Neutrino Lead Interactions: Towards an FSI model benchmark

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On Behalf of MINERvA collaboration

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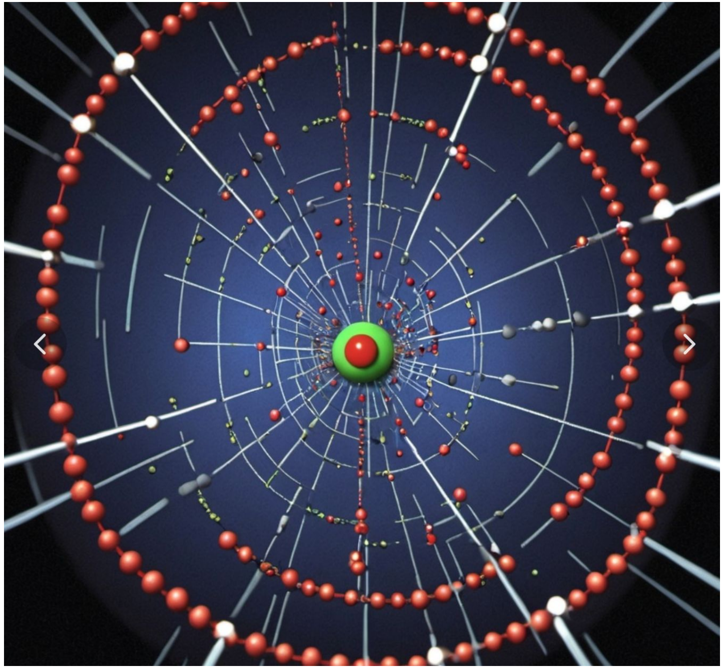
New perspectives, Fermilab

Neutrino Interactions in Pb

A heavy nucleus such as Pb can offer rich information on Final State Interactions: Interactions that occur after the initial neutrino interaction with a nucleus but before the final particles exit the nucleus.

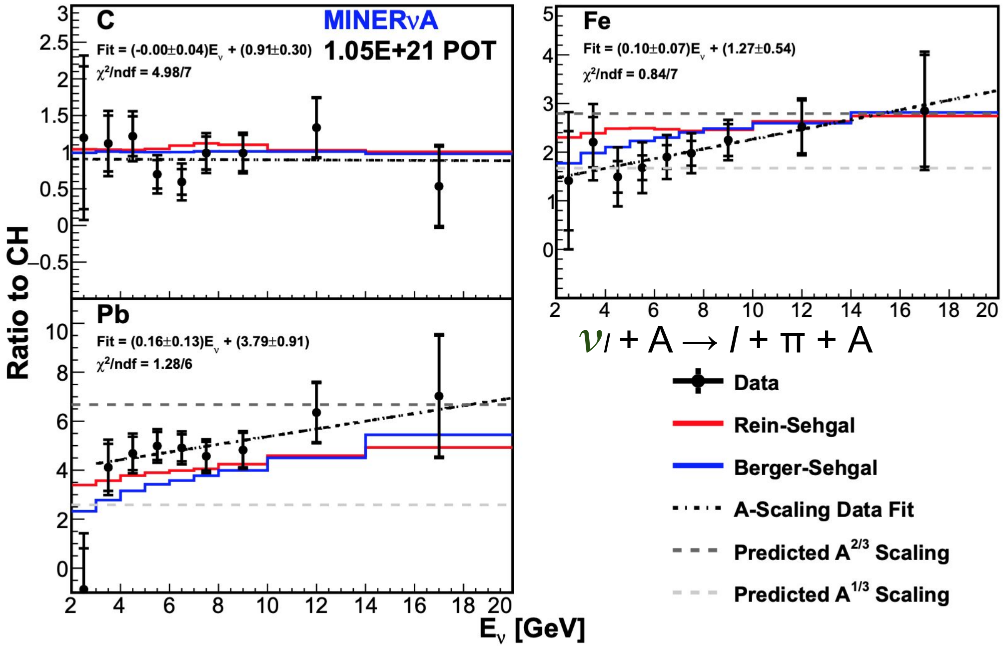
$\nu_\mu Pb$ studies complement research on neutrino interactions with argon.



This is what Dall-E thinks about neutrino interactions with lead.

Cross section on different nuclei

Previous measurements uncovered A-dependent differences in ν_μ interactions.



$\nu_l + A \rightarrow l + \pi + A$

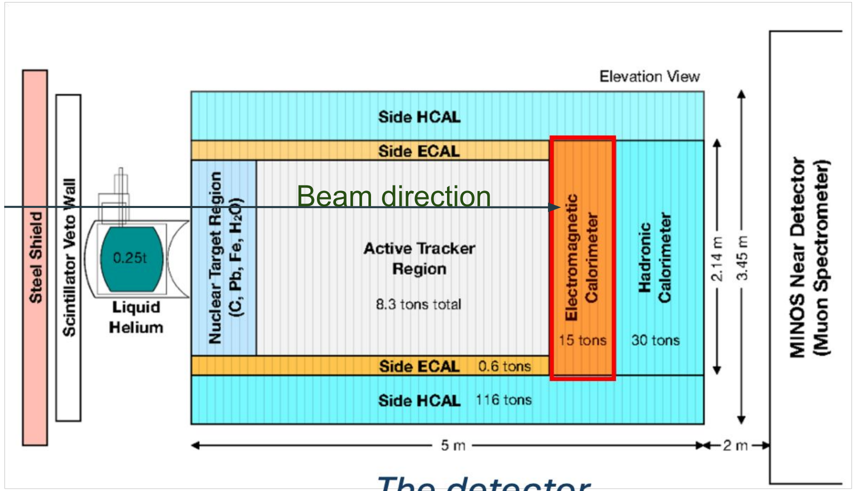
M.A. Ramirez, et al. Phys. Rev. Lett. 131, 051801

Coherent pion production cross section ratios as function of neutrino energy

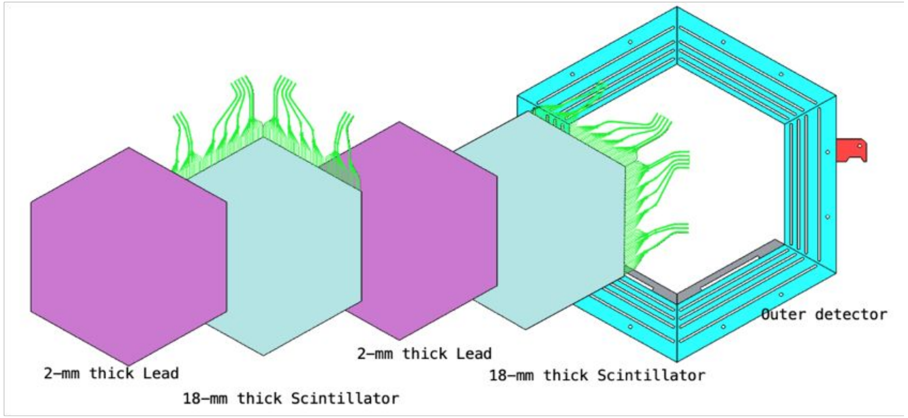
MINERvA's ECAL

Using Pb from the ECAL for neutrino analysis offers:

- Improvements in muon acceptance. Interactions closer to MINOS Near Detector.
- Fiducial mass about 4 times more than forward target.
- Better proton acceptance: smaller thickness in ECAL lead sheets.



The detector



Electromagnetic calorimeter (ECAL)

Phase Space

An effective phase space for studying nuclear effects in charged lepton scattering is transferred Three-momentum (q_3), and Available energy (E_{avail}) for a low energy transfer analysis.

E_{avail}, defined as the total visible energy collected, provides similar information to Energy transference (q_0) with less reliance on models as q_3.

