Prompt Gamma Spectroscopy for Real-Time Calcium Quantification in Proton Therapy

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Background

- Bone radiotherapy can induce **localized changes in mineral content** in irradiated bone, evolving **during treatment** and between fractions. Monitoring these changes remains challenging with standard imaging.[1]
- **Prompt Gamma Spectroscopy (PGS)** could provide **real-time calcium (Ca) mass-density quantification** as a direct metric for treatment response
- **Prompt gammas (PG):** Proton-induced inelastic nuclear scattering populates excited nuclear states, which de-excite via gammas on ps—ns timescale.
- **Clinical context**: Prompt gammas are already used for in vivo range verification to reduce range uncertainty and treatment margins. Element-specific prompt-gamma lines may additionally enable elemental analysis.[2] **Key benefit**: Elemental information without additional patient dose.

Materials and Methods

- Monte Carlo simulations in **TOPAS** with a 100 MeV transmission proton pencil beam and 10^{10} protons irradiating **two series of cylindrical phantoms**. [3]
- A lateral **$CeBr_3$** scintillator recorded the prompt-gamma spectrum, which was convoluted with an energy-dependent resolution function and ideal anticoincidence (AC) was applied to suppress escape peaks.
- Phantoms: Calibration + validation phantoms
  - Calibration: 0—100 wt% Ca
  - Validation: CT phantoms with tissue-equivalent compositions

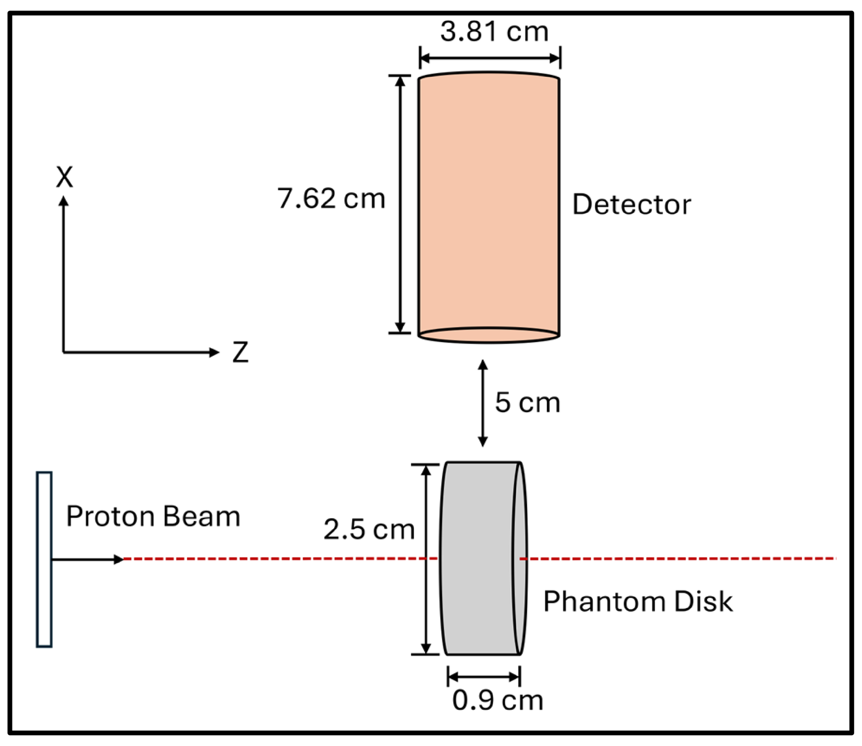

Figure 1: Schematic of the simulation geometry used for the two sets of simulations.

The Multi-peak Fit Model

- Areas from **six Ca prompt-gamma** lines were extracted via **background-subtracted** integration over predefined energy windows.
- Each peak showed an approximately **linear** dependence on Ca content ($R^2 > 0.996$), enabling linear-regression-based Ca estimates.
- Individual peak estimates were combined via **weighted fusion** into a single Ca prediction to improve robustness over any single line.

