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Proposal for an experiment with fast muons at CERN

Determination of cross sections of fast muon induced reactions to cosmogenic radionuclides

F.J. Hartmann, B. Heisinger, G. Korschinek, E. Nolte (Faculty of Physics, Technical University of Munich, D-85747 Garching, Germany)

G. Morteani (Institute of Applied Mineralogy and Geochemistry, Technical University of Munich, D-85747 Garching, Germany)

S. Neumaier (Division PPE, CERN, CH-1211 Genève 23, Switzerland)

P.W. Kubik (Paul-Scherrer-Institut, c/o ETH-Hönggerberg, CH-8093 Zürich, Switzerland)

D. Lal (Geological Research Div., Scripps Inst. of Oceanography, University of California, San Diego, La Jolla, CA 92093, USA)

Spokesman: E. Nolte
Contactman: S. Neumaier

Abstract

We propose to measure cross sections of fast muon induced reactions with targets found in the lithosphere to cosmogenic radionuclides. The reactions to be studied are nucleon induced reactions where the nucleons are produced by fast muon reactions with rocks from the lithosphere. These reaction channels to be measured are: rock(μ, μ'X) and successive C(X,X2pxn)^{10}Be (x=0, 1), O(X,X4pxn)^{10}Be (x=2-4), O(X,X2pxn)^{14}C (x=0-2), Si(X,Xpxn)^{26}Al (x=1-3), S(X,X3pxn)^{26}Al (x=3-5, 7), Ca(X,X3pxn)^{36}Cl (x=1, 3-5, 7, 9), Fe(X,Xpxn)^{53}Mn (x=0, 2-4) and ^{205}Tl(p,n)^{205}Pb, where z is an integer and X=p, n. The energy dependent cross sections can be described by one single parameter σ_0 and the energy dependence $\mathrm{E_{mean}}^{0.7}$ on the mean energy $\mathrm{E_{mean}}$. The irradiation of the targets is done at CERN. The produced radionuclides are measured by accelerator mass spectrometry in Munich, Zürich and Tucson.

Beam requirements

Experimental area:	barrack BX 82 behind the experimental hall EHN 2
Particles:	μ
Energy:	$\geq$ 100 GeV, e.g. 190 GeV

Duration of the experiment at CERN

Setting up and tests: 7 days, between March 15 and April 10, 1995.
Irradiation of the targets and data taking: 90 days, starting April 17, 1995.

Requirements from CERN

No requirements from CERN concerning scintillators, electronics or data handling. Equipment consisting of scintillators, electronics, data handling and mechanical set-up is provided by the Technical University of Munich. Installation of a few concrete blocks in the barrack would be required from CERN.

Experiment

The experiment consists of two parts:

- irradiation of targets at CERN
- measurement of the produced radionuclides with accelerator mass spectrometry at the TUM, at the ETH / PSI facility in Zürich and the AMS facility in Tucson.

Safety risks

No safety risks.

1 Introduction

The knowledge of the lithospheric (in-situ) production of cosmogenic radionuclides is important for the determination of background contributions in all low-level detection experiments, in geochemical experiments, in many fields of geophysics and also for economical reasons. In the lithosphere, because of the decrease of intensity of the secondary cosmic radiation with the depth in earth the concentration of in-situ produced cosmogenic radionuclides also decreases with the depth in earth. Depth profiles can be used to determine erosion rates by physical methods.

The feasibility of the geochemical solar neutrino experiment $^{205}\mathrm{Tl}(\nu_e, e^-)^{205}\mathrm{Pb}$ depends on the contribution and the knowledge of cosmic muon induced background events. This contribution strongly depends on the mean shielding of the geological deposit against cosmic radiation, i. e. also on the erosion in the region of the considered thallium deposit in the mine Allchar (Macedonia) in the last million years [1]. In low-level dark matter detectors, made of e.g. sapphire (Al_2O_3), the contribution of events from the decay of ^{26}Al has to be measured or estimated [2]. In hydrology, the in-situ production of radionuclides has to be known in order to determine ages, mixing and flow velocities of groundwater [3].

On the economical side, the determination of erosion rates plays an important role in the exploration of natural resources. E. g. the transformation of anhydrite into gypsum depends on the interplay of hydration and uplift history and subsequently on the erosion rate of the overburden material. Gypsum industry is therefore interested in the determination of erosion rates [4].

