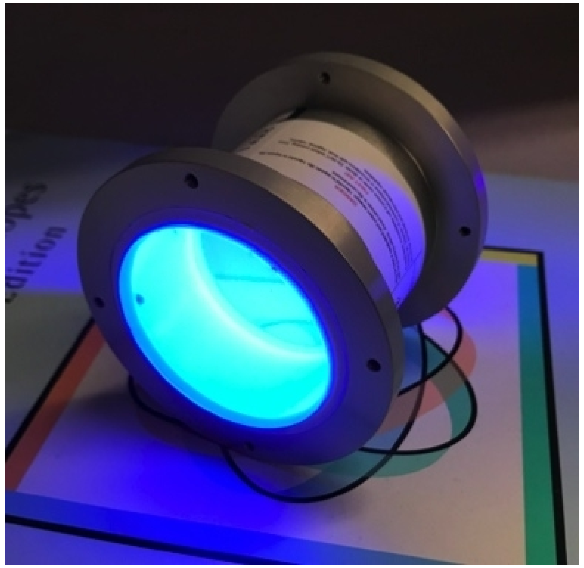
BERKELEY LAB

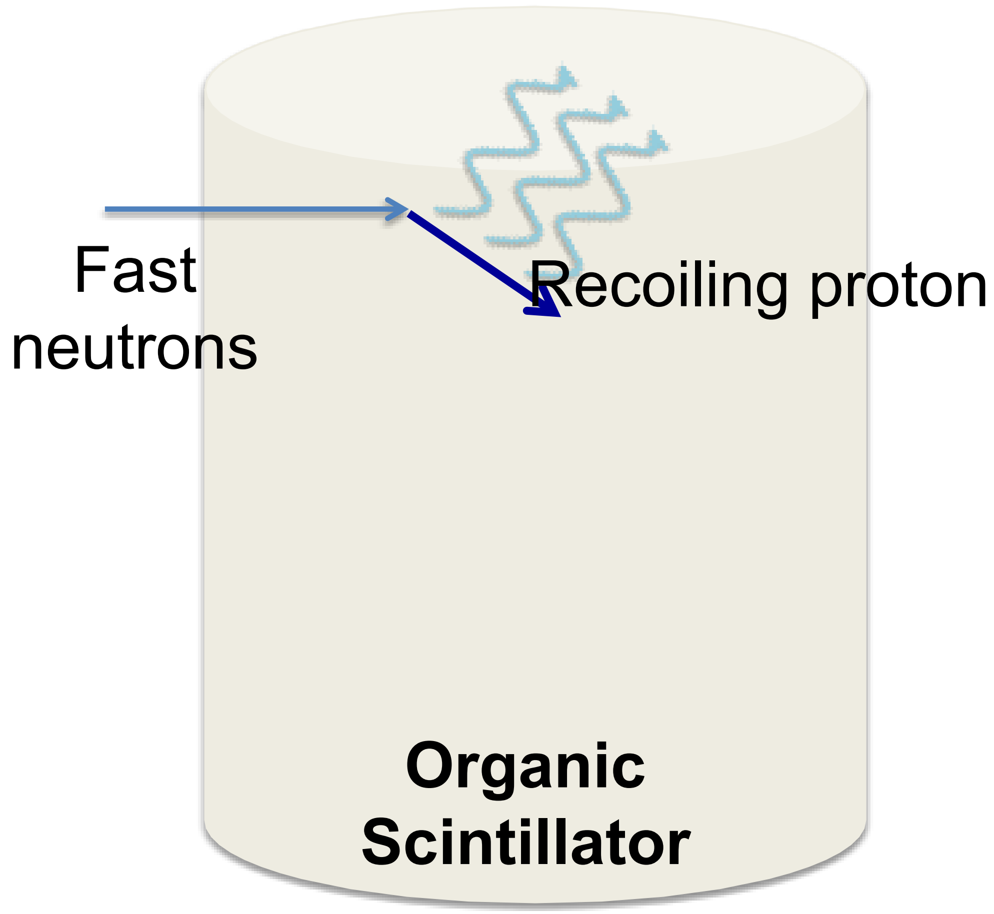
SCINT2022 -- September XX, 2022

Outline

- Fast neutron response of organic scintillators
- Experimental measurements of ionization quenching
- Quenching models considered
- Results (EJ-204, EJ-276, EJ-309, O-glass)
- Summary/Outlook



Fast Neutron Response of Organic Scintillators



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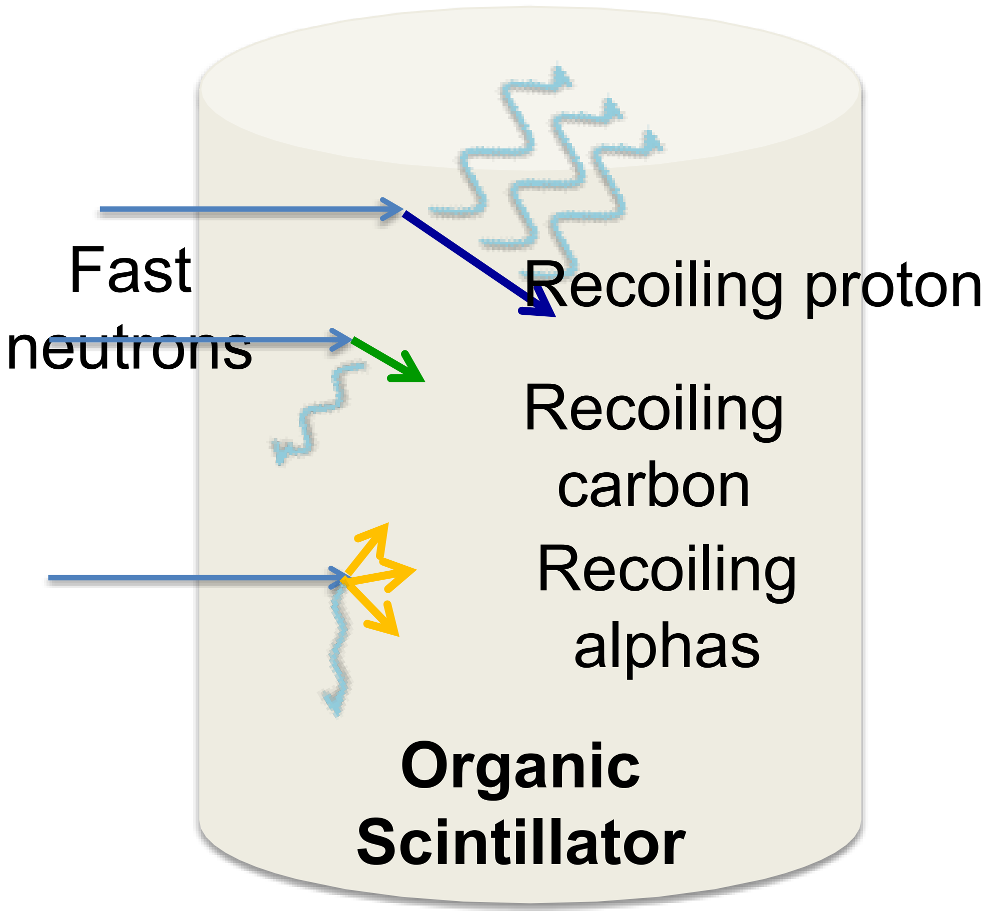
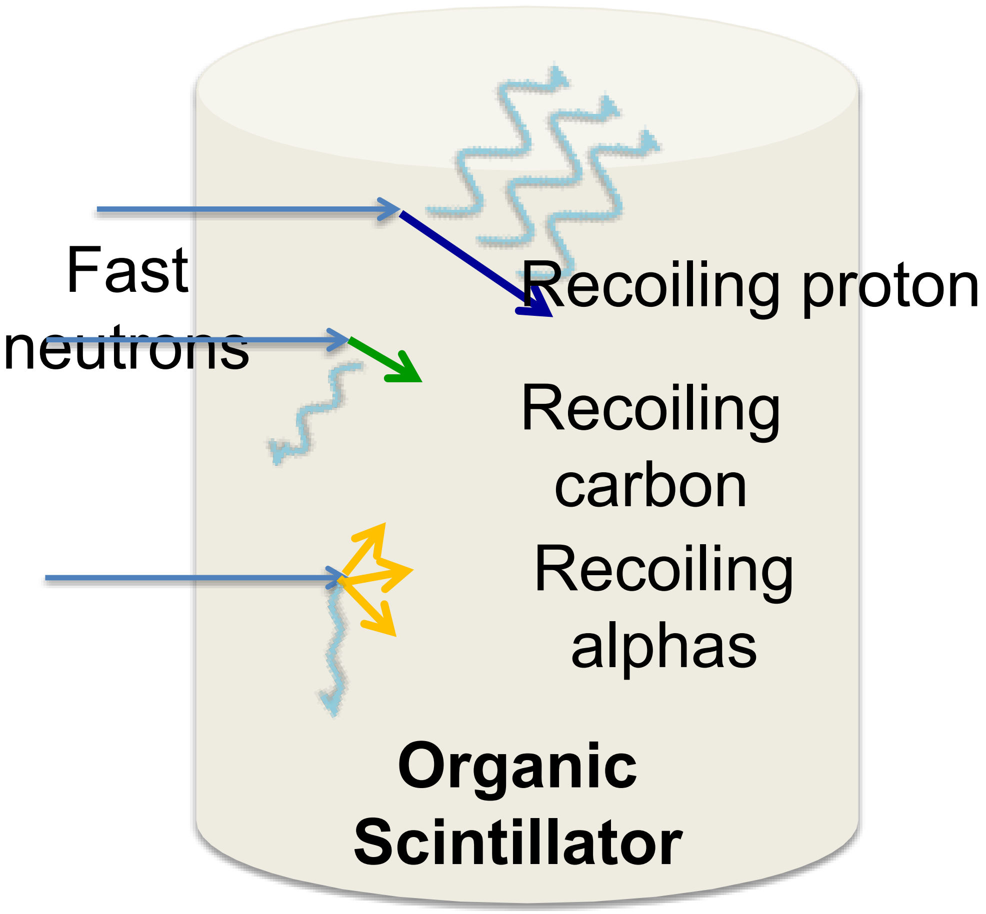


Fast Neutron Response of Organic Scintillators



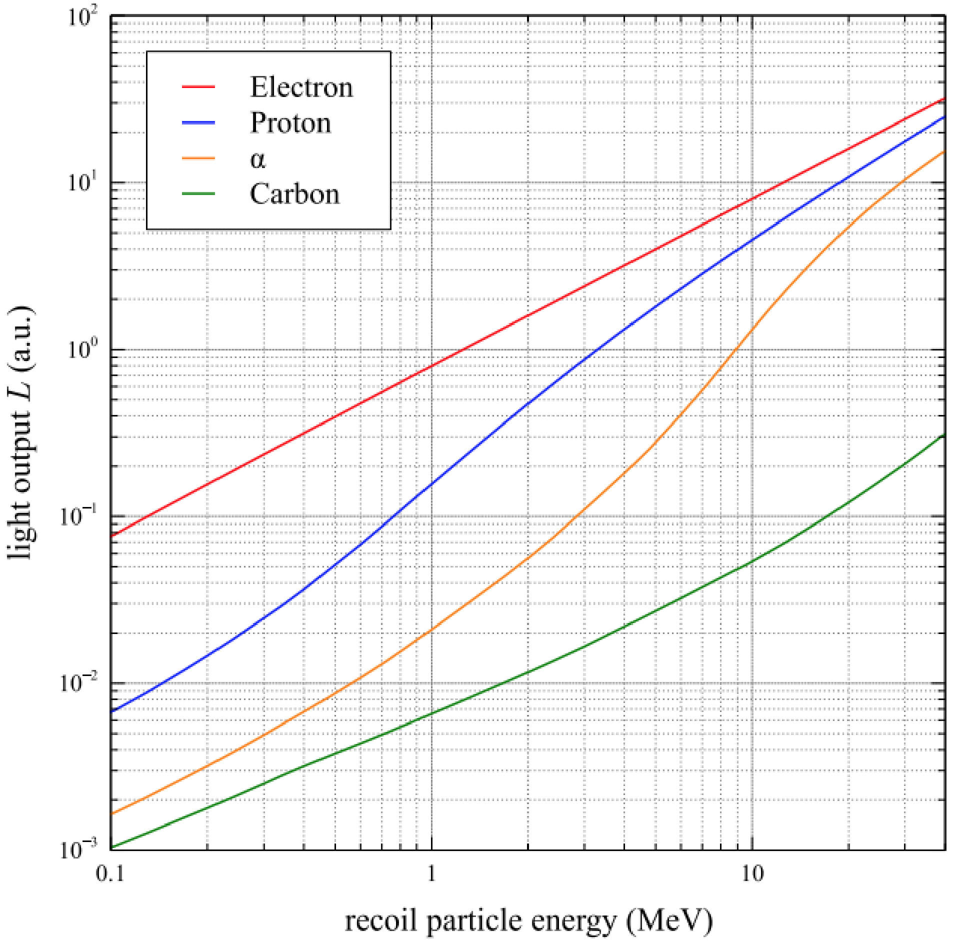


Fig. 1 Liquid scintillator light output L as a function the recoil particle energy. Data adapted from [19]

Cecconello, Jour. Fus. Energy 38(2019) adapted from Verbinski et al. NIM (1968)

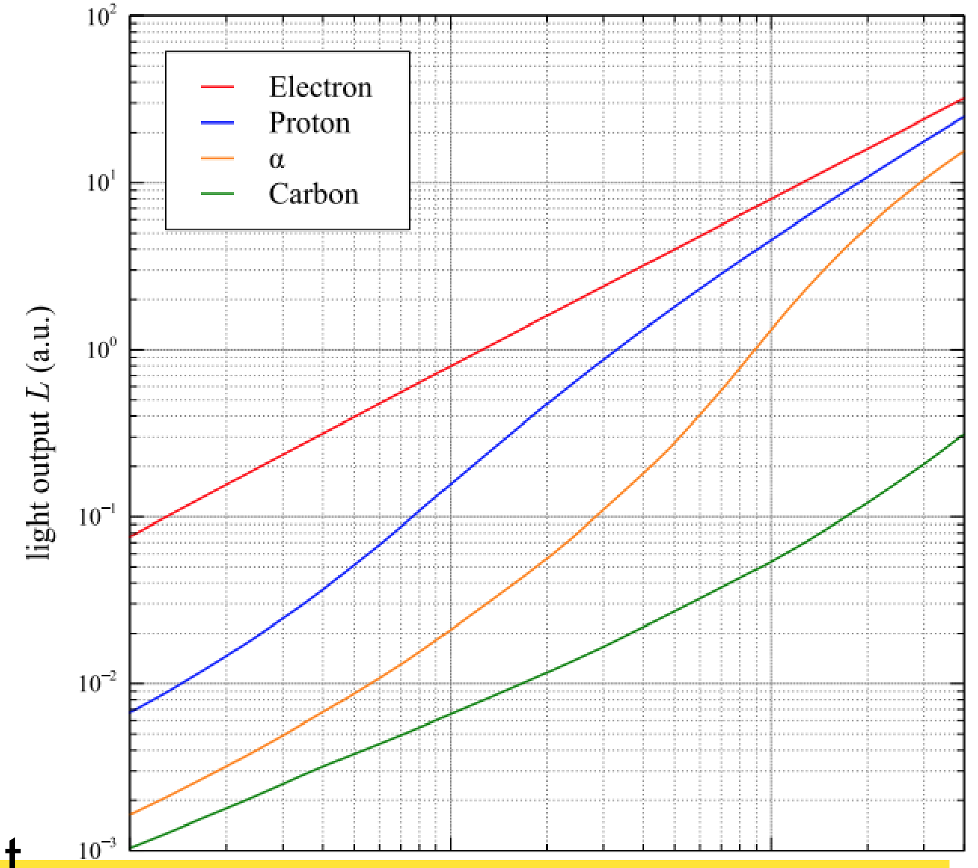
Fast Neutron Response of Organic Scintillators

Light yield of recoiling ions is important for:

- Accurate simulation of detector performance
- Inform design of new detection system

Status of the literature for fission energy range:

- Proton light yield data over limited energy range for some materials
- Alpha and Carbon data mostly non-existent

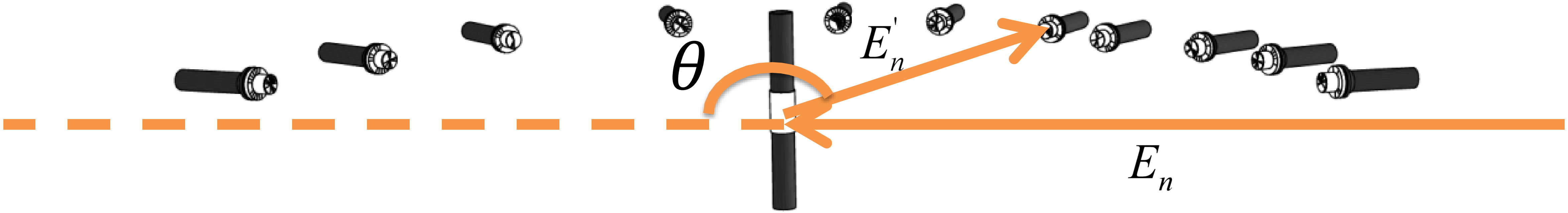


Can we find an ionization quenching model that works for :

- **A wide energy range**
- **Different recoiling ions**

adapted from Verbinski et al. NIM (1968)

Light Yield measurements at the 88-Inch Cyclotron



- Broad-spectrum neutron source for deuteron breakup
- Kinematically over-constrained system
- Simultaneous proton and carbon light yield measurements

J.A. Brown, PhD Thesis, UC Berkeley 2017.
J.A. Brown, B.L. Goldblum, et al. Journal of Applied Physics 124, (2018).
T.A. Laplace, B.L. Goldblum, et al., Phys. Rev. C 104, (2021).

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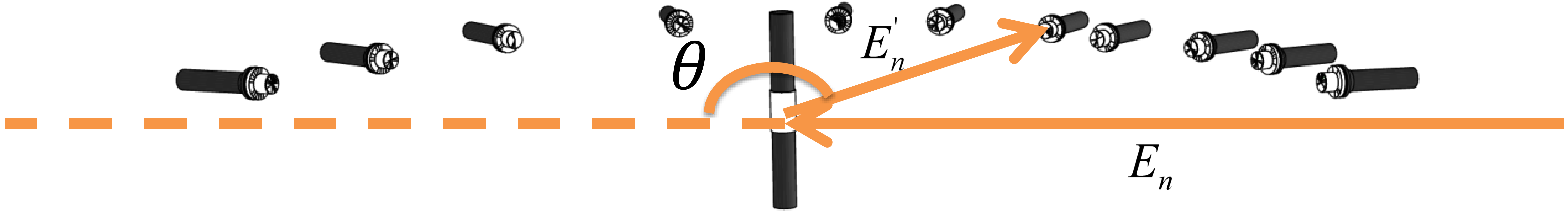

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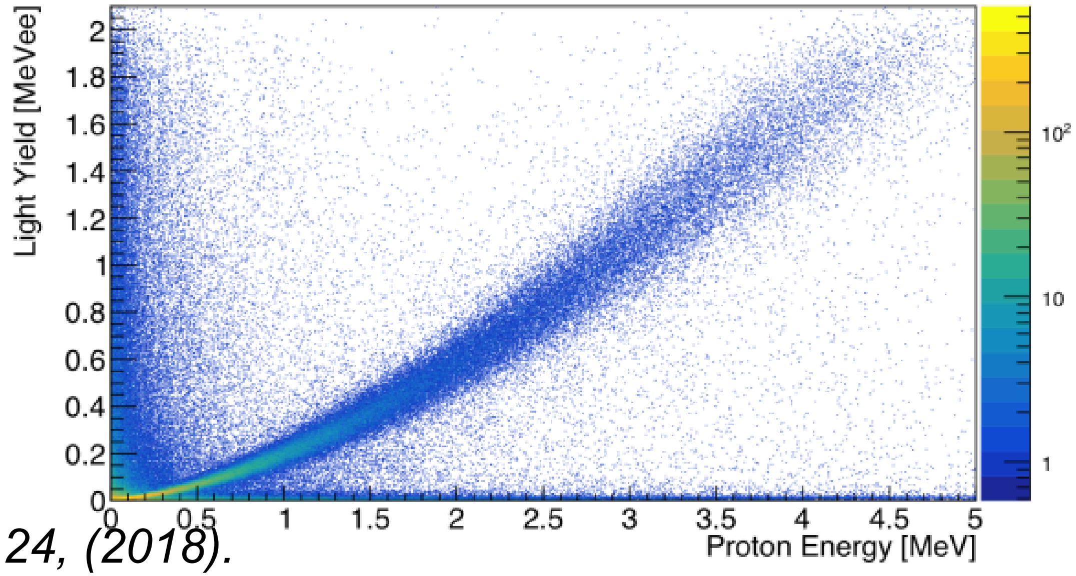

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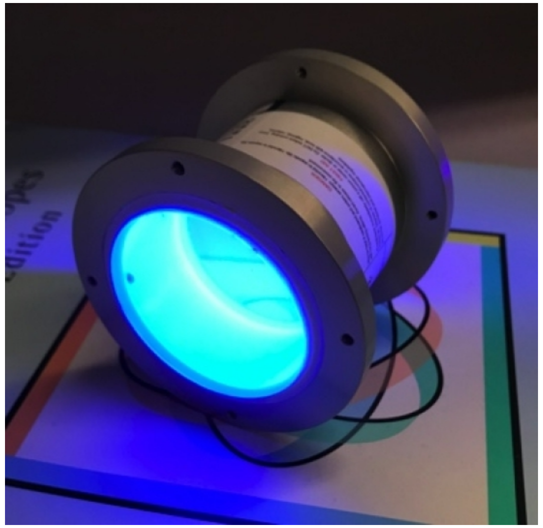
Datasets considered in this work

Scintillator	Recoil particle	Energy range (MeV)
EJ-309[10,37]	Proton	0.2–20
EJ-204[11]	Proton	0.05–5
EJ-276[37]	Proton	0.17–4.9
Organic glass[37]	Proton	0.05–20
EJ-309[36]	Carbon	2–5
EJ-204[36]	Carbon	1–4




Ionization Quenching Models

Canonical quenching model proposed by Birks (1951) :

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S\frac{\mathrm{d}E}{\mathrm{d}x}}{1 + kB\frac{\mathrm{d}E}{\mathrm{d}x}}$$

S: scintillation efficiency

kB: Birks' constant – quenching

J.B. Birks, Proc. Phys. Soc. A, 64(10) (1951)

Ionization Quenching Models

Canonical quenching model proposed by Birks (1951) :

$$\frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

If kB=0, unquenched particle
Linear light yield

S: scintillation efficiency
kB: Birks' constant – quenching

J.B. Birks, Proc. Phys. Soc. A, 64(10) (1951)

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Birks is still widely used in the literature

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S: scintillation efficiency
kB: Birks' constant – quenching

Second order quenching introduced by Chou (1952) to include bimolecular quenching:

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)}{1 + kB\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right) + C\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^2}$$

J.B. Birks, Proc. Phys. Soc. A, 64(10) (1951)

C.N. Chou, Phys. Rev. 87 (1952)

Ionization Quenching Models

Separation of nuclear and electronic stopping power by Hong (2002) :

$$S\frac{\mathrm{d}E}{\mathrm{d}x}$$

$$\frac{\mathrm{d}L}{\mathrm{d}x}=\frac{S_\mathrm{e}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{e}+S_\mathrm{n}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{n}}{1+kB_\mathrm{e}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{e}+kB_\mathrm{n}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{n}}$$

J. Hong et al., Astro. Phys. , 16(3) (2002)

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J. Hong et al., Astro. Phys. , 16(3) (2002)

Separation of nuclear and electronic stopping power and second order quenching by the Yoshida (2010) :

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S_e \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_e + S_n \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_n}{1 + kB_e \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_e + C \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_e^2 + kB_n \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_n}$$

S. Yoshida et al., NIMA 622 (2010)

Both Hong and Yoshida simultaneously fitted proton and carbon light yield data (Stilbene and KamLAND LS)

Ionization Quenching Models

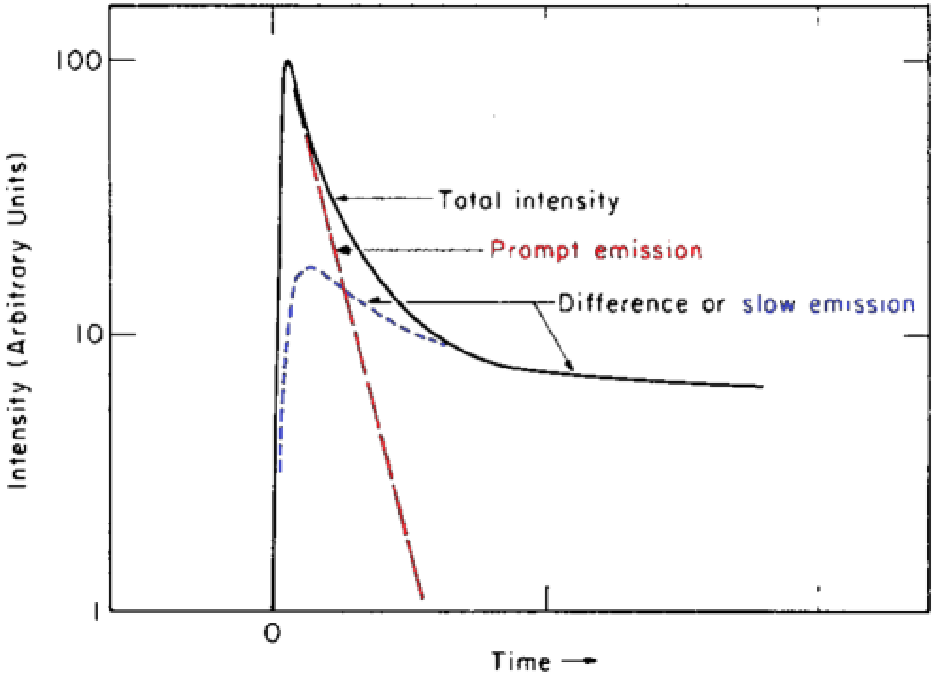
Voltz (1966) : Separation of prompt and delayed component
Separate treatment of delta rays

$$\frac{dL}{dx} = S_s\left[(1-F_s)\frac{dE}{dx}\exp\left(-B_s(1-F_s)\frac{dE}{dx}\right) + F_s\frac{dE}{dx}\right]$$

Prompt

$$+ S_t\frac{dE}{dx}\exp\left(-B_t\frac{dE}{dx}\right),$$

Delayed



D. Horrocks, Appl. Spec. 24 (1970)

R. Voltz et al., J. Chem. Phys. 45 (1966)

Ionization Quenching Models

Voltz (1966) : Separation of prompt and delayed component
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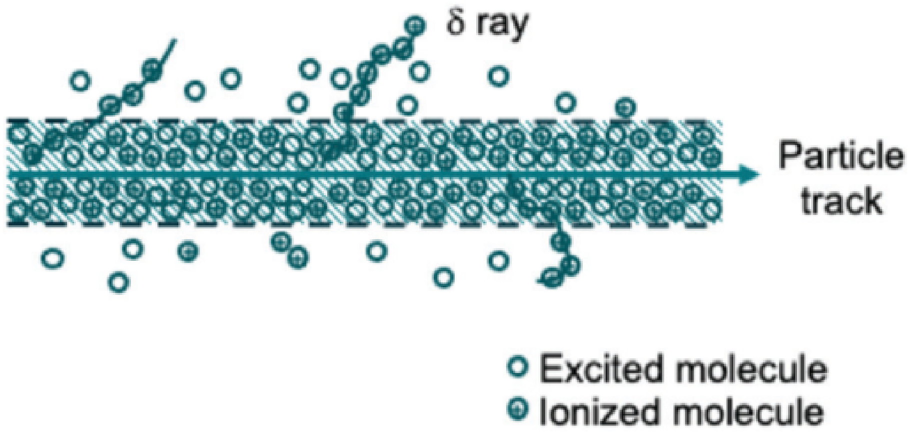
$$\frac{dL}{dx} = S_s\left[(1-F_s)\frac{dE}{dx}\exp\left(-B_s(1-F_s)\frac{dE}{dx}\right) + F_s\frac{dE}{dx}\right] + S_t\frac{dE}{dx}\exp\left(-B_t\frac{dE}{dx}\right),$$

Unquenched δ rays

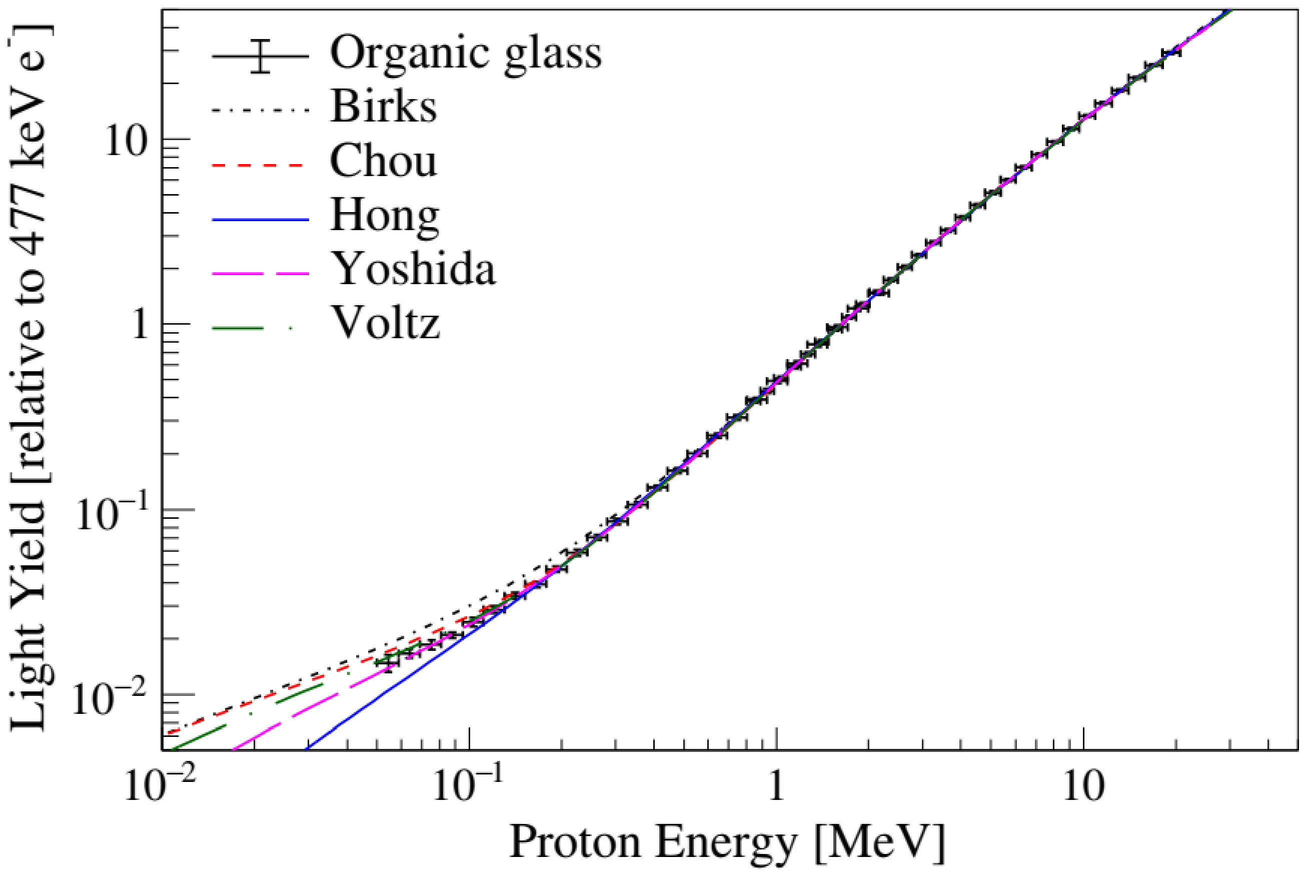


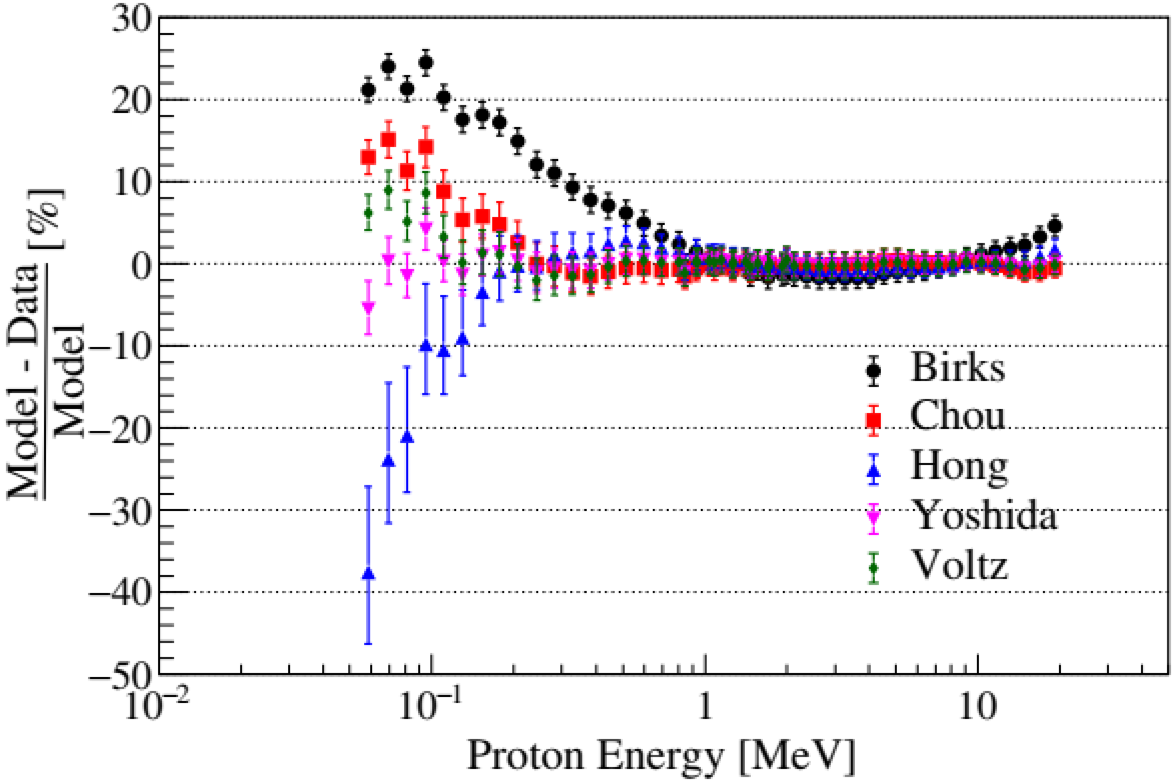
$$F_s = \frac{1}{2}\frac{\ln(4mE/MT_0)}{\ln(4mE/MI)}$$

Probability of electrons to escape the particle track

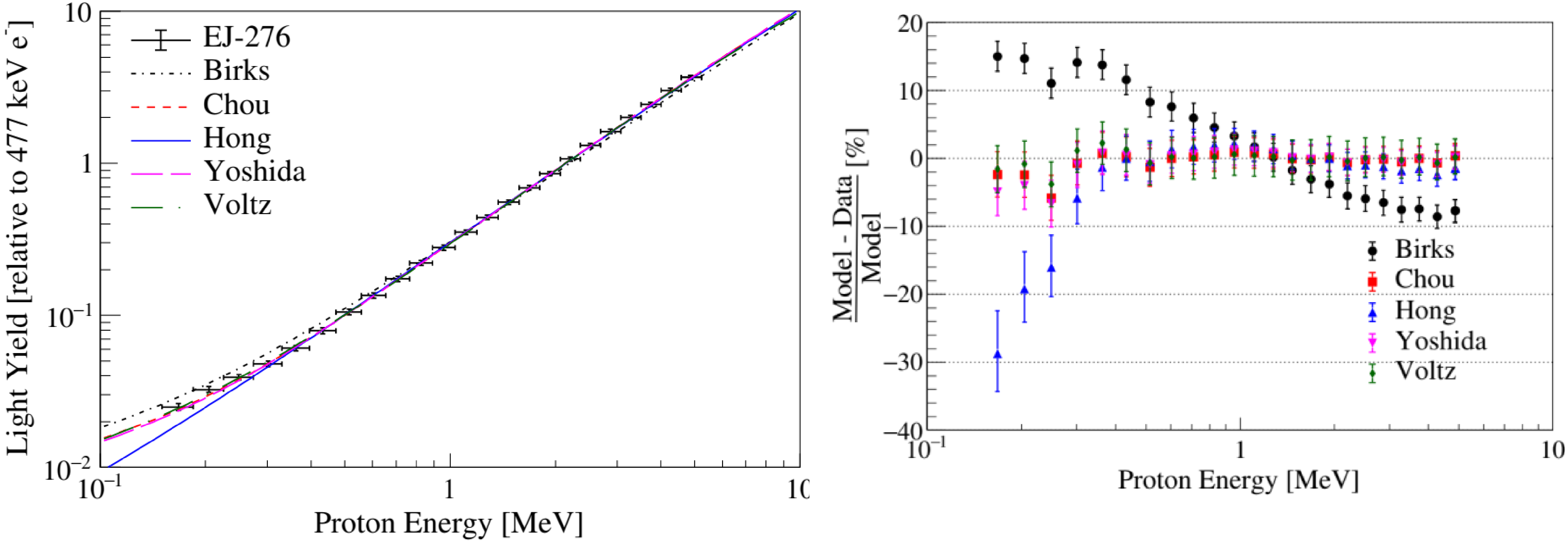
R. Voltz et al., J. Chem. Phys. 45 (1966)

Results – Protons in Organic glass



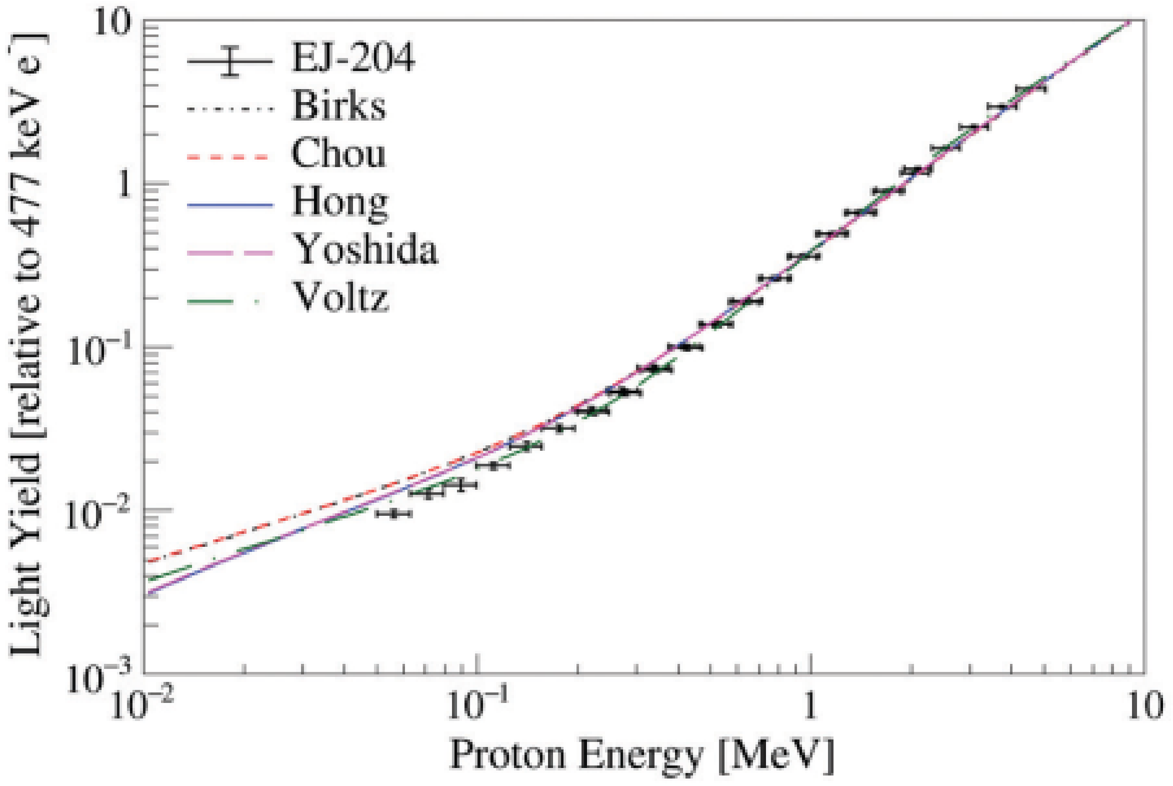


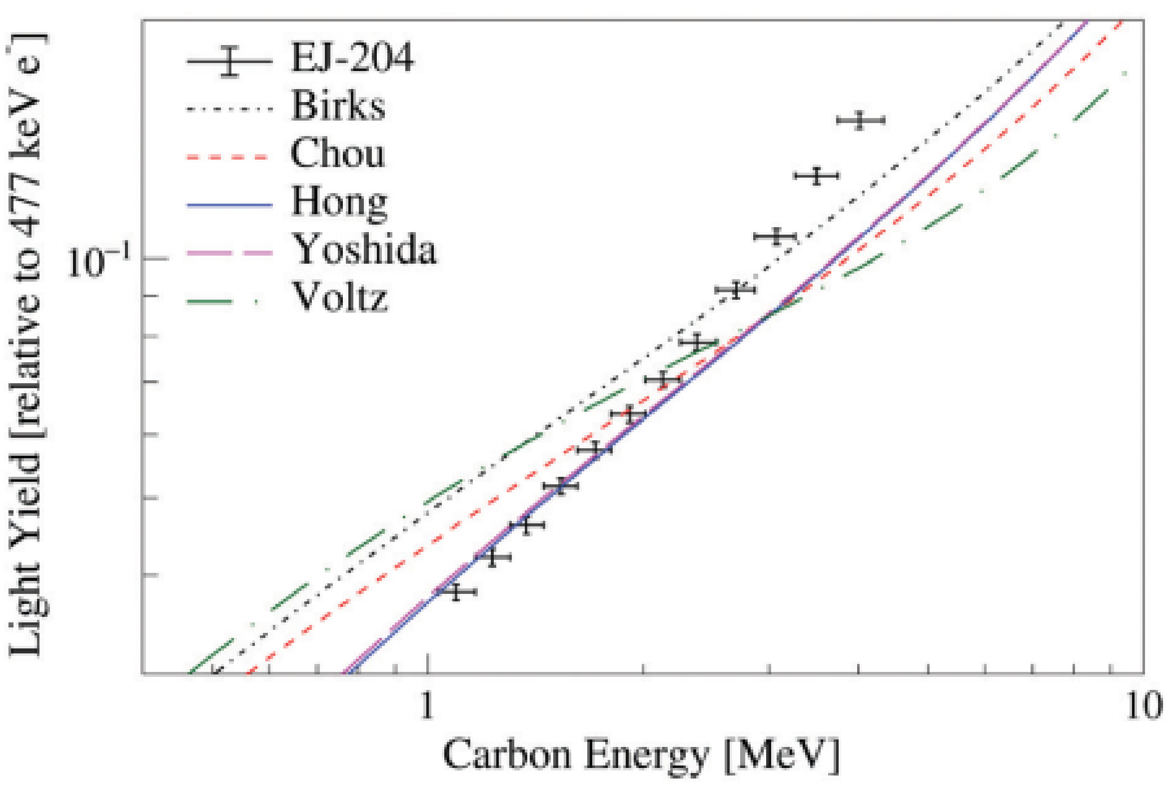
Results – Protons in EJ-276



Only the Yoshida and Voltz models reproduce proton light yield data for EJ-204, EJ-309, EJ-276 and an organic glass

Results – Simultaneous fit of proton and carbon data (EJ-204, EJ-309)





None of the models provided a reasonable fit of proton and carbon light yields simultaneously

Possible improvements

$$\frac{\mathrm{d}L}{\mathrm{d}x} = S_\mathrm{s}\left[(1-F_\mathrm{s})\frac{\mathrm{d}E}{\mathrm{d}x}\exp\left(-B_\mathrm{s}(1-F_\mathrm{s})\frac{\mathrm{d}E}{\mathrm{d}x}\right) + F_\mathrm{s}\frac{\mathrm{d}E}{\mathrm{d}x}\right] + S_\mathrm{t}\frac{\mathrm{d}E}{\mathrm{d}x}\exp\left(-B_\mathrm{t}\frac{\mathrm{d}E}{\mathrm{d}x}\right),$$

Unquenched δ rays

δ rays are treated as unquenched, but electron light yield is nonlinear at low energies

W. Moses et al., IEEE Tans. Nuc. Sci. (2012)

Treatment of delayed light should not be monotonic as a function of stopping power

Track structure modeling has also been recently attempted by some authors with promising results

T. Ogawa et al., Sci. Rep. 11 (2021)

S. Kikuta et al., Phys. Med. 89 (2021)

J. Matsuya et al., Int. J. Rad. Biol., 98 (2022)

Summary and Outlook

- Model parameters with covariance matrix for proton light yield in:
  - EJ-204 (PVT based plastic)
  - EJ-276 (PSD plastic)
  - EJ-309 (PSD liquid)
  - Organic glass developed at SNL

  ➔ Can be used to simulate detector response

- Birks does not work!
- Only the Yoshida and Voltz model reproduce proton light yield data
- None of the models reproduce proton and carbon light yield simultaneously

- Potential improvements to the Voltz model and status of stopping power data are also discussed in manuscript

T. Laplace et al., Mat. Adv. 3 (2022)
Part of the special issue honoring Prof. Williams

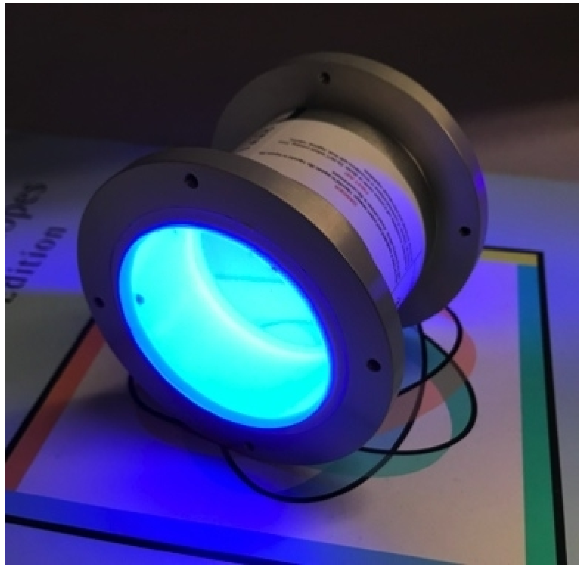
Acknowledgements

B. Goldblum, J. Brown, T. Li, G. LeBlanc, J. Manfredi

E. Brubaker and the SVSC collaboration

B. Goldblum, E. Bourret and the scintillator collaboration

This work was performed under the auspices of the U.S. Department of Energy National Nuclear Security Administration by Lawrence Berkeley National Laboratory under Contract DE-AC02-05CH11231 The project was funded by the U.S. Department of Energy, National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D). Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This work was also supported by the Department of Energy National Nuclear Security Administration through the Nuclear Science and Security Consortium under Award Number DE-NA-0003180.

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