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Determination of the Specific Activities of the Cosmogenic Nuclides ^{10}Be and ^{26}Al in Meteorites from the Sahara by Means of Accelerator Mass Spectrometry*

By B. Meltzow[1], U. Herpers[1], J. Romstedt[2], B. Dittrich-Hannen[3], P. W. Kubik[4] and M. Suter[3]

[1] Abteilung Nuklearchemie, Universität zu Köln, D-50674 Köln
[2] Institut für Planetologie, Universität Münster, D-48149 Münster
[3] Institut für Teilchenphysik, ETH Hönggerberg, CH-8093 Zürich
[4] Paul Scherrer Institut, c/o ETH Hönggerberg, CH-8093 Zürich

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Abstract

In 30 samples of meteorites from the Sahara the specific activity of ^{26}Al, and in the case of rare meteorite types also that of ^{10}Be was determined. In most cases, the measured data are consistent with the suggestions about possible pairings which were based on mineralogical and petrographical investigations. The investigated CR and CH chondrites were found to be saturated in ^{26}Al and ^{10}Be. The ^{26}Al and ^{10}Be production rates can be assumed to be (44.5 ± 0.9) dpm/kg and (20.7 ± 0.3) dpm/kg, respectively, for CR as well as (30.1 ± 0.9) dpm/kg and (16.7 ± 0.4) dpm/kg for CH chondrites. Furthermore the ^{26}Al data of 11 ordinary chondrites can also be interpreted as saturation activities and allow the assumption of $3 \cdot 10^6$ y to be the lower limit of the exposure ages of these meteorites. In the case of Acfer 277, in addition to the ^{10}Be and ^{26}Al determinations, a study on nuclear tracks was performed. These data suggest that the investigated sample was located at no more than 8 cm below the original surface of a meteoroid of a radius between 25 cm and 65 cm which traveled through space $(0.3 \pm 0.1) \cdot 10^6$ y before entering the earth's atmosphere.

Introduction

Cosmic ray particles interact with planetary surfaces, meteoroids and cosmic dust. By inelastic nuclear processes a large variety of stable and long-lived nuclides is produced. These cosmogenic nuclides constitute a unique record of the history of the irradiated bodies in the solar system as well as of the history of the cosmic radiation itself. To obtain these informations from the investigation of cosmogenic nuclides Michel *et al.* [1, 2] developed a physical model basing on detailed measurements of thin-target cross-sections of the underlying nuclear reactions and on simulation experiments with artifical meteoroids which allows the interpretation of the abundances of cosmogenic nuclides in meteorites, e.g. ^{10}Be and ^{26}Al, with respect to their collision and exposure history. The quality of the calculated production rates of cosmogenic nuclides based on this model has to be verified by measured production rates which are in the case of radionuclides represented by the specific saturated activity. Therefore we determined ^{10}Be and ^{26}Al specific activites in a suite of samples belonging to rare meteorite classes, thus extending the existing data set. These activities can also provide clues to the decision if two meteorites derive from the same meteoroid (i.e., pairing of two samples).

The production of cosmogenic nuclides in any target depends on kind and energy of the bombarding particles. Two constituents of the cosmic radiation are distinguished according to their origin: the galactic and the solar cosmic rays (GCR and SCR). The origin of the GCR lies outside the solar system in the galaxy, whereas the SCR particles are emitted from the sun during short-term events, the solar flares. The SCR particles are of lower energies (<200 MeV/A) than the GCR particles, therefore their interactions are restricted to the outmost surface (depth <15 g cm^{-2}) of the irradiated material and the production of reactive secondary particles can be widely neglected. In the case of the GCR particles the situation is much more complicated. Due to their higher energies, secondary particles, in particular neutrons, become important and the depth scale on which GCR interactions occur extends to several hundreds of g $\cdot$ cm^{-2} [3]. Details about the composition and spectral distribution of these two components of the cosmic radiation are given in Refs. [4–6].