In the first few hundred meters of the lithosphere, the concentrations of radionuclides (e. g. ^{26}Al) in a mineral (e. g. SiO_2) are in the range of 10^{-20} to 10^{-14} (e. g. for ^{26}Al / Si) and the concentration ratios of the radionuclide to the same element (e. g. ^{26}Al / Al) are for clean minerals typically in the range of 10^{-15} to 10^{-9}. Therefore, high sensitivity detection as accelerator mass spectrometry (AMS) is needed and experiments are difficult. Measured depth profiles of radionuclides can be compared with calculated ones in order to determine erosion rates when the involved cross sections and branching ratios are known. It is the aim of the proposed experiments to measure cross sections of fast muon induced reactions with targets from the lithosphere to cosmogenic radionuclides by irradiating chemically clean mineral and elemental targets with fast muons and by measuring the produced radionuclides with AMS.

2 Lithospheric production of radionuclides

In the lithosphere, radionuclides are produced by secondary cosmic ray induced reactions and by U, Th induced background reactions (P_{bg}). The secondary cosmic ray induced reactions comprise spallation reactions (P_{spall}), reactions with stopped negative muons (P_{μ^-}) and reactions induced by fast muons ($P_{\mu\mathrm{fast}}$) . If the radionuclide can be produced by neutron capture reactions ($P_{(n,\gamma)}$), neutrons originating from all reactions listed above can contribute. The total production rate P is thus obtained to be

$$P = P_{\mathrm{spall}} + P_{\mu^-} + P_{\mu\mathrm{fast}} + P_{\mathrm{bg}} + P_{(n,\gamma)}$$

The spallation reactions with the nucleonic component of the cosmic radiation are dominant in the first few meters of the earth. This contribution decreases very rapidly with the depth z with $\exp(-z/\Lambda)$ where Λ equals about 1.5 mwe (meter water equivalent, 2.7 mwe $\approx$ 1 m) [5].

The production rate due to reactions with stopped negative muons can be expressed by

$P_{\mu^-}(z) = I_{\mu^-}(z) \cdot f_C \cdot f_D \cdot (\Sigma f_I(A) \cdot f(xn + yp + w\alpha)) \cdot f(J^\pi)$ with
- $I_{\mu^-}(z)$ the rate of stopped negative muons in the earth as function of the depth z,
- f_C the chemical compound factor [7],
- f_D the nuclear capture probability [6],
- $f_I(A)$ the isotopic abundances of the target nuclei,
- $f(xn + yp + w\alpha)$ the probability of the channel to the investigated nucleus after μ^- capture, and
- $f(J^\pi)$ the population probability of the isomeric or ground state of the investigated nucleus.

$I_{\mu^-}(z)$ can be taken from [8] or can be obtained by differentiating the fast vertical muon flux [9, 10], by integrating over the solid angle [9] and by multiplying with the percentage of negative muons [8]. The contribution of stopped negative muons is dominant in depths between a few meters and typically about 40 m.

Between about 40 meters and a few hundred meters, reactions due to fast muons are dominant. For a given target and a given product nucleus, this contribution can be described by $P_{\mu\mathrm{fast}} = \Phi_{\mu\mathrm{fast}} \cdot \sigma$ [10], where $\Phi_{\mu\mathrm{fast}}$ is the flux of fast muons [10] and where the energy dependent cross section σ according to the Wolfendale rule [11] is given by $\sigma = \sigma_0 \cdot E_{\mathrm{mean}}{}^{0.7}$ where E_{mean} is the mean muon energy at the considered depth.

Typically below depths of a few hundred meters, U and Th induced background reactions are important.

For the case of ^{26}Al produced in quartz (SiO_2), the calculated saturation ratios ^{26}Al/Si are shown in Fig. 1 as a function of depth for the discussed reactions. In an experiment performed at the PSI Villigen (CH), the factor $(\Sigma f_I(Si) \cdot f(xn)) \cdot f(5^+)$ has been measured to be (2.4 ± 0.3) % [12]. For σ_0, a tentative value of 30 μb was used. The background contributions due to the reaction $^{23}Na(\alpha, n)^{26}Al$ were estimated using concentrations of 60 ppm Na, 0.5 ppm U and 0.5 ppm Th.

Since the cosmogenic production rate depends on the depth, measurements of depth profiles of cosmogenic radionuclides in the first few hundred meters of the earth allow the deduction of erosion rates over a time period in the range of the life time of the radionuclide if all contributions to the production of the radionuclide are known.

