MODELING THE RECOIL LOSS OF COSMOGENIC NUCLIDES IN MICROMETEORITES.
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Introduction: Micrometeorites are extraterrestrial dust grains with grain sizes between ~20 μm and a few 100 μm, typically weighing less than 1 g. They can be collected in areas with no or only minor terrestrial sedimentation like ice and snow layers and / or deep see sediments. Another source for micrometeorites / IDPs are high flying aircrafts, which collect such grains in the Earth stratosphere [1].

While they travel through the solar system, micrometeorites are irradiated by galactic cosmic-rays (GCR) and solar cosmic-rays (SCR), which results in the production of a variety of cosmogenic nuclides. However, for a proper interpretation of the cosmogenic nuclide record with respect to, e.g., exposure ages, a detailed knowledge of the production rates is needed. In contrast to stony and iron meteorites, where reliable physical models exist [2,3], no model exists for such small objects like micrometeorites.

In contrast to the GCR, which has a mean penetration depth of ~250 g/cm^2, SCR particles penetrate only the upper few g/cm^2 of the irradiated object. Since meteorites usually suffer severe ablation losses during atmospheric entry, most SCR induced effects get lost. Consequently, SCR produced cosmogenic nuclides have only been found in very few meteorites. In contrast to the rather large objects, the temperatures in micrometeorites usually do not exceed a few 100 °C while they pass through the atmosphere [4], which reduces ablation losses and therefore preserves SCR induced effects. Since the SCR particle fluxes are a few orders of magnitude higher than GCR flux densities, preserved SCR effects very often dominate the total cosmogenic inventory [5]. Consequently, a study of cosmic-ray exposure histories for micrometeorites should focus as a first approach on SCR induced effects, i.e., on high flux densities with particles having energies below 200 MeV.

Model: Modeling the cosmogenic production rates in micrometeorites requires – apart from considering all relevant nuclear production pathways – a detailed knowledge of recoil losses. Our model, which is developed to quantify such losses, is shortly summarized here: For the incident SCR spectrum we use an exponentially decreasing rigidity function of the form

$$J_0 \propto e^{\left(\frac{R}{R_0}\right)} dE$$

where J_0 is the flux density of primary SCR particles [cm^{-2}s^{-1}MeV^{-1}], R is the rigidity in MV, depending on the energy E, the particles rest energy, the elementary charge, and the charge number of the nucleus. For the characteristic rigidity R_0 we assume $R_0 = 125\ MV$ [5]. For each incident energy of the SCR spectrum we calculated for all relevant target product combinations (see Table 1) the recoil spectrum for all relevant product nuclides, i.e., we consider for each product nuclide the full isobaric production. The calculations for energies between 1 MeV – 245 MeV were performed using the TALYS-1.0 code [6].

Table 1: Relevant target-product combinations considered in our model to quantify recoil losses

Cosmog. nuc.	Target element
^{3}H	C, N, O, Na, Mg, Al, Si, Ca, Fe, Ni
^{3,4}He	C, N, O, Na, Mg, Al, Si, Ca, Fe, Ni
^{10}Be	C, N, O, Na, Mg, Al, Si, Ca, Fe, Ni
^{14}C	C, N, O, Na, Mg, Al, Si, Ca, Fe, Ni
$^{20-22}$Ne	Na, Mg, Al, Si, Ca, Fe, Ni
^{26}Al	Mg, Al, Si, Ca, Fe, Ni
^{36}Cl	Cl, K, Ca, Ti, Fe, Ni
^{36,38}Ar	K, Ca, Fe, Ni
^{41}Ca	K, Ca, Ti, Fe, Ni
^{44}Ti	Ti, Fe, Ni
^{53}Mn	Fe, Co, Ni
^{60}Fe	Ni
^{59}Ni	Ni
$^{78,80-84,86}$Kr	Sr, Rb, Y, Zr, Nb
^{129}I	Te, Ba, La
$^{124,126-132,134}$Xe	Ba, La

As the next step we calculated for each individual recoil energy and for each individual product nuclide / isobar the stopping range, i.e., the travel distance of that nuclide in the micrometeorite, for which we assume a chemical composition close to CI chondrites [7]. Assuming now a homogeneous production and a spherical target enables to calculate the recoil loss for the given nuclide at the given recoil energy. Considering now all possible recoil energies (as given by TALYS) gives the total recoil loss of that nuclide for the given incident SCR projectile energy. In the next step we consider the full isobaric yield and all possible SCR energies and are finally able to quantify recoil losses as a function of grain size and the shape of the SCR particle spectrum. Note that the present version of model calculations is limited to protons as projectiles and incident energies of less than 245 MeV, i.e., it is applicable to SCR effects only. As a next step we will extend the model to cover also GCR induced effects and recoil losses in presolar grains. A flowchart of the model is shown in Fig. 1.