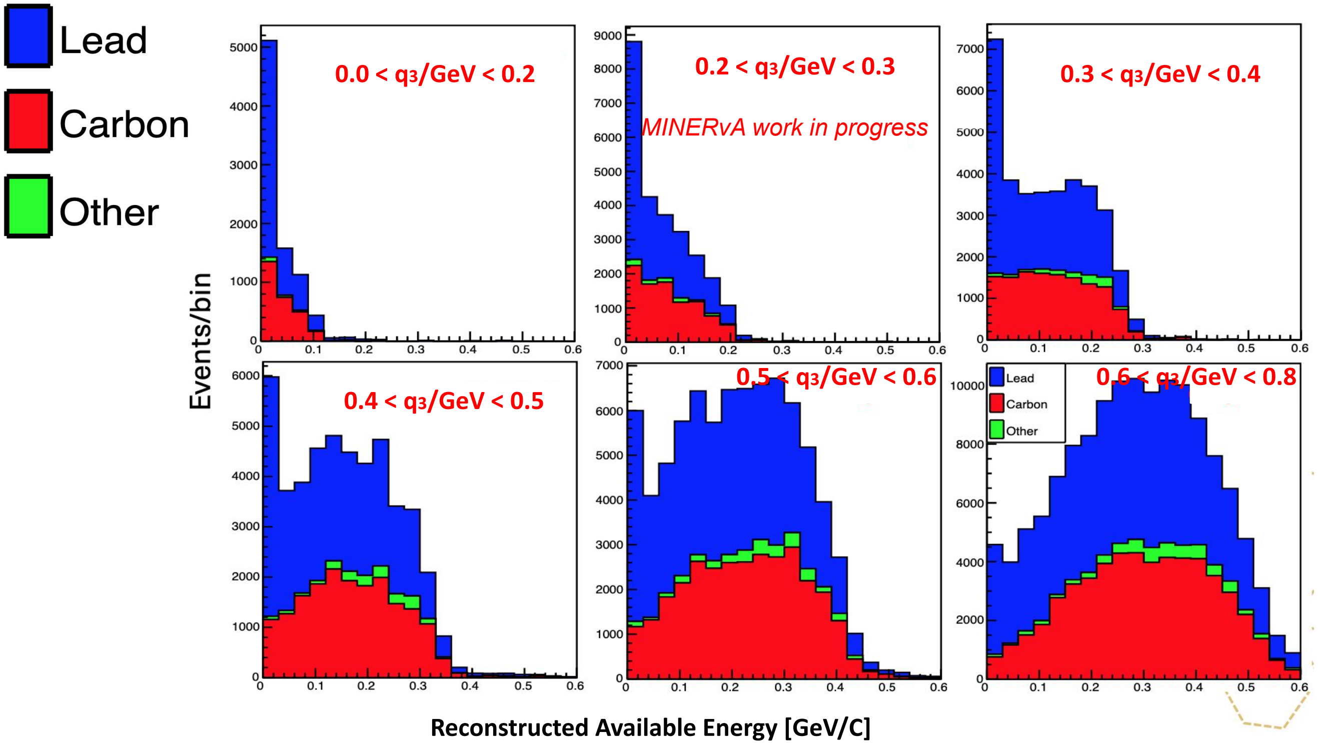
$$E_{\text{avail}} = \sum T_p + \sum T_{\pi^\pm} + \sum E_{\text{particles}}$$

Where

$$\sum E_{\text{particles}} = \sum E_{K^\pm} + \sum E_{e^\pm} + \sum E_{\pi^0} + \sum E_\gamma + \sum E_{\text{other}}$$