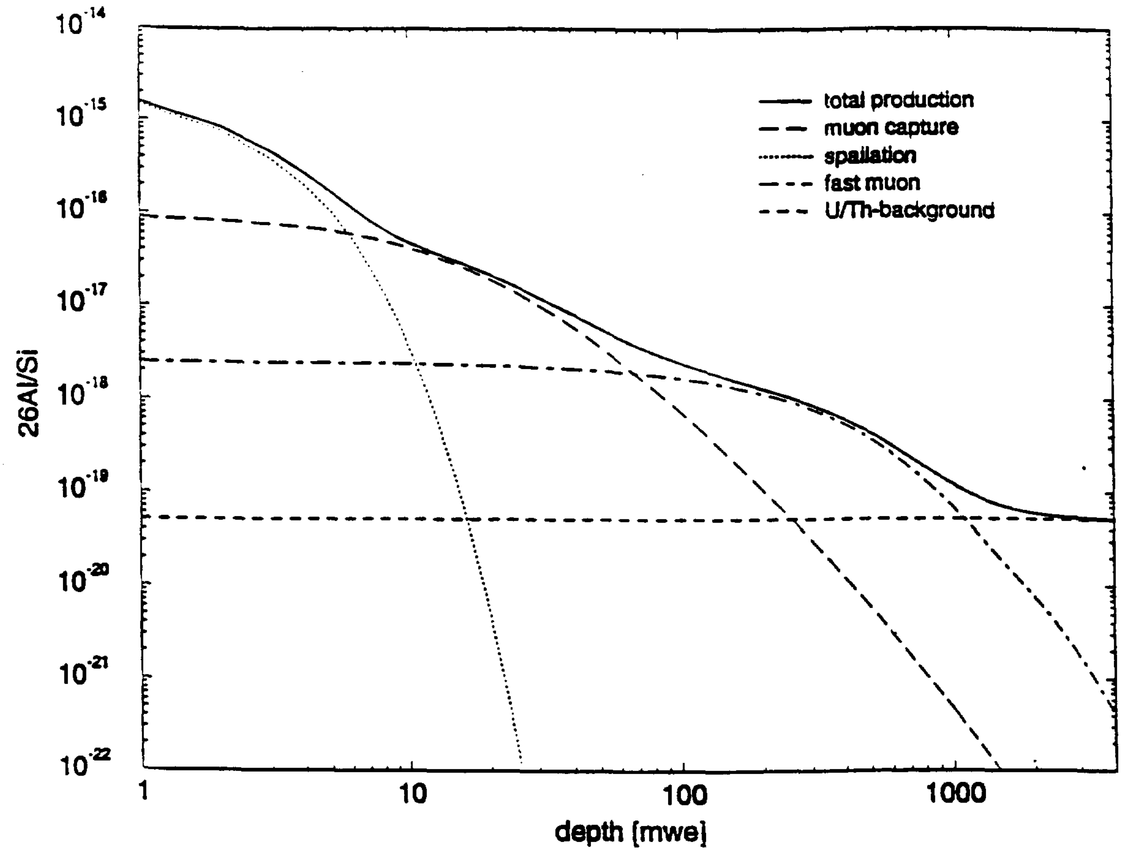

Figure 1: Calculated depth profiles of ^{26}Al concentrations in quartz samples for vanishing erosion taking into account spallation, reactions with stopped and with fast muons and U/Th induced background reactions.

3 Minerals and radionuclides to be studied

Since the erosion rates can be obtained from depth profiles within the lifetime of the analysed radionuclide it is most advantageous to use and study minerals from which several radionuclides are produced. Sets of minerals and radionuclides to be studied are:

^{10}Be, ^{14}C, and ^{26}Al from quartz (SiO_2),
^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl from gypsum ($CaSO_4$),
^{26}Al, and ^{53}Mn from pyrite (FeS_2), and
^{10}Be, ^{14}C, and ^{36}Cl from limestone, calcite or aragonite ($CaCO_3$).

In the case of the ^{205}Tl target, the fast muon induced background reaction ^{205}Tl(p,n)^{205}Pb shall be determined with good precision in order to obtain the pure solar neutrino induced contribution $^{205}\mathrm{Tl}(\nu_e, e^-)^{205}\mathrm{Pb}$ in the geochemical experiment which uses the mineral lorandite ($TlAsS_2$). In Fig. 2 the background to signal ratio is plotted for this experiment as function of erosion rate. It is seen, that the precise knowledge of erosion rate and background contribution is crucial for this experiment. The preliminary value of 0.55 μb for σ_0 was obtained by using the yield of ^{203}Pb after fast muon irradiation of Tl and ^{203}Tl targets at CERN and the cross sections of ^{203}Tl(p,n)^{203}Pb and ^{205}Tl(p,n)^{205}Pb [1].

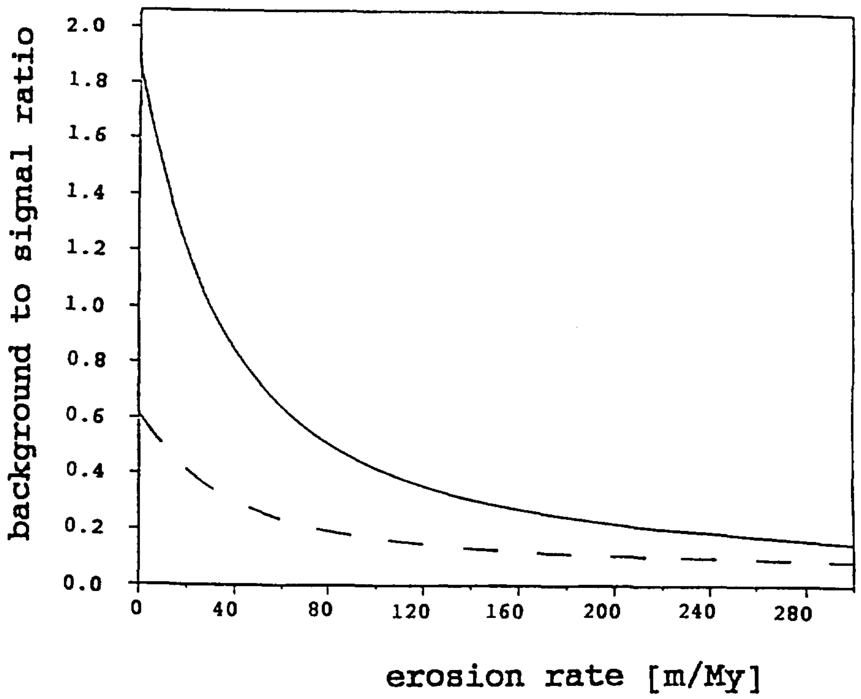

Figure 2: Background to signal ratio R for the geochemical ^{205}Tl solar neutrino experiment as function of the erosion rate for an actual depth of the deposit of 120 m, for a σ_0 value of 0.55 μb and for a solar neutrino rate of 260 SNU.

The involved reaction channels with fast muon produced nucleons X are the following ones:

$C(X, X2pxn)^{10}Be$, $x = 0, 1$
$O(X, X4pxn)^{10}Be$, $x = 2$–4
$O(X, Xpxn)^{14}C$, $x = 0$–2
$Si(X, Xpxn)^{26}Al$, $x = 1$–3
$S(X, X3pxn)^{26}Al$, $x = 3$–$5, 6$
$Ca(X, X3pxn)^{36}Cl$, $x = 1, 3$–$5, 7, 9$
$Fe(X, Xpxn)^{53}Mn$, $x = 0, 2$–4
$^{205}Tl(p,n)^{205}Pb$.

The dominant channels for the first seven reactions are:

$^{12}C(X, X2p)^{10}Be$
$^{16}O(X, X4p2n)^{10}Be$
$^{16}O(X, X2p)^{14}C$
$^{28}Si(X, Xpn)^{26}Al$
$^{32}S(X, X3p3n)^{26}Al$
$^{40}Ca(X, X3pn)^{36}Cl$
$^{56}Fe(X, Xp2n)^{53}Mn$.

The half-lives of the relevant radionuclides are ^{10}Be ($1.51 \cdot 10^6$ y), ^{14}C (5,730 y), ^{26}Al (716,000 y), ^{36}Cl (301,000 y), ^{53}Mn ($3.7 \cdot 10^6$ y) and ^{205}Pb ($15.2 \cdot 10^6$ y).

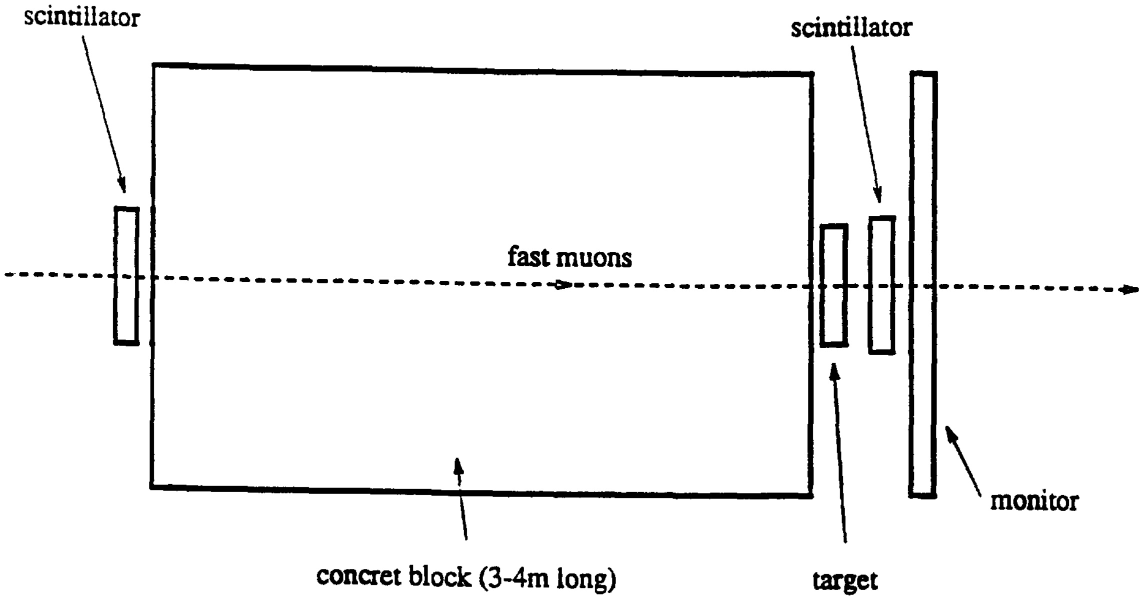

Figure 3: Experimental set-up.

4 Proposed experiments

The simple experimental set-up is shown in Fig. 3. Concrete blocks of about 4 m length are used for the generation of nucleons X by the fast muon beam. Targets of C, SiC, SiO_2, S, CaO, Fe and Tl behind the concrete block will be irradiated with the fast muon produced nucleons. Two scintillation counters are installed before and after the concrete blocks for counting the muons. For the measurement and evaluation of the lateral intensity distribution of the produced nucleons at the location of the targets, a monitor is used. This monitor can be Fe.

The chemical treatment of the samples is done in Zürich, Munich and La Jolla. Since the targets are chemically pure, stable carriers of the same element as the investigated radionuclide are added during the chemical procedures. Because in AMS ratios radionuclide / element (as e. g. ^{26}Al / Al) are measured, the yield of the chemical extraction does not enter here.

The yields of the long-lived radionuclides ^{10}Be, ^{14}C,^{26}Al, ^{36}Cl, ^{53}Mn and ^{205}Pb are measured after physical and chemical treatment of the irradiated targets with accelerator mass spectrometry (AMS). ^{10}Be will be measured at the ETH / PSI facility in Zürich, ^{14}C at the AMS facility in Tucson, ^{26}Al, ^{36}Cl and ^{53}Mn will be measured at the Munich accelerator laboratory. The AMS method for detecting ^{205}Pb has been developed at GSI Darmstadt. The final method is not yet established.

The errors in the final result are due to statistics in the AMS experiment, to uncertainties in the lateral intensity distribution of the fast muon produced nucleons and to the chemical treatment. The errors in the final result are expected to be smaller than 10 %. Different chemical behaviours of radionuclide and carrier were not observed in these standard treatments in many past experiments.

5 Experimental procedure with natural targets

The natural targets contain many impurities, e. g. quartz samples also contain aluminum silicates. The optical selected quartz grains are cleaned chemically with ortho-phosphoric acid (84%) and are washed with weak tetrafluorboric acid (5%) [13]. Even after physical and chemical cleaning, e. g. the Al content in the cleaned quartz sample is in the range of 40 to 200 ppm. No carrier has to be added in this case. For separating the Al from the quartz the grains are dissolved with hydrofluoric acid. After the dissolution of the quartz Be can be separated simultaneous with an anion exchange column. The ratio ^{26}Al / Si is obtained from the measured ratio ^{26}Al / Al and from the Al concentration in quartz. This concentration has so far been measured by XRF (X ray fluorescence) and in a few cases by ICP-OES (ion coupled plasma - optical emission spectroscopy). The XRF method is considered to be not so precise for small concentrations below 100 ppm. In future, the determinations of Al concentrations in the cleaned quartz samples will be done by ICP-OES.

The determinations of the Cl content in limestone or gypsum can be done chemically, by ion chromatography or by neutron activation, the Mn content in Pyrite can be measured by neutron activation.

Be has a low abundance in quartz and carbonates. It has to be added as carrier also in the natural samples. This fact simplifies the determination of the ratio ^{10}Be / O.

6 Erosion rates

The influence of different erosion rates on the calculated depth profiles is shown in Fig. 4 for the case of in-situ production of ^{26}Al in quartz. Also shown are preliminary experimental values from drill cores from Oberpfalz (Northern Bavaria) and first measurements with low statistics from Oberndorf close to Kitzbühel (Austria). It is seen that the Oberpfalz values are described reasonably well with an erosion rate of 0 to 10 m/My for the last million years, whereas the very preliminary Oberndorf values are described by erosion rates in the range of 100 m/My. These very early ^{26}Al data will be improved and complemented by ^{10}Be and possibly by ^{14}C data. Via the measurement of depth profiles, it should be possible to determine erosion rates within 10 %.

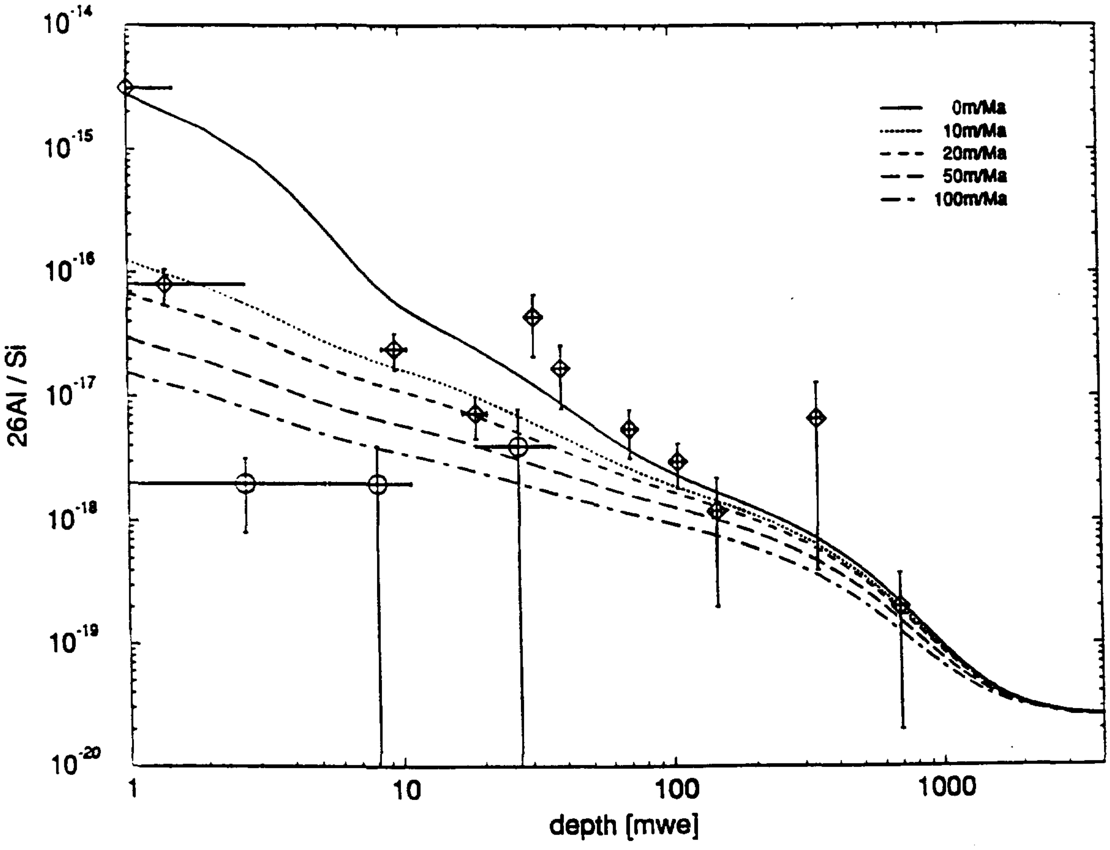

Figure 4: Measured and calculated ^{26}Al / Si ratios for quartz samples in the earth's crust as function of the depth in mwe in the lithosphere for an altitude of 660 m above sea level for the surface points for various erosion rates ϵ.

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