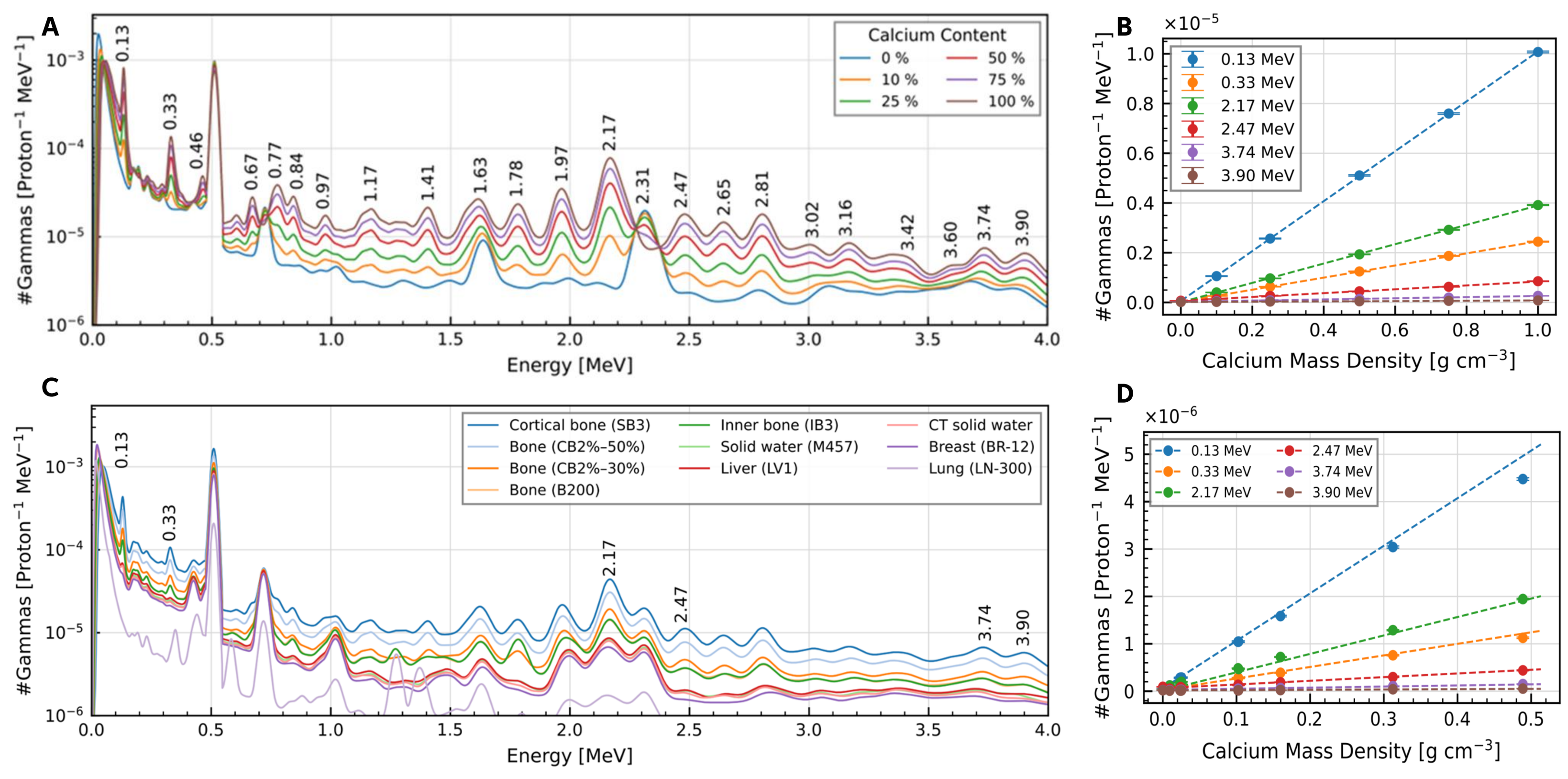

Figure 3: Simulated gamma spectra for Ca-calibration-mixtures and tissue-equivalent validation materials, with linear peak—Ca relationships for six Ca lines.
(A) Calibration spectra. (B) Peak area vs Ca (linear fits). (C) Tissue-equivalent spectra. (D) Overlay of tissue-equivalent peak areas on calibration fits.

Identified Nuclear Reaction Channels

Nuclear reaction identification via Geant4 particle tracking cross checked with NuDat3 database and TALYS calculations. Multiple nuclear reaction pathways contribute to characteristic spectral peaks.

Peak selection criteria for calcium quantification:

- Minimal overlap with O, C, N, and P emission lines
- Strong emission yield and high prominence above background

Six calcium-specific lines identified satisfying the criteria: 0.13, 0.33, 2.17, 2.47, 3.74, and 3.90 MeV

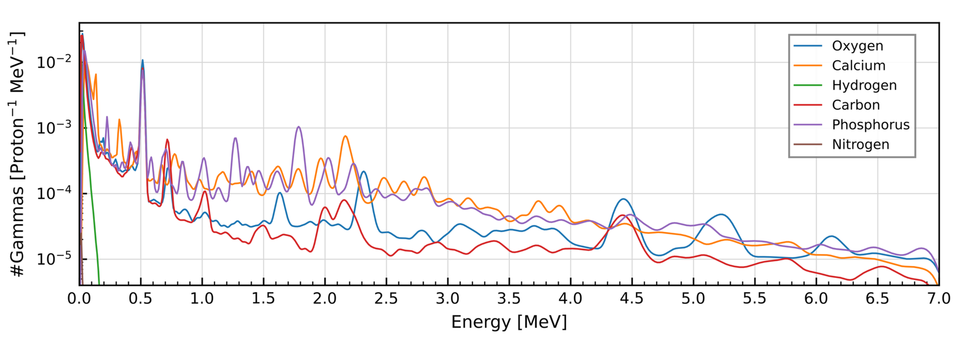

Figure 2: Simulated gamma spectra for pure elements (O, C, H, N, P, and Ca) with identical densities under 100 MeV proton irradiation.

