Determination of Production Rates of Cosmogenic Nuclides by Muon Capture Reactions

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Muon capture reactions are an important production mechanism of cosmogenic radionuclides in the lithosphere [1]. They also contribute to the background of low level detection experiments and to atmospheric production.

Atmospheric production

In the atmosphere, by far the dominant production channel for cosmogenic radionuclides is spallation. Even close to the surface of the earth, μ^- capture reactions contribute only in the percent range. The production by spallation can be obtained by e. g. measuring cross sections and their energy dependence for the involved channels and by using measured neutron and proton fluxes in the atmosphere. The production by μ^- capture reactions is obtained by measuring the branchning ratios of the relevant particle emission channels after μ^- capture and by using the rate of stopped muons in the atmosphere. In comparison with the calculated production rates by spallation reactions rain water experiments indicate that there is an appreciable excess of muon produced nuclides, e. g. ^{39}Cl from Ar, compared to others [2]. Radionuclides produced by μ^- capture reactions on atmospheric argon are ^{39}Cl and ^{38}Cl ans the relevant reactions are: $^{40}\mathrm{Ar}(\mu^-,\nu_\mu \mathrm{n})^{39}\mathrm{Cl}$ and $^{40}\mathrm{Ar}(\mu^-,\nu_\mu 2\mathrm{n})^{38}\mathrm{Cl}$. For the calculation of the production by μ^- capture reactions the yield of the short–lived radionuclide ^{39}Cl after μ^- capture in Ar was measured.

Production by muon capture reactions

The production of nuclides after μ^- capture in a target element is described by $\mathrm{P}_{\mu^-} = \mathrm{I}_{\mu^-} \cdot \mathrm{f_C} \cdot \mathrm{f_D} \cdot \mathrm{f}^*$ with I_{μ^-} the rate of stopped negative muons, $\mathrm{f_C}$ the chemical compound factor [3], $\mathrm{f_D}$ the nuclear capture probability [4] and f^* the branching ratio of the particle emission channel.

In some previous simulation experiments we determined the branching ratios of ^{10}Be and ^{26}Al in $\mathrm{SiO_2}$, ^{26}Al in sulfur, ^{36}Cl in Ca, and estimated the branching ratio of ^{53}Mn in Fe [5]. For the determination of the branching ratios of $\mathrm{O}(\mu^-,\nu_\mu \mathrm{pxn})^{14}\mathrm{C}$, $\mathrm{C}(\mu^-,\nu_\mu \mathrm{pxn})^{10}\mathrm{Be}$, $\mathrm{Cu}(\mu^-,\nu_\mu \mathrm{pxn})^{60}\mathrm{Co}$, $\mathrm{Ca}(\mu^-,\nu_\mu \mathrm{xn})^{38}\mathrm{Ar}$, $^{40}\mathrm{Ar}(\mu^-,\nu_\mu \mathrm{n})^{39}\mathrm{Cl}$ and $^{40}\mathrm{Ar}(\mu^-,\nu_\mu 2\mathrm{n})^{38}\mathrm{Cl}$ additional simulation experiments were done at the Paul-Scherrer-Institut.

Simulation experiment at PSI

Several targets (quarz, polyethylen, copper, nickel, metallic calcium, argon) were irradiated with slow muons at the muon beam μE4 at the Paul–Scherrer–Institut. The number of stopped and captured muons have been determined by measuring the characteristic muonic X-rays during irradiation with a HP–Germanium detector. The experimental set-up is shown in Fig. 1. The numbers of the produced nuclides have to been measured in several ways: the radionuclides by γ spectroscopy and accelerator mass spectrometry (AMS) and the stable nuclid ^{38}Ar (in Ca) with mass spectrometry.

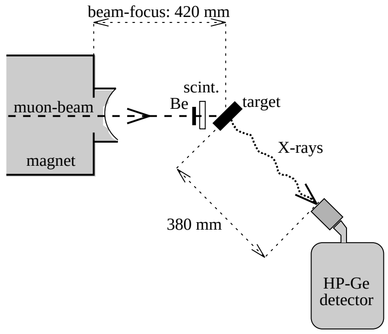

Fig. 1: Experimental set-up at the muon beam μE4 at PSI.

The argon gas target was irradiated with negative muons of a momenta of $64\,\frac{\mathrm{MeV}}{\mathrm{c}}$ with a stopping rate in Ar of $6.8 \cdot 10^6\,\frac{\mu^-}{\mathrm{sec}}$ and the nuclear capture probability in Ar of 0.742 [4]. The produced ^{38}Cl and ^{39}Cl were measured with γ spectroscopy, from which the branching ratios for the particle emission channels $^{40}\mathrm{Ar}(\mu^-,\nu_\mu \mathrm{n})^{39}\mathrm{Cl}$ and $^{40}\mathrm{Ar}(\mu^-,\nu_\mu 2\mathrm{n})^{38}\mathrm{Cl}$ were determined to be $\mathrm{f}^*(^{39}\mathrm{Cl}) = 0.43 \pm 0.04$ and $\mathrm{f}^*(^{38}\mathrm{Cl}) = 0.08 \pm 0.01$.

There were $2.86 \cdot 10^{10}$ μ^- stopped in the copper target and the nuclear capture probability in Cu is 0.928 [4]. The branching ratio of the nuclear emission channel of $\mathrm{Cu}(\mu^-,\nu_\mu \mathrm{pxn})^{60}\mathrm{Co}$ was determined with γ spectroscopy to be $\mathrm{f}^*(^{60}\mathrm{Co}) = (9.8 \pm 0.4) \cdot 10^{-3}$. This branching ratio have to be known for example for the muon induced production of ^{60}Co in copper, used in dark matter detectors, during the storage near the earth's surface.

The quarz target was sent to D. Lal (Scripps Inst. of Oceanography, La Jolla) for the chemical extraction and AMS measurement of ^{14}C. For the measurement of ^{38}Ar with mass spectrometry at ETH Zürich, the detection sensitivity has to be improved. Both works are in progress.

References

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