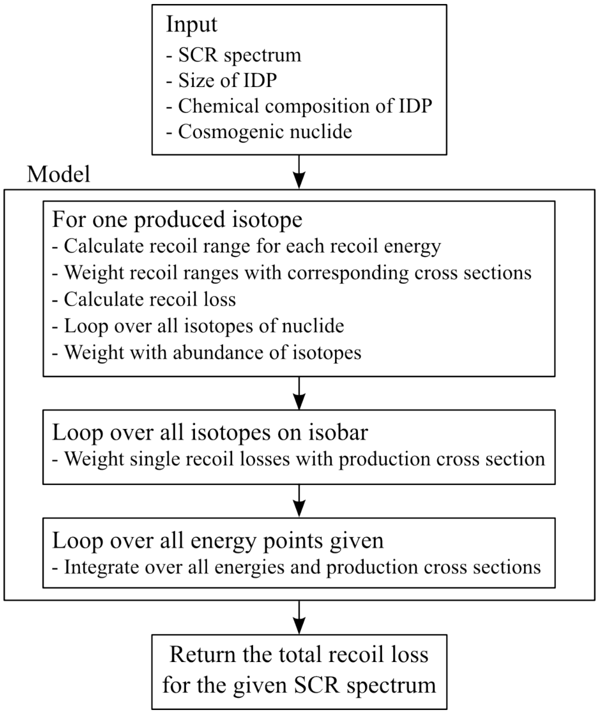

Figure 1: Flowchart of our model

Results: As a first result we report correction factors for the cosmogenic ratios ^{10}Be/^{26}Al, ^{21}Ne/^{26}Al, and ^{21}Ne/^{38}Ar for grains with radii between 0.3 µm and 1024 µm. The correction factor c is defined as $c = m/p$ with p the cosmogenic produced ratio without recoil losses and m the measured ratio affected by recoil losses. The data are shown in Fig. 2. For radii lower than 0.3 µm the recoil losses for all considered isotopes become larger than 99%, which prevents us from giving proper correction factors. For small grain sizes the recoil losses for light isotopes are much larger than for the heavier isotopes, leading to relatively large correction factors. For larger grains the correction factor becomes one, because in such grains recoil losses are only minor. Note, however, that a correction factor of one does not necessarily imply that there is no recoil loss, it only means that recoil losses (if any) for both nuclides are very similar. Using the data shown in Fig. 2 we can correct recoil losses of cosmogenic nuclides in micrometeorites using only measured data, i.e., without knowing a priori the pre-atmospheric size of the micrometeorite. By way of example, measuring ^{10}Be/^{26}Al and ^{21}Ne/^{26}Al ratios lower than the (predicted) SCR produced ratios by ~60% and ~10%, respectively, we can conclude that the pre-atmospheric size of the studied micrometeorite was ~3 µm (assuming a spherical object). However, for a 3 µm object we calculate a recoil loss for ^{21}Ne of about 99%. Consequently, the measured cosmogenic ^{21}Ne concentration has to be corrected by that amount to obtain a reliable cosmic-ray exposure age.

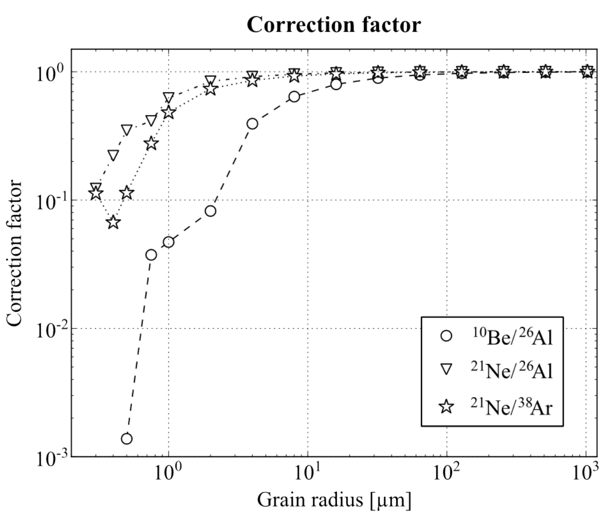

Figure 2: Model calculation for the correction factor of the given isotope ratios

Summary and Outlook: We present a purely physical model to quantify recoil losses in all types of grains and all types of irradiation environments where the maximum projectile energy is below ~245 MeV. Here we exemplary discuss recoil losses of cosmogenic nuclides in the irradiation of micrometeorites with solar cosmic-rays. The model enables one either to determine the pre-atmospheric size of the micrometeorites and to quantify the recoil losses based on measured data only or to determine the shape of the projectile spectrum, i.e., the rigidity, if the grain size of the irradiated object is a priori known. To validate the model predictions we currently perform irradiation experiments with monoenergetic protons of various energies at the Paul Scherrer Institute / Villigen, Switzerland. Finally using state-of-the-art Monte Carlo methods we will extend the model to higher energies to cover also recoil losses for GCR produced nuclides in presolar grains.

References: [1] Duprat J. et al. (2007) *Adv. in Space Res. 39,* 605–611. [2] Leya I. and Masarik, J. (2009) *Meteoritics & Planet. Sci., 44,* 1061–1086. [3] Ammon K. et al. (2009) *Meteoritics & Planet. Sci., 44,* 485–503. [4] Bradley J.P. (2005) Interplanetary dust particles. In *Meteorites, comets, and planets*, edited by Davis A. M. Treatise on Geochemistry, vol. 1. Amsterdam: Elsevier. pp. 689–711. [5] Bodemann R. (1993) Zur Wechselwirkung der solaren kosmischen Strahlung mit extraterrestrischer Materie – Messung von Wirkungsquerschnitten und Modellrechnungen. Ph.D. Thesis, Universität Hannover, Germany. 293pp. [6] Koning A.J., Hilaire S. and Duijvestijn M.C. 2005. *Proc. of the Int. Conf. on Nuc. Data for Sci. and Tech. – ND2004.* 769:1154. [7] Palme H. and Jones A. (2005) Solar System Abundances of the Elements. In *Meteorites, comets, and planets*, edited by Davis A. M. Treatise on Geochemistry, vol. 1. Amsterdam: Elsevier. pp. 41–61.