The production rate of a cosmogenic nuclide from a particular target element depends, apart from the properties of the bombarding radiation, on the size of the irradiated body and on the shielding depth of a sample in it. The chemical composition of a sample will define the total production rate in the sample. The production rate also depends on the bulk chemical composition of the irradiated body, which influences primary and secondary particle fields, since multiplicities, stopping and attenuation properties depend on atomic and mass number of the irradiated matter. Therefore, when studying the interaction of cosmic ray particles with meteoroids (i.e., meteorites before entering the earth's atmosphere) one has to take into ac-

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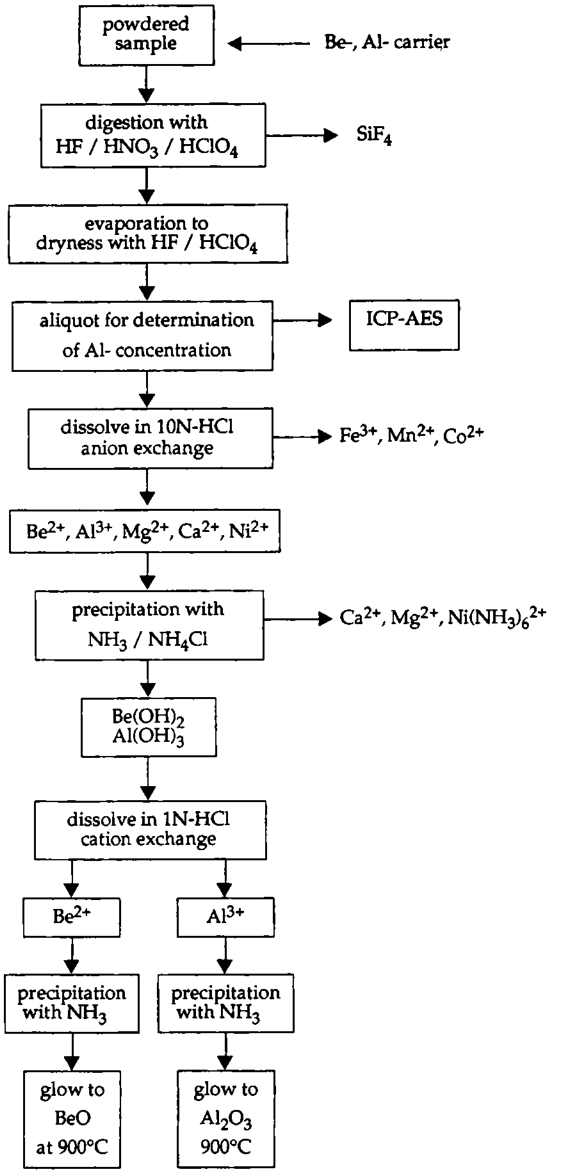

Fig. 1. Separation scheme for ^{10}Be and ^{26}Al from meteorites.

count that there are differences in the chemical composition of the different meteorite classes. Details about the classification of meteorites are given in Refs. [7–10].

Apart from the well-known finds and falls of Antarctic and non-Antarctic meteorites, during the last years also in the Sahara and other hot deserts extensive meteorite discoveries were made.

Experimental

30 samples from the Algerian Sahara were kindly placed at our disposal by the Institut für Planetologie, Münster.

^{10}Be and ^{26}Al concentrations were measured by means of accelerator mass spectrometry (AMS). Samples measured by this method were prepared using a chemical procedure which is shown schematically in Fig. 1. The separation procedure was developed by Vogt and has been described in detail previously [11, 12]. Modifications of single steps in the separation scheme were performed in this study, e.g. the application of NH_3/NH_4Cl instead of NH_3 for the precipitation of the hydroxides (thus avoiding Mg in the precipitate). The masses of the samples prepared for AMS measurements varied from 50 mg to 250 mg. The AMS measurements were performed at the PSI-ETH AMS facility in Zurich. Descriptions of the AMS technique are given in Refs. [13, 14].