Total energy of particles except neutrons

Neutrino interactions in the ECAL

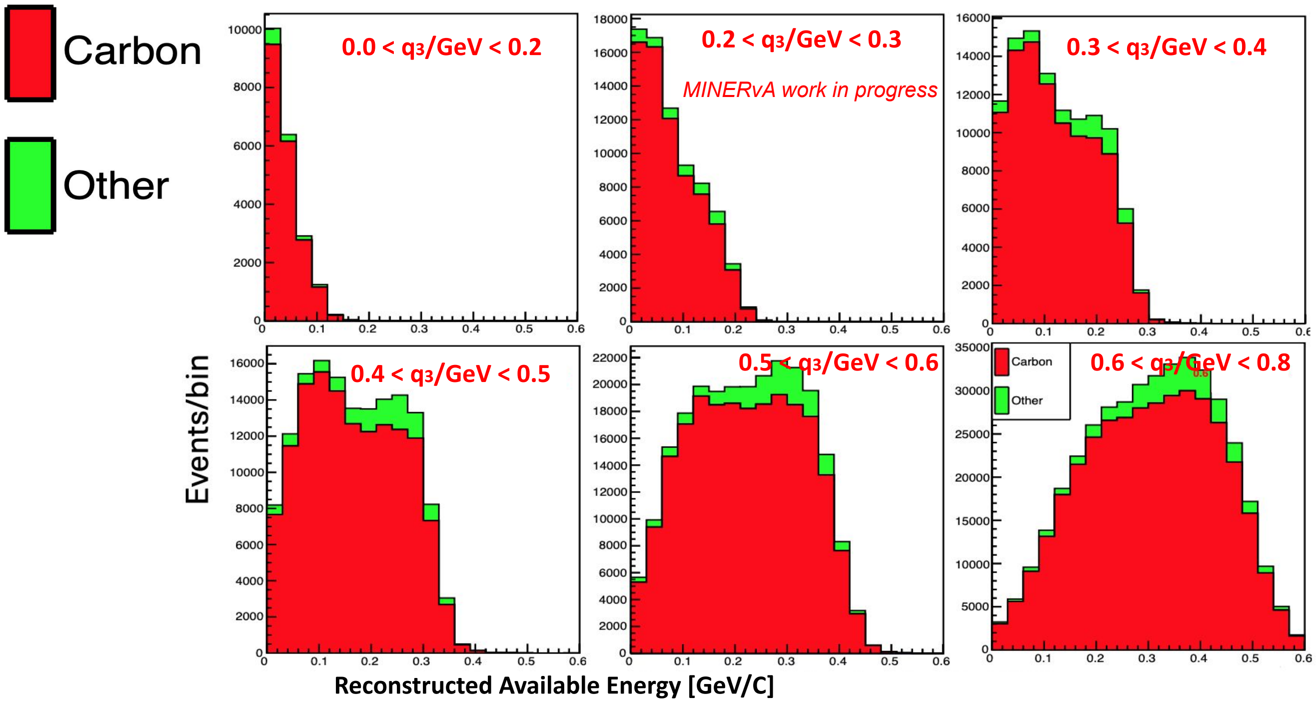


Differences between lead and carbon are likely driven by FSI absorption-like effects.

FSI effects are prominent at low E_{avail}.

Simulated event distributions in the ECAL as function of the material with expected statistics.

Neutrino interactions in the Tracker region



The comparisons with carbon located in the tracker region in the detector are performed to subtract background plastic scintillator events.

Simulated event distributions in the Tracker as function of the material with expected statistics.

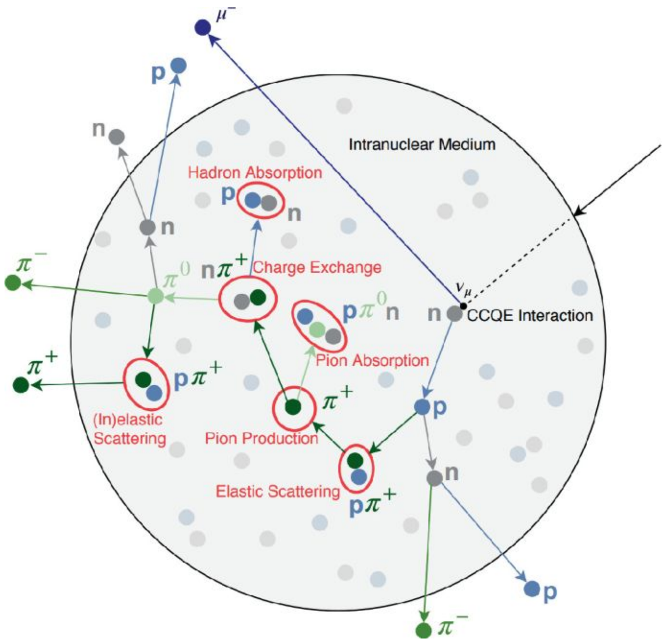
GENIE 3 vs GENIE 2

The MINERvA simulation utilizes **GENIE v2.12.6**, Geant4 9.2. with Minerva Tune MnvTunev1*.

The final deliverable aims to establish a systematic budget by improving and assessing the FSI uncertainty.

A difference in FSI treatments between GENIE 3 and GENIE 2 is their A dependence in Pions

For nucleons in a hA model, the fates the nucleon can experience are charge exchange (CEX), single nucleon knockout (inelastic) , multi-nucleon knockout, or pion production.

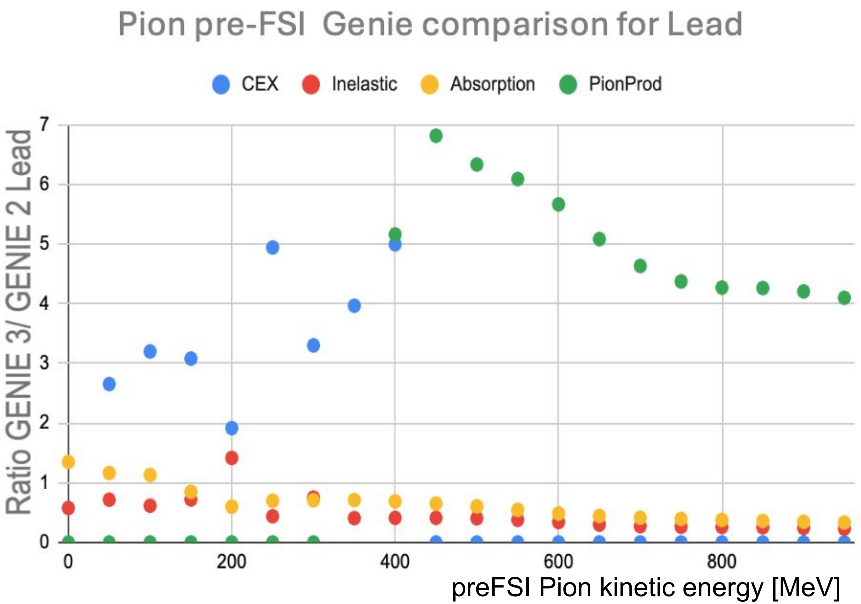


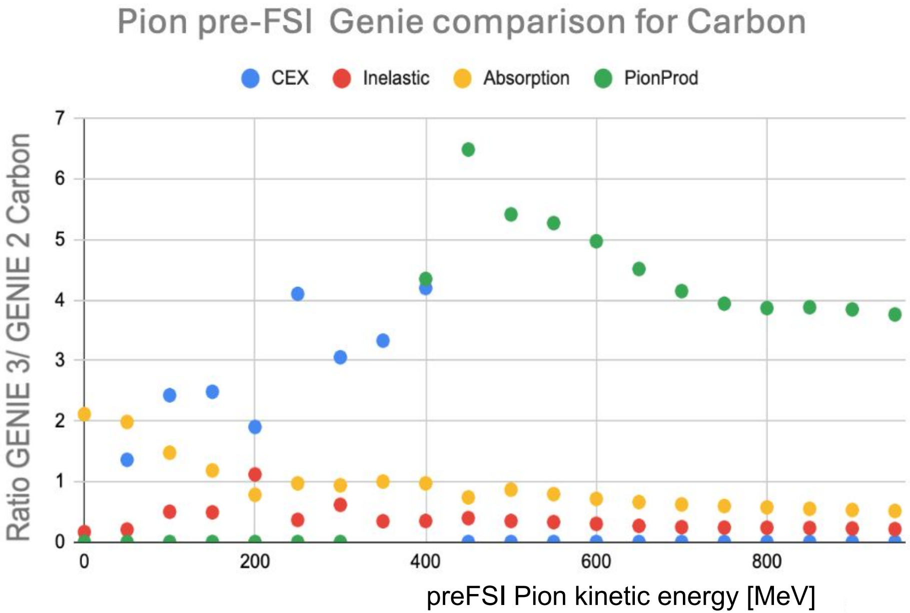
Mistry, K.V.J. (2023). Neutrino Interactions.
Final State Interactions fates

*MnvTuneV1:
-Valencia RPA applied to QE (RFG)
-Non-resonant pion production reduction,
-Low recoil fit (LE) applied to Valencia 2p2h

Extrapolating from GENIE 2 to GENIE 3

The ratio of fate fraction rates between GENIE 3 and GENIE 2 serves as the initial step in weighting MINERvA events.





This comparison is done at the GENIE level, not in the Monte Carlo simulations.

Conclusions and Next steps

- Our future measurements aim to enhance the accuracy of predictions for DUNE, significantly contributing to its mission by providing more reliable data for its groundbreaking neutrino research.

- Weight development for nucleons is also necessary for the final analysis.

- Model comparisons will aid in quantifying FSI uncertainties and refining measurements.

Thanks

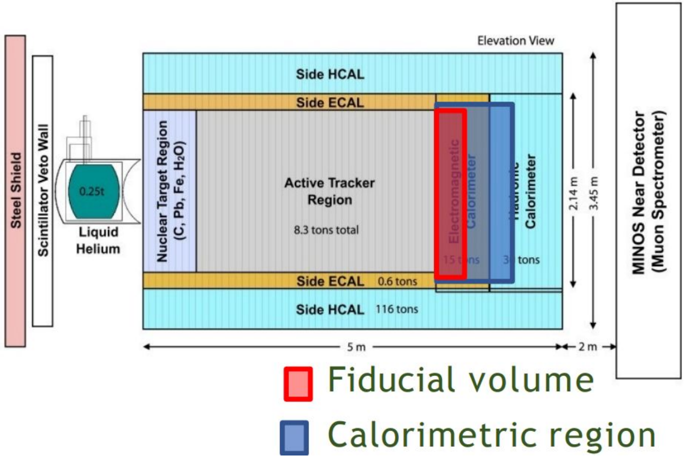
The MINERvA collaboration

This work was under the supervision of Professor Jeffrey Nelson and closely guided by Professor Richard Gran. We acknowledge the support from the National Science Foundation (Award 2111053) and the U.S. Department of Energy.

Back Up

Overview of MINERvA Experiment

Low recoil analysis in the front half ECAL as function of the Available Energy and three-momentum transferred



Definitions:

$$E_{Avail} = \sum T_p + \sum T_{\pi^+} + \sum T_{\pi^-} + \sum E_{\pi^0} + \sum E_e + \sum E_\gamma + \sum (E_{b^+} - M_p) + \sum (E_{b^-} + M_p)$$

$$q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$$

$$Q^2 = 2E_\nu (E_\mu - p_\mu Cos\theta_\mu) - M_\mu^2$$

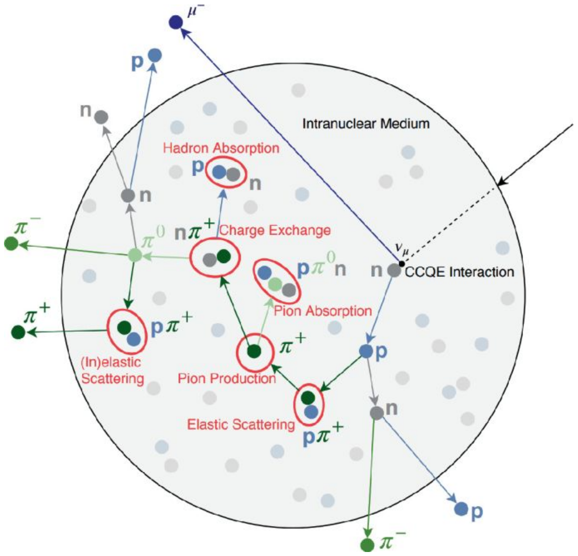
- Simulated data
  minervame1A DSCAL special sample (1.44x10^20 POT) minervame1A NX sample (2.72x10^20 POT)

CC neutrino (helicity)
- Fiducial volume
- From z=8590 mm to z=8916 mm (Modules 85-90)for ECAL
- From z=5990 mm to z=8340 mm (Modules 27-81) for Tracker sample
- 850mm apothem.
- Muon angle lower than 30 degrees
- Neutrino energy between 2 and 20 GeV
- Muon energy greater than 1.5 GeV

Final State Interactions

Looking for **fates** for nucleons or pions

- Only 1 daughter in the FSI (first daughter is the last daughter).
  - Absorption on 3 nucleons (Particle ID of daughter > 2000000000)
  - No Scattering (|ID energy – First daughter energy – offset | equals to zero)
  - Charge exchange (ID particle different than ID of the first daughter)
  - Elastic (anything else with only one daughter)
- More than 1 daughter in the FSI
  - Nucleons to Pions (parent is not a pion but daughters has pions)
  - Absorption on 3 nucleons (parent is a pion but there is not pions in the final state)
  - Charge exchange Multi nucleons (first daughter is a nucleon cluster before phase decay)
  - Knock out (anything else)



Offset: carbon = 25 MeV, lead = 44 MeV.