Simulation of In-situ Production by Fast Muon Induced Reactions

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Fast muon induced reactions are besides spallation and muon capture reactions the main in-situ production mechanism for cosmogenic radionuclides in the lithosphere. Their contribution is dominant in depths greater than 100 $\frac{\mathrm{hg}}{\mathrm{cm}^2}$ and important in the determination of background in all low level detection experiments, as e.g. in cryogenic dark matter detectors made of sapphire (Al_2O_3), or in geochemical experiments, as e.g. the geochemical solar neutrino experiment $^{205}\mathrm{Tl}(\nu_e, e^-)^{205}\mathrm{Pb}$. In geophysical applications as for the determination of exposure ages or erosion rates, the knowledge of fast muon induced reactions is also important. The production rate by fast muon induced reactions is negligible for shallow depths, but for short exposure ages in comparison with the lifetime of the radionuclide the deduced spallation production rates have to be corrected for muon induced reactions.

Fast muon induced reactions and production rates

Penetrating fast muons initiate nuclear and electromagnetic cascades in rock or targets. Cosmogenic radionuclides are produced in nuclear reactions of nucleons, pions and photons generated by this cascades. This fast muon induced reactions are characterized by an effective cross section σ_0 and the energy dependence $\sigma(\mathrm{E}) = \sigma_0 \cdot \mathrm{E}^{0.7}$ with the muon energy E in GeV. The production rate can be expressed by $\mathrm{P}_{\mu\mathrm{fast}}(\mathrm{z}) = \sigma_0 \cdot \Phi_\mu(\mathrm{z}) \cdot \bar{\mathrm{E}}(\mathrm{z})^{\beta(\mathrm{z})} \cdot \mathrm{N_T}$ with $\mathrm{N_T}$ number of target nuclides per cm^2. The total muon flux $\Phi_\mu(\mathrm{z})$, the mean muon energy $\bar{\mathrm{E}}(\mathrm{z})$ and the power $\beta(\mathrm{z})$ at a considered depth z can be taken from the differential muon flux $\Phi(\mathrm{E,z})$ given by [1]. At depths greater than 300 $\frac{\mathrm{hg}}{\mathrm{cm}^2}$ $\beta(\mathrm{z})$ can be approximated by ≈ 0.7 according the Wolfendale rule [2]. This factor was confirmed in a previous experiment [3].

Simulation experiment at CERN (NA54)

For the determination of effective cross sections σ_0, a set of targets has been irradiated with 190 GeV muons at the high energy muon beam M2 at CERN. The intensity was $\approx 4 \cdot 10^7$ per spill with a cycle time of 14.4 sec. The irradiations (NA54) were done parasitic to the experiment NA47 of the Spin–Muon–Collaboration (SMC). The secondary particle shower was obtained by a concret block of 3 m length. The shower is full developed after this length [4,3], and the mean energy loss of 190 GeV muons in 3 m concret block is 2.4 GeV [5]. The experimental set-up is shown in Fig. 1. The muons were counted with the hodoscope H5 of the SMC about 40 m up in the beam. The beam position and conditions at the site of the targets were measured with a movable scintillator. To record the total shower a lateral activation profile was measured using 35 Fe and Ni monitor disks (Fig. 2). A preliminiary result for the effective activation at the targets was about 15.4 % of the total activation.

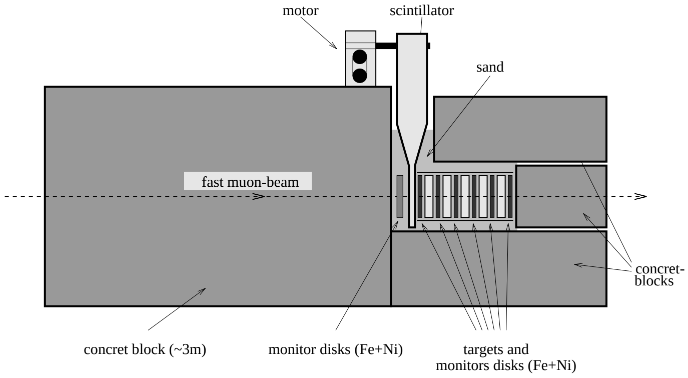

Fig. 1: Experimental set-up at high energy muon beam M2 at CERN.

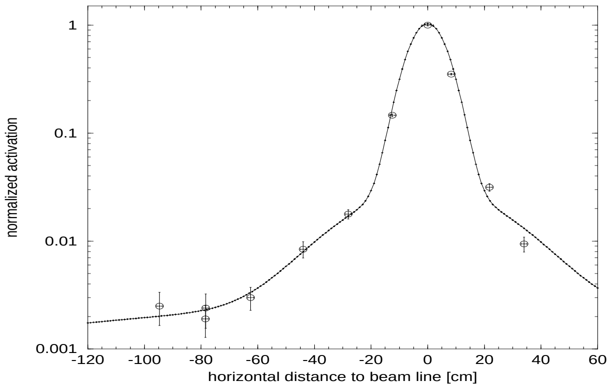

Fig. 2: Lateral activation profile of ^{54}Mn in Fe

The following targets were irradiated to produce the listed radionuclides, the number of fast muons are coreccted by 10 % dead time:

target	muons	radionuclides
SiO_2	$1.62 \cdot 10^{13}$	^{10}Be, ^{26}Al
SiO_2	$1.37 \cdot 10^{13}$	^{14}C
$CaCO_3$	$1.62 \cdot 10^{13}$	^{36}Cl
Fe	$2.55 \cdot 10^{12}$	^{53}Mn
S	$2.55 \cdot 10^{12}$	^{26}Al
Al_2O_3	$1.62 \cdot 10^{13}$	^{26}Al, ^{22}Na
Cu	$1.37 \cdot 10^{13}$	^{60}Co
Tl	$1.62 \cdot 10^{13}$	^{205}Pb

The produced ^{22}Na and ^{60}Co were measured with γ spectroscopy. Preliminary results for the effective cross sections σ_0 are 11.3 μbarn for Al to ^{22}Na and 13.7 μbarn for Cu to ^{60}Co. The other listed radionuclides will be measured with accelerator mass spectrometry. A first result for σ_0 of ^{26}Al in Al_2O_3 is 87 μbarn. The chemical treatment and ams measurement of the other radionuclides is in progress.

References

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