For ^{10}Be, the standard "S555" with a nominal ^{10}Be/^{9}Be ratio of $95.5 \cdot 10^{-12}$ was used. For ^{26}Al, the standards used were "Al9" and "Al1092" with a nominal ^{26}Al/^{27}Al ratio of $1190 \cdot 10^{-12}$ and $134 \cdot 10^{-12}$, respectively. The half-lives adopted to convert the measured data of ^{10}Be and ^{26}Al nuclides into activities were $1.51 \cdot 10^6$ y and $716 \cdot 10^3$ y for ^{10}Be and ^{26}Al, respectively.

^{26}Al was also measured non-destructively by γ-γ-coincidence counting. This technique has been described in detail elsewhere [15, 16]. Samples investigated in this manner had masses from 3 g up to 37 g. The accuracy of this method is about 5%.

In Fig. 2, the correlation between the ^{26}Al concentrations determined by γ-γ-coincidence counting and AMS is shown. The individual measurements are represented by different symbols, the solid line was obtained by linear regression. The results of both methods agree, except for a few data points, within the range of the errors. Discrepancies between both methods are not necessarily erroneous, but can rather be explained by the different sizes of the samples used. Due to depth effects, SCR effects or chemical inhomogeneities, the activity of a cosmogenic nuclide is not uniform within a large sample.

Results and discussion

The results of the ^{10}Be and ^{26}Al determinations in C chondrites are given in Table 1, the results of mesosiderites and other rare classes of Saharian meteorites are given in Table 2. Table 3 contains the results of ^{26}Al determinations via γ-γ-coincidence spectrometry of some ordinary chondrites from the Acfer region, which predominantly were performed for a comparison with results of AMS measurements. The classification of the meteorites indicated in the tables was done by Bischoff *et al.* [17]. For some of the meteorites, exposure ages based on ^{21}Ne determinations [10, 18, 19] are available. These ages are included in the last column of Tables 1 and 2.

As reported earlier [20], the ^{10}Be and ^{26}Al data of the two CO3 chondrites Acfer 202 and Acfer 243 indicate that the two meteorites are not paired.

Based on their ^{10}Be and ^{26}Al concentrations, a pairing of the three meteorites Acfer 087, Acfer 186 and El Djouf 001 classified as CR seems very certain. This interpretation of the data is supported by results of mineralogical and petrographical investigations [18].

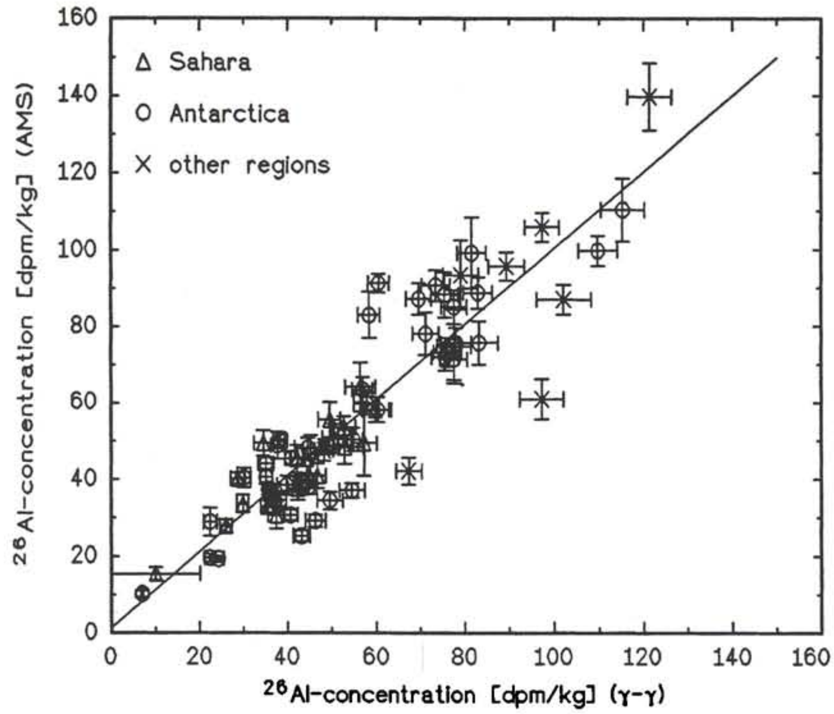

Fig. 2. Comparison of the ^{26}Al concentration measured by AMS and γ-γ-coincidence spectrometry.