E_{peak} [MeV]	E_γ [MeV]	Nuclear Reaction
0.13	0.130	$^{38}K^*_{0.130} \rightarrow {}^{38}K_{g.s}$
0.33	0.328	$^{38}K^*_{0.459} \rightarrow {}^{38}K_{0.130}$
2.17	2.167 2.127 2.208 2.217	$^{38}Ar^*_{1.410} \rightarrow {}^{38}Ar_{g.s.}$ $^{34}S^*_{2.127} \rightarrow {}^{34}S_{g.s.}$ $^{36}Ar^*_{4.178} \rightarrow {}^{36}Ar^*_{1.970}$ $^{37}Ar^*_{2.217} \rightarrow {}^{37}Ar_{g.s.}$
2.47	2.467 2.523	$^{39}Ca^*_{2.467} \rightarrow {}^{39}Ca_{g.s.}$ $^{39}K^*_{2.523} \rightarrow {}^{39}K_{g.s.}$
3.74	3.737	$^{40}Ca^*_{3.737} \rightarrow {}^{40}Ca_{g.s.}$
3.90	3.904	$^{40}Ca^*_{3.904} \rightarrow {}^{40}Ca_{g.s.}$

Table 1: Prompt-gamma transitions from proton-induced reactions on ^{40}Ca. [4]

RESULTS AND CONCLUSION

- **Prediction performance**: sub-1 wt% Ca prediction precision using the 6-line multi-peak + fusion approach on validation data set spectra
- **Multi-peak fusion outperforms single line approaches and improves robustness** to detector-resolution broadening and peak overlap with neighboring non-Ca peaks
- **Conclusion**: This supports the technical feasibility of real-time Ca quantification with PGS, with potential future clinical use for lesion-specific Ca tracking and adaptive strategies in proton therapy of bone cancer and bone metastases.

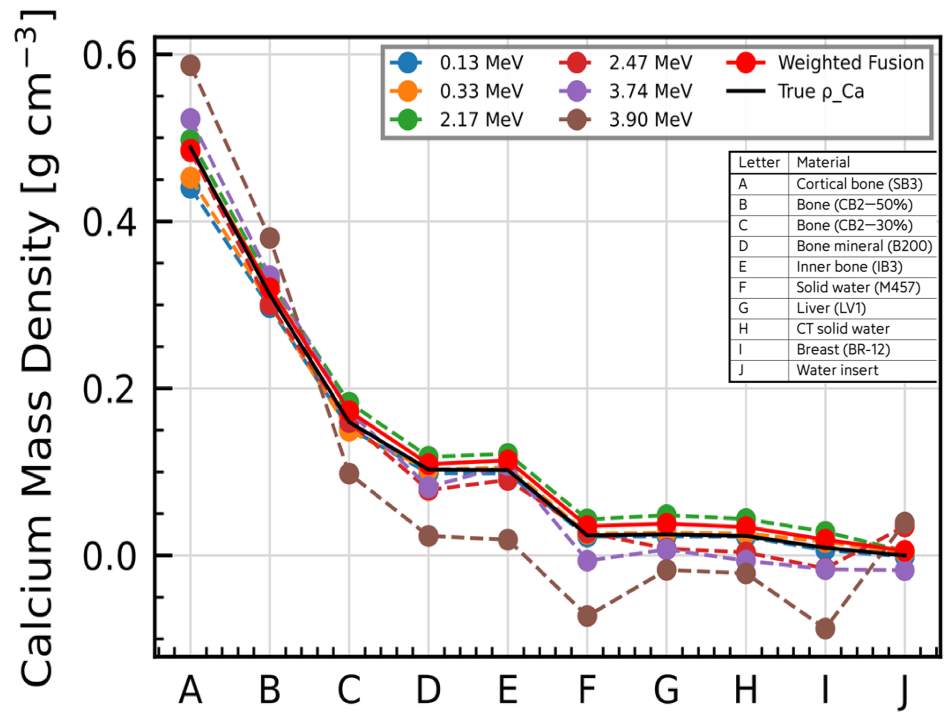

Figure 4: Predicted vs reference Ca mass density for tissue-equivalent materials.

Future Work & Outlook

- **Simulation refinements**: include a more realistic beam energy modulation, spectral attenuation and energy straggling via tissue-equivalent shielding materials, surrounding the samples and realistic AC.
- **Experimental validation**: measurements with hydroxyapatite or β-TCP to confirm simulated spectral features under realistic detector conditions.

References, Declaration and more Information: