

Comparative study of simulated and measured isotope production in target and HPGe detector in muon capture experiments

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Precision determination of muonic X ray spectra from negative muon capture requires rigorous identification and subtraction of background γ ray lines arising from nuclear re-actions induced in the target material and in the high purity germanium (HPGe) detector itself. This work presents a systematic Monte Carlo (MCNP6) simulation study of isotope production channels in typical muon capture experiments, where negative muons (momentum 33–40 MeV/c) are stopped in solid targets (e.g., BaCO₃, Mo, Se, Ti). The simulations incorporate full three-dimensional geometry, particle transport for muons, neutrons, protons, electrons, and γ rays, and detailed nuclear data libraries.

Negative muon nuclear capture excites the daughter nucleus, which de-excites primarily by neutron evaporation (neutron energies up to 30–40 MeV) followed by γ ray cascades. In a BaCO₃ target (95% enrichment in ¹³⁶Ba), the simulations predict production of ¹³⁵Cs, ¹³⁶Cs, ¹³⁴Cs and ¹³³Ba with characteristic γ lines at 604.7 keV (¹³⁴Cs), 661.7 keV (¹³⁷Cs) and 818.5 keV (¹³⁶Cs). However, comparison with experimental γ spectra reveals peaks such as the peak 608.2 keV. The simulations identify these as originating from neutron induced reactions in surrounding structural materials and, crucially, within the HPGe crystal itself: 608.2 keV corresponds to ⁷⁴Ga (608.54 keV, (n,n') second level gamma) and background ²¹⁴Bi (609.31 keV).

A key result is the quantification of radioisotope production directly inside the HPGe detector. Fast neutrons from muon capture interact with germanium isotopes (⁷⁰Ge, ⁷²Ge, ⁷³Ge, ⁷⁴Ge, ⁷⁶Ge) via (n,n'), (n,2n), (n,p) and (n, γ) reactions, producing long lived activities: ⁶⁹Ge (39 h, 1107 keV), ⁷¹Ge (11.4 d, 198 keV), ⁷⁵Ge (82.8 min, 265 keV) and ⁷⁷Ge (11.3 h, 211 keV, 264 keV). These generate a time dependent background that cannot be eliminated by passive shielding or simple coincidence. Additionally, muon decay in orbit electrons (Michel spectrum up to 52.8 MeV, boosted to ~70 MeV) produce bremsstrahlung photons >11 MeV, which pair produce positrons whose annihilation yields γ rays up to 6–7 MeV, further complicating the high energy muonic X ray region.

The Monte Carlo approach successfully separates the measured spectrum into three components: (i) prompt muonic X rays and capture γ rays from the target, (ii) neutron induced background from the detector and surrounding materials, and (iii) natural terrestrial/cosmic background. Simulated total events in the 0–10 MeV range have good agreement with experimental data, validating the method. This work provides a framework for accurate background (induced and natural) gamma-rays identifications and subtraction, improving the extraction of ordinary muon capture rates and nuclear matrix elements for 0 $\nu\beta\beta$ decay. The methodology is extendable to other target nuclei like ¹⁰⁰Mo, ⁷⁶Se, ⁴⁸Ti.

References

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