Table 1. ^{10}Be and ^{26}Al concentrations in C chondrites from the Sahara measured by means of AMS and γ-γ-coincidence spectrometry

Meteorite	Sample	Class	^{26}Al [dpm/kg]		^{10}Be [dpm/kg] AMS	T_{rad} [10^6 y]
			γ-γ	AMS		
Acfer 094	A 094	CM3	36.8±1.8	33.2±2.1	14.6±0.3	
Acfer 202	A 202	CO3	57.3±2.9	49.4±8.4	23.5±0.8	
Acfer 243	A 243	CO3	28.7±1.7	40.2±1.8	14.4±0.3	
				40.2±2.4	15.0±0.3	
Acfer 087	A 87	CR	42.2±1.7	45.7±2.7	17.5±0.7	6
Acfer 186	A 186	CR	46.8±1.9	40.9±3.2	21.5±0.3	6
El Djouf 001	Dy 1	CR	48.7±2.4	40.6±3.0	19.8±0.7	6
Acfer 082	A 82	CV3	26.0±1.3	27.7±1.6	8.5±0.2	
Acfer 086	A 86	CV3	35.5±1.7	32.9±1.6	15.4±0.3	
Acfer 272	A 272	CV3	42.3±2.2	37.7±3.1	13.0±0.3	
Acfer 182	A 182	CH	29.8±1.2	33.6±2.7	16.3±0.6	12.2
Acfer 207		CH	–	29.5±1.5	16.8±0.5	12.2

Remarkable about this pairing is the fact that the El Djouf location is more than 500 km apart from the Acfer location. The investigation on 53 H, L and LL chondrites from the Sahara by Wlotzka *et al.* [21] indicates that the terrestrial ages of 98% of these meteorites are less than 40000 years. Assuming that this is true for C chondrites also, the terrestrial age of the CR chondrites is negligible compared to the half-lives of ^{10}Be and ^{26}Al. Thus, as reported previously [20], the exposure age of $6 \cdot 10^6$ y implies that the ^{10}Be and ^{26}Al activities are in saturation and consequently represent production rates. The average production rates of the three investigated samples are (44.5±0.9) dpm/kg for ^{26}Al and (20.7±0.3) dpm/kg for ^{10}Be. In the case of ^{26}Al, this is consistent with the activity range reported for other carbonaceous chondrites [22–24].

In the case of the CV3 chondrites, based on the ^{10}Be and ^{26}Al concentrations a pairing seems very improbable. This conclusion is supported by mineralogical and petrographical investigations [17].

The ^{10}Be and ^{26}Al concentrations of the two meteorites Acfer 182 and Acfer 207 classified as CH indicate a pairing. This interpretation of the data is confirmed by the results of mineralogical and petrographical investigations [9]. If the terrestrial age of these meteorites is negligible, in this case, too, regarding the high exposure age of 12,2 million years, the ^{10}Be and ^{26}Al activities appear to be saturated. The

Table 2. ^{10}Be and ^{26}Al concentrations in mesosiderites and other classes from the Sahara measured by means of AMS and γ-γ-coincidence spectrometry

Meteorite	Sample	Class	^{26}Al [dpm/kg]		^{10}Be [dpm/kg] AMS	T_{rad} [10^6 y]
			γ-γ	AMS		
Acfer 063	A 063	Meso	37.4±1.9	30.7±3.6	7.0±0.2	
					7.3±0.8	
	Silicate		–	67.0±3.4	12.1±0.2	
Acfer 265	A 265	Meso	30.7±2.1	–	6.3±0.5	
	Silicate		–	–	8.4±0.7	
Ilafegh 002	Il 2	Meso	33.9±1.9	–	3.7±0.3	
	Silicate		–	–	7.6±0.6	
Acfer 217	A 217	R	56.5±3.4	64.1±6.4	22.9±0.3	35
Acfer 277	A 277	Ure	<10	15.5±1.7	2.6±0.1	
					2.6±0.1	
Ilafegh 009	Il 009	EL 7/6	68.6±3.4	–	18.2±0.3	
					18.7±0.4	
					17.3±0.7	
Tanezrouft 031	T 31	E	34.5±2.1	49.4±3.3	13.0±0.5	

average production rates therefore can be assumed to be (30.1±0.9) dpm/kg and (16.7±0.4) dpm/kg for ^{26}Al and ^{10}Be, respectively. The ^{10}Be data of the two mesosiderites Acfer 063 and Ilafegh 002 (Table 2) and also the ^{10}Be concentrations in the stone phases of both meteorites indicate that they are not paired. On the basis of the ^{10}Be and ^{26}Al data a pairing of Acfer 063 and Acfer 265 seems probable, but the ^{10}Be data of the stone phases are in contradiction to that conclusion. A magnetic separation of the iron phase from the stone phase was done for the three mesosiderites to investigate the ^{10}Be and ^{26}Al concentrations in the stone phase separately. Taking the saturation activities of eucrites as references (21.8±0.7 and 93±14 dpm/kg, respectively [25]), the ^{10}Be and ^{26}Al concentrations in the stone phase of Acfer 063 appear to be undersaturated. Assuming these average saturation activities, the ^{10}Be and ^{26}Al concentrations imply an exposure age of $(1-2) \cdot 10^6$ y.

The ^{26}Al and ^{10}Be concentrations of Acfer 277, a member of the rare meteorite class of ureilites, are strikingly low. Such low concentrations are often indicative of low exposure ages or high shielding depths of the sample, but other combinations of exposure age and shielding depth are also conceivable between these two extremes. Therefore model calculations for the production of ^{26}Al and ^{10}Be in ureilites were performed by Michel [26] which offer the possibility of an interpretation of the measured data in view of the exposure history of Acfer 277.

In Fig. 3 the calculated ^{10}Be and ^{26}Al concentrations in the center of a meteoroid with chemical composition of ureilites, belonging to different exposure ages are plotted versus the preatmospheric radius. According to this diagram the measured ^{26}Al and ^{10}Be concentrations of 15.5±1.7 and 2.6±0.1, respectively, restrict the range of the exposure age of Acfer 277 to $(0.2-0.5) \cdot 10^6$ y. Assuming small radii (<20 cm) of the meteoroid the exposure ages corresponding to the measured ^{26}Al and ^{10}Be concentrations deviate very much from each other. The production of ^{10}Be varies hardly with the radius of the meteoroid in this region, whereas the production of ^{26}Al decreases strongly with decreasing radius. The best conformity (within 2 σ) in the interpretation of the ^{26}Al and ^{10}Be data on this basis can be obtained with the assumption

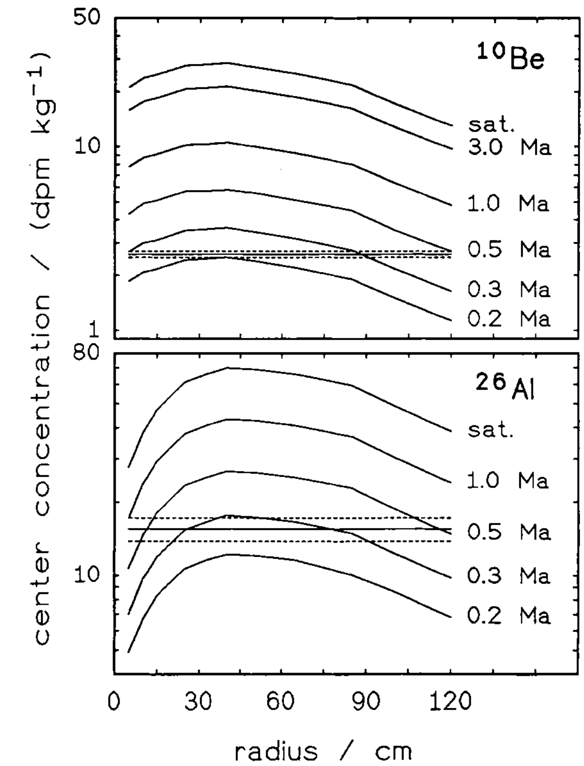

Fig. 3. Relation between ^{10}Be and ^{26}Al concentrations in the center of a spherical ureilite and its radius. The curves are model calculations, the parameters at the right denoting the respective exposure ages (1 Ma = 10^6 y). The solid and dashed horizontal lines represent the concentrations measured in Acfer 277 and their standard deviations, respectively.

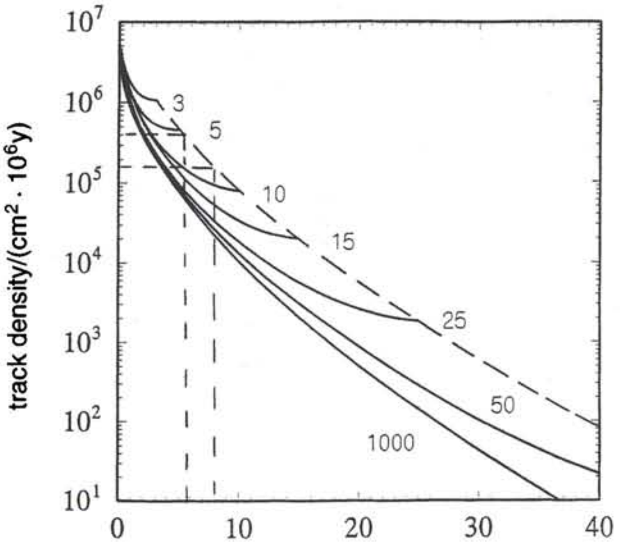

Fig. 4. Semi-empirical relation between the track density and the depth of a sample in a spherical body assuming symmetrical ablation. The parameters at the end of the curves denote the respective radius of the body. The dashed horizontal lines represent the average track densities measured in Acfer 277 for exposure ages of $0.2 \cdot 10^6$ y (0.2 Ma) and $0.5 \cdot 10^6$ y (0.5 Ma), respectively.

of a preatmospheric radius of the meteoroid greater than 25 cm.

So far only the situation of a sample near the center of the meteoroid has been considered. But still the possibility exists that the sample was located at a depth which was smaller than the radius of the meteoroid. It is not possible to draw a conclusion concerning the three parameters exposure age, preatmospheric radius and shielding depth on the basis of the ^{26}Al and ^{10}Be data exclusively. Therefore a determination of nuclear tracks produced by the heavy nuclei of the galactic radiation was performed in Acfer 277 to get further informations about this meteorite. In Fig. 4 the semi-empirical track densities of nuclear tracks in spherical bodies with symmetrical ablation according to Bhattacharya *et al.* [27] based on the revised exposure age of St. Severin [28] are plotted versus the shielding depth of the sample for different meteoroid radii. The average nuclear track density was determined in olivine grains of Acfer 277, which were etched under standard conditions [29], to $3.34 \cdot 10^4$ tracks/cm^2. With regard to a comparison to the semi-empirical relation (Fig. 4), the measured value has to be standardized to pyroxene by multiplication with the factor 2.4 [30].

In Fig. 4 the resulting nuclear track densities for a exposure ages of $0.2 \cdot 10^6$ y and $0.5 \cdot 10^6$ y are also plotted. According to this diagram the maximum shielding depth which is close to the minimum preatmospheric radius, covers the range from 5.5 cm to 8 cm which corresponds to irradiation ages of $0.2 \cdot 10^6$ y and $0.5 \cdot 10^6$ y, respectively. Thus a center position in a meteoroid with a radius greater than 25 cm can be excluded. A shielding depth of 19 cm, e.g., would require, on the basis of the measured nuclear track density in Acfer 277, an exposure age of $10 \cdot 10^6$ y which means saturation for the radionuclides ^{26}Al and ^{10}Be. Assuming the semi-empirical track densities for meteoroid radii between 25 cm and 1000 cm which differ hardly in the interesting region, a shielding depth of 2−5 cm seems to be the best approximation. According to the model calculations at this depth the production of ^{26}Al and ^{10}Be in meteoroids with radii from 25 cm to 120 cm show only a slight variation with increasing radius, merely a soft tendency of decrease for both radionuclides can be observed for radii greater than 85 cm. Subsequently the measured radionuclide concentrations can be consistently interpreted assuming any radius between 25 and 120 cm. With the fact that there was found only a single piece of 41 g [31] of this ureilite, the assumption of a sample near the surface of a very big meteoroid seems very unlikely. Considering the more confined range of meteoroid radii between 25 cm and 65 cm, the exposure age can be determined to $(0.3 \pm 0.1) \cdot 10^6$ y assuming that the terrestrial age is negligible.

