On the Saturation of Response of Inorganic Scintillators to Slow Charged Particles

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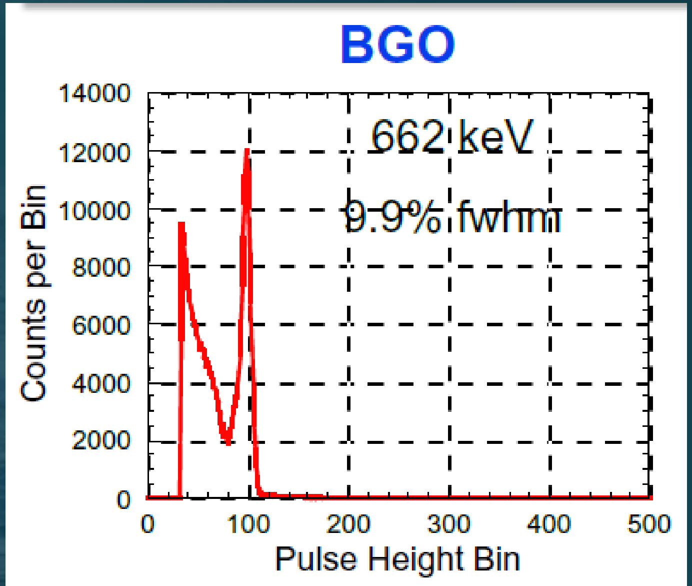
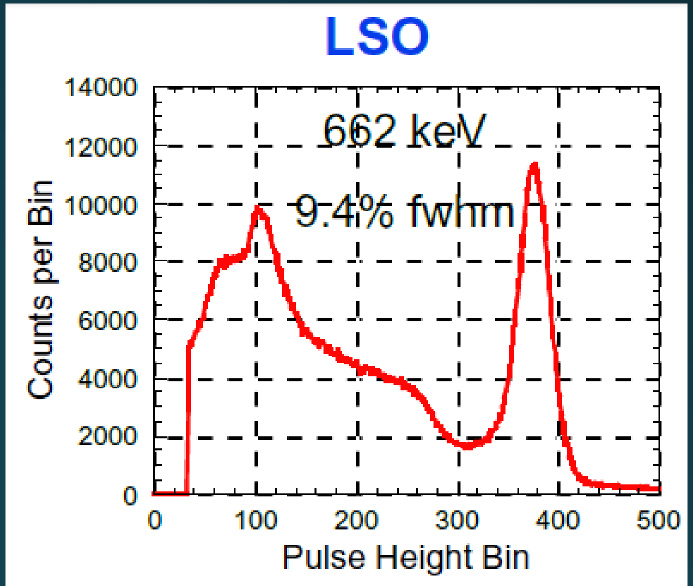
What is the Problem? And Who Cares?

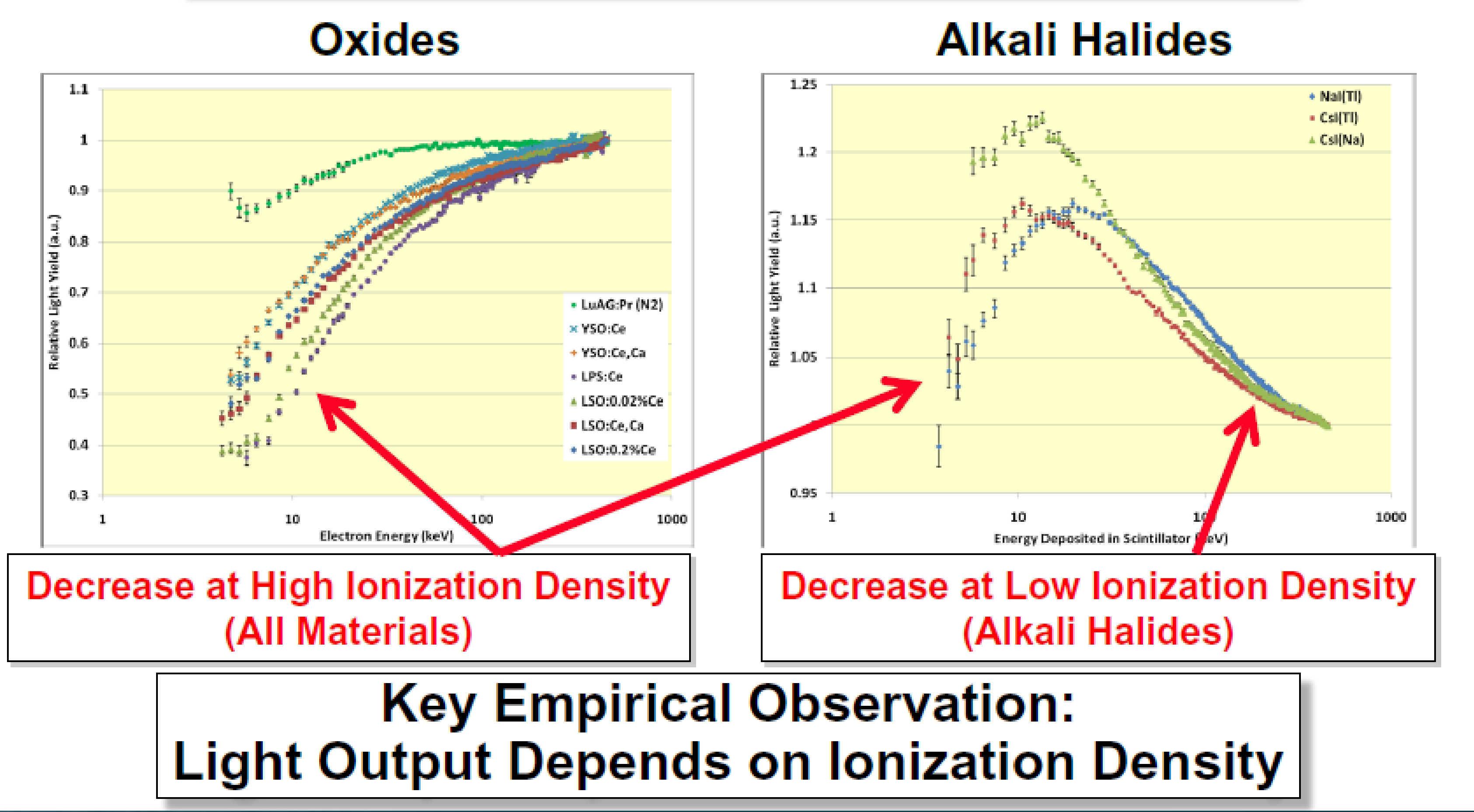
- Inorganic scintillators (mostly crystals) are used for very precise energy measurements:
  - Nuclear (photon) spectroscopy
  - Particle identification in nuclear physics experiment ΔE-E spectrometers
  - Very high precision hadron calorimetry(?)
  - Composition of high energy cosmic rayes
- Old wisdom: energy resolution dominated by photostatistics – need very bright scintillators





NOT True!!!

New area of research: Non-proportionality of scintillation



From B. Moses, SCINT2015

Conclusions
(My Picture)

B. Moses, SCINT2011

Light Yield Reduction at High Ionization Density:
- Caused by Auger-like process (excited carriers collide)

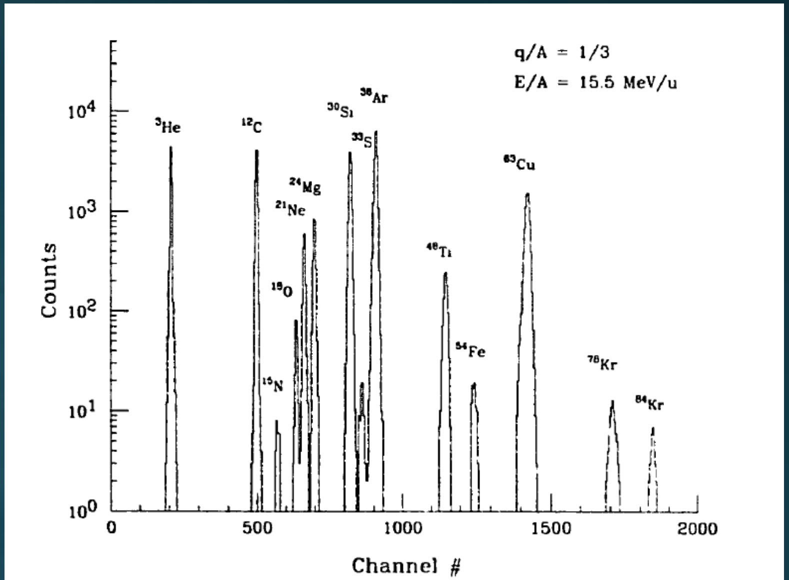
Light Yield Reduction at Low Ionization Density:
- Competition between luminescence & trapping
- Only when two particle luminescence process present
- Different e/h mobilities ➔ two particle processes?

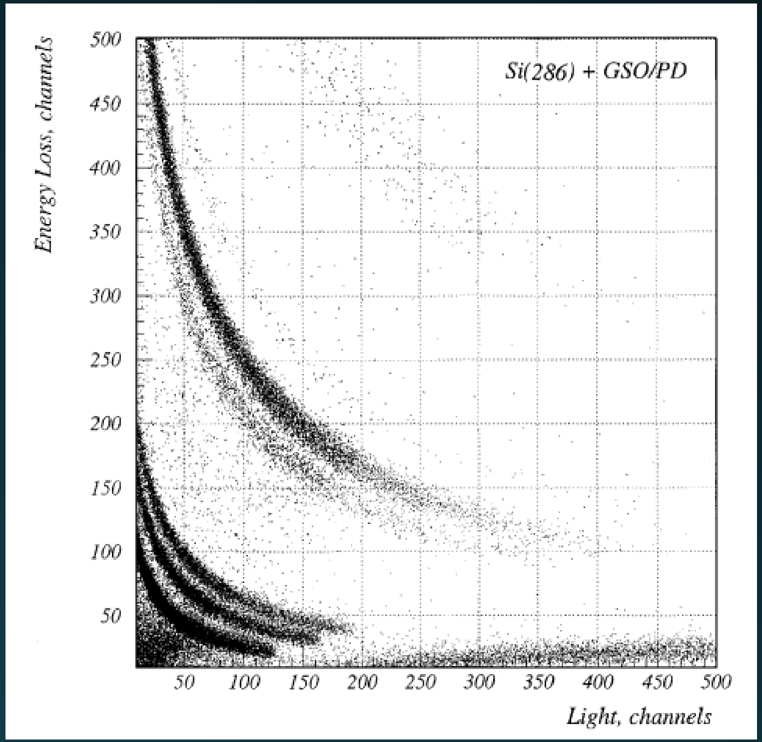
Mobility (Especially of Holes) Important
- Want hole mobility ≈ electron mobility
- Want high electron & hole mobility

- Considerable Progress in Recent Years
- A Complete Theory Remains Elusive
- A Predictive Theory Is Possible

Quest:
Understand the physics of non-proportionaliy to design new, proportional scintillating materials

Particle Identification in Nuclear Physics Experiments

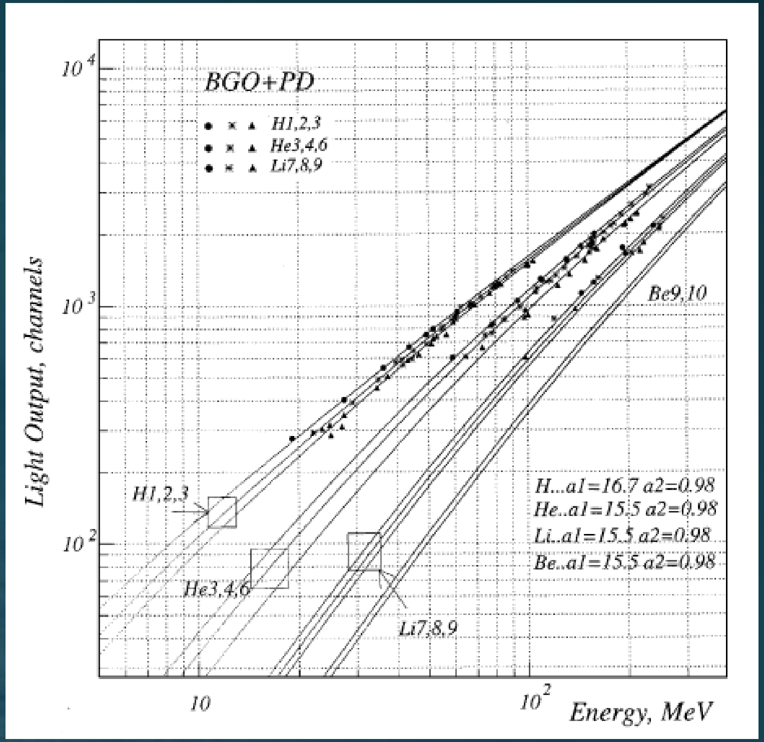




Need detailed calibration of the response of crystals as a function of nucleus (A,Z) and energy.
Long list of careful (and difficult!) experiments.

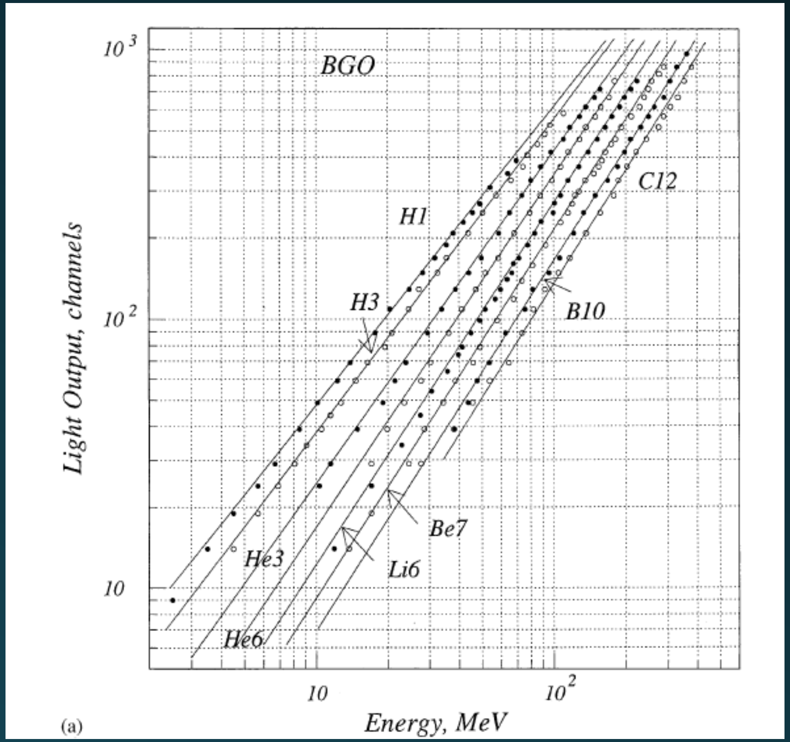
Examples of the Existing Data Sets

V. Avdeichikov et al NIMA 439



Dubna

V. Avdeichikov et al, NIMA 484



Uppsala

$$L(E,A,Z) = a_1\left(E - a_2 AZ^2 \ln\left|\frac{E + a_2 AZ^2}{a_2 AZ^2}\right|\right)$$

Several other semi-empirical expressions of $L(E,A,Z)$ with three [7] or four [6,8,19] parameters were proposed to describe the light output as a function of E and Z. Some of the expressions [6,19] exclude the A-dependence, which is not acceptable in view of our experimental data. Unfortunately, we could not find any regular behavior of the a_1 and a_2 parameters as a function of Z and A.

Appears complicated:
large differences in response between different ion species and crystals

$$L(Z,A,E) = a_1(Z,A)E^{a_2(Z,A)}$$

$$a_1(Z, A = 2Z) = 0.82 + 14.10\exp(-0.461Z)$$

for CsI(Tl),

$$a_1(Z, A = 2Z) = 0.10 + 13.08\exp(-1.683Z) + 1/Z$$

for BGO, GSO(Ce).

and

$$a_2(Z, A = 2Z) = 1.255 - 0.387\exp(-0.349Z) \quad \text{for CsI(Tl)},$$

$$a_2(Z, A = 2Z) = 1.336 - 0.705\exp(-0.967Z) \quad \text{for GSO(Ce)},$$

$$a_2(Z, A = 2Z) = 1.362 - 0.948\exp(-1.295Z) \quad \text{for BGO}.$$

The A dependence of the light output can be parameterized by the expressions

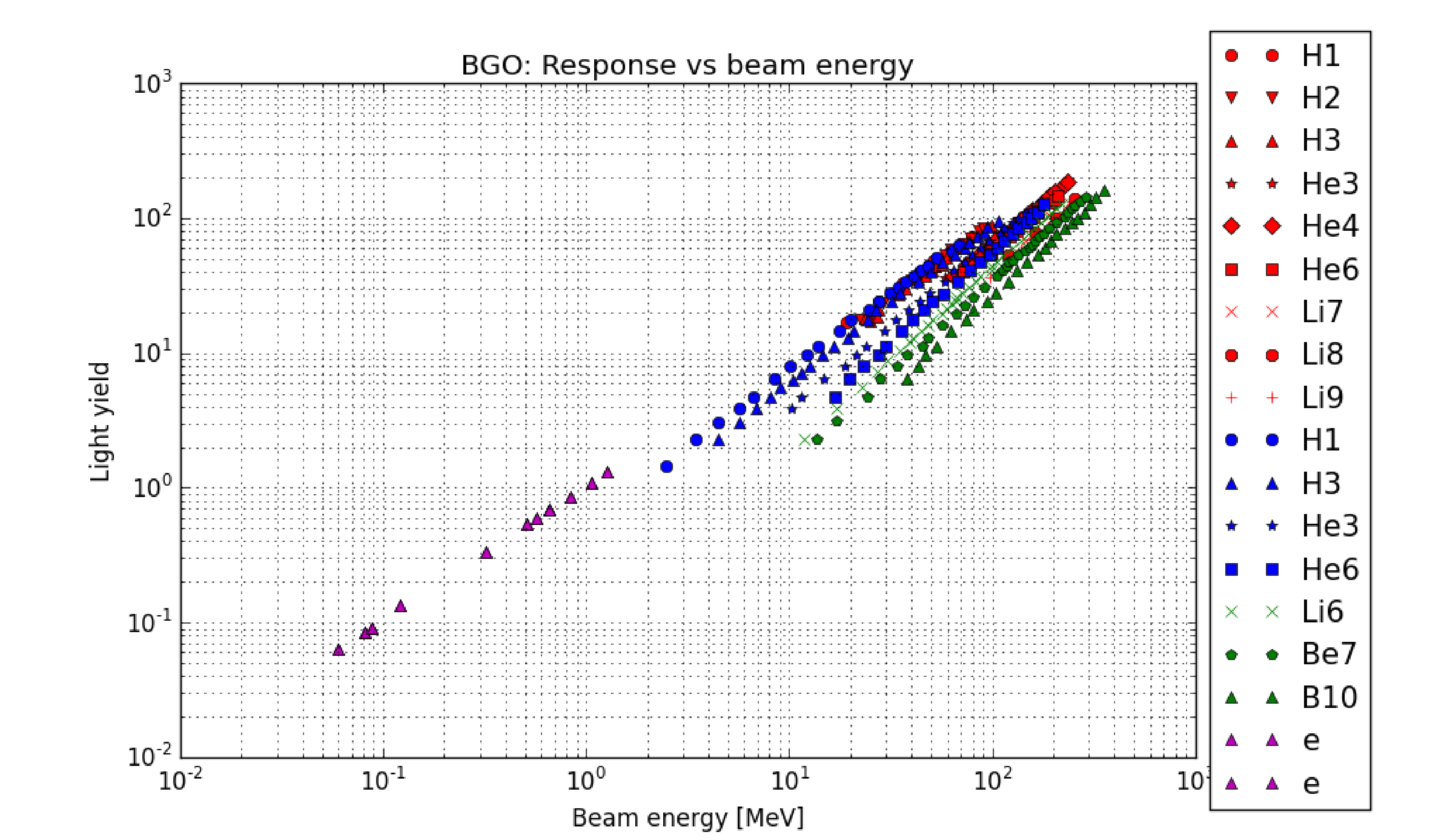
$$a_1(Z, A) = a_1(Z, A = 2Z)[1 - k_1(A/2 - Z)/\sqrt{Z}], \quad (2)$$

$$a_2(Z, A) = a_2(Z, A = 2Z)[1 + k_2(A/2 - Z)/Z]. \quad (3)$$

High Precision Hadron Calorimetry(?)

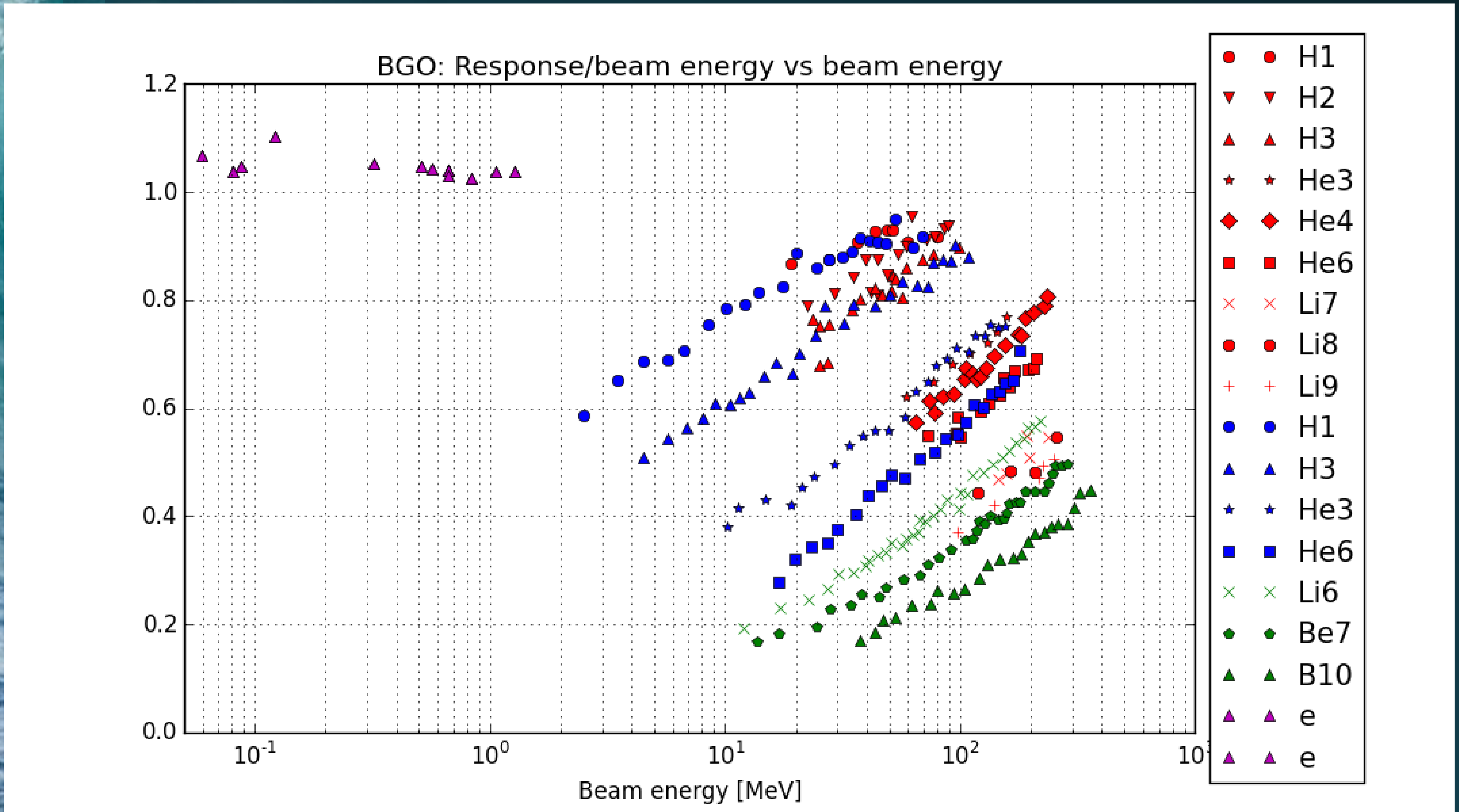
- Some fraction of hadron shower energy is deposited by slow protons and nuclear fragments
- If their contribution to the overall signal is poorly understood they may cause a significant degradation of energy resolution
- How comes that things can be so complicated??
- Light = $E_{transferred}$ X light/per energy
- At the low energies the interactions are purely elastic: the crystal responds to the electromagnetic disturbance caused by the moving charge
- It should not depend on the incoming particle

Step 1: combine the data



- Combine Dubna and Uppsale ion data (need 15% relative calibration adjustment)
- Combine ion and photon response using a dedicated measurement (L. Swiderski et al, Swierk)
- Too large dynamic range, use Response = L/E instead

Response of BGO crystal to different particles (part 1: as a function of E)



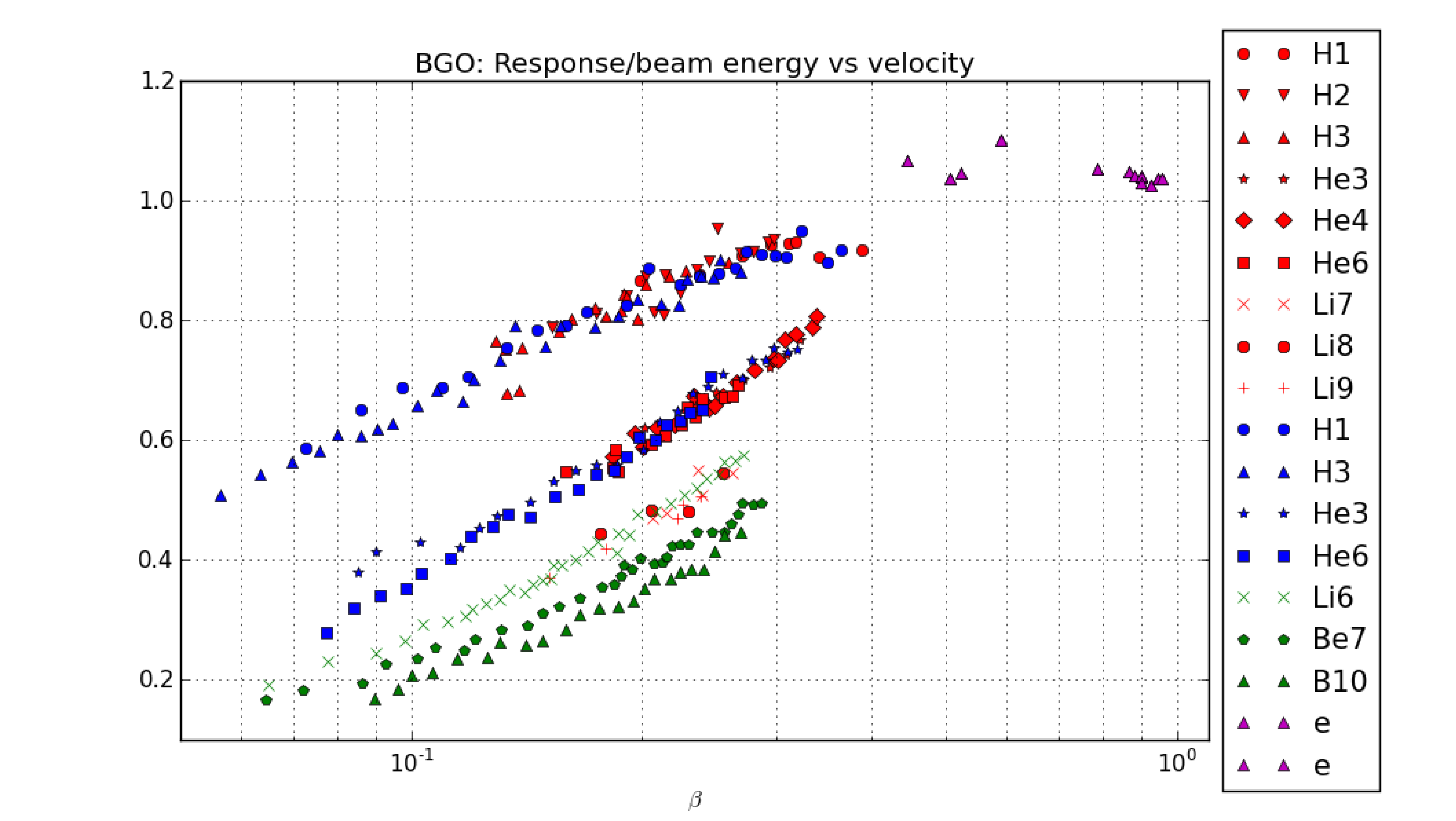
Large difference of response between different isotopes of the same elements.

Large difference of response between electrons and hadrons.

How does the crystal know what particle carries the charge through the medium??

They move with different speed!

Response of BGO crystal to different particles (part 2: as a function of v)



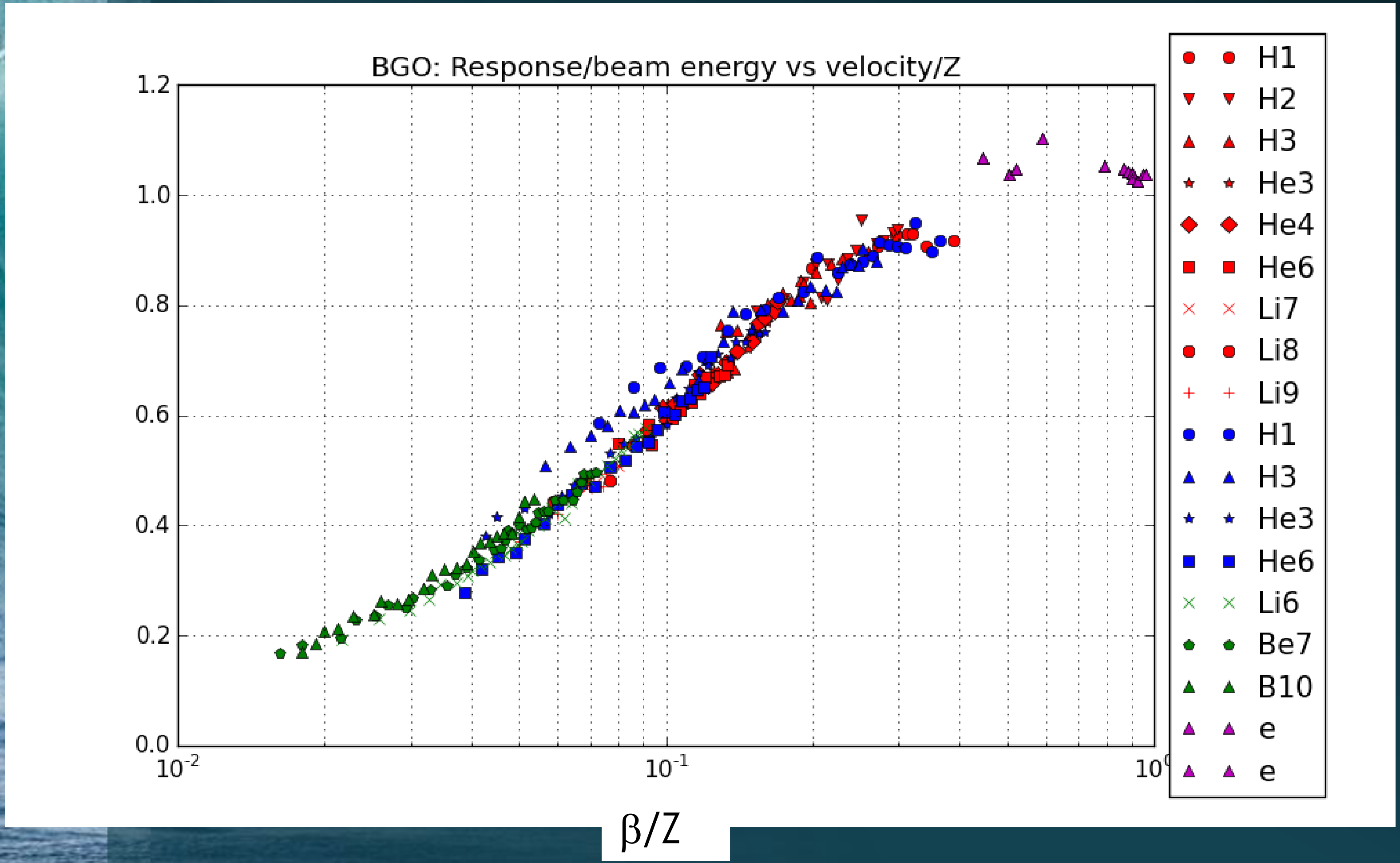
Response of BGO crystal to different particles (part 2: as a function of v)

- Response of the BGO crystal to different isotopes of the same element is the same, when then they move with the same velocity
- Response of protons, deuterons and tritons it same as for electrons, when they move with the same velocity
- At the same velocity the response is different to particles of different charge. Why??
- Progress in understanding of non-proportionality: suppression of light production as a function of the dE/dx. At these energies

$$\frac{dE}{dx} \approx A\frac{Z^2}{\beta^2}$$

- If the suppression depends on the crystal only, the response should be a function of β/Z

Response of BGO crystal to different particles (part 3: as a function of v/Z)



- Non-linearity of response to slow charged particles is independent of the particle type
- Progress in the development of fundamental understanding of the dynamics of light production in crystals can be exploited to evaluate the impact of the saturation effects for hadron calorimetry

Conclusions

- Response of the inorganic crystals to slow charged particles can be represented by a particle-independent function describing the quenching of the light production as a function of the local energy density.
- This function depends on the scintillator, but not on the measured particle.
- Hadron and ion data can be used to provide the cross check of the electron/photon data and to extend the range of the energy loss densities available for the validation of the emerging theories of the response non-proportionality
- Non-linearities of response are known with the sufficient accuracy to derive the contribution the the energy resolution of homogeneous hadron calorimeters..