Regarding only the ^{10}Be concentration and the track density in Acfer 277, smaller radii (between 6 cm and 20 cm) could be possible, but the higher ^{26}Al concentration requires higher radii. One possibility for the explanation of an increased ^{26}Al concentration is the supplemental production by SCR particles which in principle is likely at a depth of 2−5 cm. The lower value for the ^{26}Al concentration in the 3 g sample measured by γ-γ-coincidence spectrometry could be a hint on probable SCR effects in Acfer 277. Differences between both methods, though, could also be caused by deviations in the chemical composition. The determination of an ^{26}Al depth profile could be helpful for a solution of this problem.

Summing up on the basis of the presented investigations on Acfer 277, it can be assumed that the investigated sample was located at no more than 8 cm shielding depth in a meteoroid of a radius between 25 cm and 65 cm which traveled through space $(0.3 \pm 0.1) \cdot 10^6$ y before entering the earth's atmosphere.

Table 3. ^{26}Al concentrations in ordinary chondrites from the Sahara measured by means of γ-γ-coincidence spectrometry

Meteorite	Class	^{26}Al [dpm/kg]
Acfer 005	H3.9	58.8±2.9
Acfer 006	H3.7	49.0±2.5
Acfer 031	H5	50.5±2.5
Acfer 038	H5	52.9±4.2
Acfer 073	H5	49.6±2.5
Acfer 074	L6	59.9±3.0
Acfer 118	L6	49.2±2.5
Acfer 123	H3.9	65.1±3.2
Acfer 157	L6	52.8±2.6
Acfer 193	LL4−6	55.7±2.8
Acfer 228	L5	63.3±3.2
Acfer 255	L6	15.7±1.3

Acfer 217 classified as a member of the Rumuruti-type chondrite group (R) is another interesting sample that has been discussed in more detail previously [19]. Therefore here we present only the conclusions which can be made on the basis of model calculations for Acfer 217: The concentrations of all cosmogenic nuclides can be consistently interpreted only if a preatmospheric radius between 15 and 65 cm, a single stage exposure history and a terrestrial age low compared to the half-life of ^{26}Al are assumed.

Table 3 contains the results of the investigation of ^{26}Al in 12 ordinary chondrites from the Sahara by γ-γ-coincidence spectrometry. As mentioned before, this investigation was primarily performed to extend the existing data set for the comparison to ^{26}Al investigations by AMS which was shown in Fig. 2. In addition, due to the well known mean production rates for ordinary chondrites, saturated activities and consequently a lower limit of exposure ages could be verified by the measured concentrations.

The mean production rates of ^{26}Al in H chondrites according to different authors are given as 56.1 ± 1.0 [32] and 56.0 ± 8.0 [33], respectively. In the case of L and LL chondrites they were reported as 60.2 ± 0.8 [32] and 60.0 ± 7.0 [33], respectively. Assuming these mean production rates all ^{26}Al activities in ordinary chondrites presented here except for Acfer 255 can be interpreted as saturated. Thus $3 \cdot 10^6$ y can be assumed to be the lower limit of the exposure ages for these saturated meteorites. In addition the terrestrial age of these meteorites can be considered to be negligible compared to the half-life of ^{26}Al. In the case of Acfer 255 the lower activity may be caused by a lower exposure age, a high terrestrial age or specific shielding conditions. Further investigations are needed for the interpretation of this ^{26}Al concentration.

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