Earth and Planetary Science Letters, 53 (1981) 203–210

[6]

PRODUCTION CROSS SECTIONS OF ^{26}Al, ^{22}Na, ^{7}Be FROM ARGON AND OF ^{10}Be, ^{7}Be FROM NITROGEN: IMPLICATIONS FOR PRODUCTION RATES OF ^{26}Al AND ^{10}Be IN THE ATMOSPHERE

J.-L. REYSS, Y. YOKOYAMA and F. GUICHARD

Centre des Faibles Radioactivités, Laboratoire mixte C.N.R.S.-C.E.A., 91190 Gif-sur-Yvette (France)

Received February 14, 1980
Revised version received January 20, 1981

The cross sections for production of ^{7}Be (1.2 ± 0.3; 2.6 ± 0.7 and 5.2 ± 1.4 mb), ^{22}Na (1.5 ± 0.3; 2.8 ± 0.6 and 2.8 ± 0.6 mb), and ^{26}Al (1.9 ± 0.4; 3.0 ± 0.6 and 3.2 ± 0.7 mb) from the spallation of argon at, respectively, 480, 880 and 2980 MeV are measured. In the course of the same irradiation as that of argon, the cross sections for production of ^{7}Be (9.0 ± 2.1 and 9.3 ± 2.1 mb) and ^{10}Be (1.5 ± 0.4 and 2.6 ± 0.6 mb) from nitrogen at, respectively, 450 and 2950 MeV are also measured. Experimental results are compared with the values calculated from the semi-empirical formula of Silberberg and Tsao. The production rates of ^{26}Al and ^{10}Be in the atmosphere by galactic cosmic rays calculated from the measured cross sections are: $(1.1 \pm 0.3) \times 10^{-4}$ and $(2.1 \pm 0.5) \times 10^{-2}$ atoms cm^{-2} s^{-1}, respectively. These rates are compared with experimental results. The potential use of ^{26}Al/^{10}Be ratio for dating marine sediments and evaluating cosmic dust influx is discussed in the light of these cross section values.

1. Introduction

Bombardment of atmospheric constituents by galactic cosmic rays (GCR) produces two radionuclides that have million-year half-lives: ^{10}Be ($T_{1/2}$ = 1.5×10^{6} years) is produced from nitrogen and oxygen, ^{26}Al ($T_{1/2} = 0.716 \times 10^{6}$ years) from argon.

Measurement of these nuclides in marine environment [1–3] and in Polar ice [4,5] provides useful information about variation of the GCR flux over the past million years [6,7], oceanic sedimentation rates, growth rates of manganese nodules [8,9] and oceanic residence times of dissolved beryllium and aluminium [10,11].

^{7}Be ($T_{1/2}$ = 53 days) and ^{22}Na ($T_{1/2}$ = 2.60 years) are also produced by GCR in the atmosphere and are useful in the study of the movement of air masses.

For such applications, it is indispensable to know the production rates of these cosmogenic nuclides in the atmosphere. The production rates could be calculated if the cross sections for production were known as a function of energy. However, the cross section for production of ^{26}Al from argon have not previously been measured experimentally because of the technical difficulties involved in the measurement of such long-lived nuclides; similarly the cross sections for production of ^{7}Be, ^{22}Na from argon and those of ^{7}Be from nitrogen have not been measured for energies more than 600 MeV. However, half or more of atoms of these nuclides can be produced with particles having energies >600 MeV (primary + secondary).

We report here experimental results of liquid argon and nitrogen irradiated with protons of high energies and discuss their implications for the production of ^{26}Al and ^{10}Be in the atmosphere.

2. Experimental procedures

2.1. Irradiation

Brodzinski and Wogman [12], showing that the liquid argon contained in a glass Dewar can be irradiated with a proton beam without any cooling device

0012-821X/81/0000–0000/$ 02.50

and without significant loss of argon, measured the cross section of short-lived spallation products of argon. We used a similar system of irradiation but with a larger Dewar and a much longer irradiation time in order to produce sufficient activity of ^{26}Al.

Liquid argon and nitrogen were bombarded with the external proton beam of the "Saturne" synchrotron of Saclay. Four irradiations were carried out, two at 500 MeV each, one at 900 MeV and one at 3000 MeV. The beam was pulsed at a rate of 3×10^{11} protons each 5 seconds.

Two glass Dewar of 14.5 cm internal diameter were placed in the beam, one behind the other. Argon was in the first Dewar, and nitrogen was in the second. The last was used for two reasons:

(1) To verify if there was an appreciable contribution of the recoil products of ^{22}Na and ^{26}Al from the glass of the Dewar (since it is not possible to produce these nuclides in nitrogen, any appreciable activity of ^{22}Na and ^{26}Al in the second recipient might be due to the recoil products from the glass; in fact we found neither ^{22}Na nor ^{26}Al in this Dewar after the irradiation).

(2) The cross section for production of ^{10}Be from nitrogen could be measured with the same beam as that of ^{26}Al from argon. With such an arrangement of the targets, the ratio of the cross section for production of ^{26}Al from argon to that of ^{10}Be from nitrogen can be measured independently of the absolute value of fluxes.

Protons fluxes were monitored by the spallation products induced in three aluminium foils (each 1.4 mg cm^{-2} thickness) which were placed before, between and behind the Dewar.

Immediately after each irradiation, the liquids were transferred from the "irradiation" Dewar to the pre-cooled "counting" Dewar in the manner of Brodzinski and Wogman [12]. We used this technic to assure that evaporation of argon did not carry away the non-volatile spallation products. We let the argon slowly evaporate through a filter paper. During the evaporation we counted periodically the "counting" Dewar with a gamma-ray spectrometer consisting of a 110-cm^3 Ge(Li) detector (resolution: 2.3 keV at 1330 keV). The activities of ^{24}Na and ^{28}Mg showed a decay with the well-known half-lives of 15 hours and 21 hours respectively, which means that there was no loss of these nuclides during the evaporation of argon. No activities were found in the filter paper; this fact assures also no loss of the non-volatile spallation products.

After all the argon had evaporated, the "counting" Dewar was rinsed with a solution of 1*N* HCl containing beryllium, sodium and aluminium carriers to dilute the spallation products. The solution and the empty "counting" Dewar were counted separately by the gamma-ray spectrometer, and we assured that all the detectable activities were transferred to the solution. We assured also by the same method, that the empty "irradiation" Dewar did not contain the argon spallation products. The nitrogen Dewar was treated in the same way except for the counting of ^{24}Na and ^{28}Mg which were not formed in that liquid.

2.2. *Chemical separation*

Sodium was separated from the solution by two successive extractions using an inorganic ion-exchanger: hydrated antimony pentoxide (HAP) [13]. The extraction yield of ^{22}Na was 96%. Aluminium and beryllium were then precipitated by NH_4OH, and separated from the residual activity of ^{22}Na. Beryllium was separated from aluminium by precipitation with NH_4OH in the presence of EDTA. Further purifications of beryllium were carried out by anion and cation exchange. The purified aluminium and beryllium were finally converted to BeO and Al_2O_3. The chemical yields of the beryllium and of the aluminium were determined by gravimetry, and were more than 80% for all samples.

2.3. *Counting*

The counting of ^{7}Be, ^{22}Na and ^{26}Al was done using the above-mentioned Ge(Li) gamma-ray spectrometer. ^{26}Al was also measured by a NaI(Tl) coincidence gamma-gamma spectrometer [14].

The ^{10}Be activity was counted with a gas flow-type proportional counter [9,15]. Since the ratio of activities ^{7}Be/^{10}Be was about 10^7 immediately after the irradiation, we waited more than three years for the decay of ^{7}Be. Then, the beta activities of the BeO samples were periodically counted for more than 6 months to verify the absence of short-lived activities.

TABLE 1

Adopted monitor cross sections and proton fluxes energy and flux in each Dewar are calculated taking into account beam losses in target

Protom beam energy (MeV)	$\sigma^{27}Al(p,x)^{22}Na$ (mb)	Energy in argon (MeV)	Flux in argon (10^{15} p)	Energy in nitrogen (MeV)	Flux in nitrogen (10^{15} p)
500(a)	14.2 *	480	1.15 ± 0.14	450	2.42 ± 0.29
500(b)	14.2 *	480	1.50 ± 0.18		
900	15.0 *	880	1.43 ± 0.17		not measured
3000	11.1 **	2980	0.29 ± 0.04	2950	0.25 ± 0.03

* Heydegger et al. [17].
** Tobailem et al. [16].

2.4. Energies and fluxes of protons

We used relatively thick targets (20 g cm^{-2} for argon and 12 g cm^{-2} for nitrogen + 1.4 g cm^{-2} for glass) in comparison with the currently used targets for cross section measurements of short-lived products: a thickness of a few grams per square centimeter. Therefore, the losses in energies and in fluxes of the proton beam during its passage through the targets should be taken into account. Using a value of 2 MeV g^{-1} cm^2 for the energy loss of protons, we calculated the mean energy of protons in the targets (Table 1).

Since our targets are thick, there are low-energy secondary particles. But, the fact that most of the cross sections involved are increasing rapidly with energy tends to minimise the error caused by this effect, except the case of $^{14}N(p,x)^7Be$ which have a relatively flat excitation function. However, our results on this last reaction are in good agreement with those obtained with thin targets (Fig. 4).

Concerning the proton fluxes, activities of ^7Be, ^{22}Na and ^{24}Na in the Al-foil monitors were measured. We adopted the $^{27}Al(p,x)^{22}Na$ reaction as the monitor of fluxes for reasons which will be given later. The production of ^{24}Na from aluminium can be largely influenced by the $^{27}Al(n,\alpha)^{24}Na$ reaction due to the presence of low-energy secondary neutrons in such thick targets. The $^{27}Al(p,x)^7Be$ reaction may have a large uncertainty in the absolute values of its excitation function, because there are only few measurements [16], especially in the steep part of its excitation function (between 300 and 2000 MeV). This reaction, however is not sensitive to low-energy secondary particles, and therefore we used it for the purpose of measuring the decrease of the beam flux during its passage in the targets: 9–14% loss according to the beam energy.

Tobailem et al. [16] compiled the cross sections for the $^{27}Al(p,x)^{22}Na$ reaction. We adopted their value for 3000 MeV. For 500 MeV and 900 MeV, we adopted the results of recent measurements made by Heydegger et al. [17]. The average fluxes (Table 1) were deduced from the incident fluxes which have been determined from the ^{22}Na activities of the first monitor, taking into account the beam losses in the targets. Those losses have been estimated from the $^{27}Al(p,x)^7Be$ reactions.

3. Results

Table 2 summarizes the results of the experimental determination of the cross sections for production of ^7Be, ^{22}Na and ^{26}Al from argon at 480 MeV, 880 MeV and 2980 MeV. The cross sections measured values for production of ^7Be and ^{10}Be from nitrogen at 450 MeV and 2950 MeV are given in Table 3. The error listed in Tables 2 and 3 are the quadratic sum of the uncertainties in the proton fluxes (15% including the incertitudes on monitor cross sections, ^{22}Na counting, and flux loss in the target), the errors in the chemical yields (3–5%), and the errors in the counting (10–15%).

We calculated the values of various cross sections according to the semi-empirical formula of Silberberg and Tsao [18]. The ratios between the experimental

TABLE 2

Spallation cross sections of ^{7}Be, ^{22}Na and ^{26}Al from argon

Energy (MeV	$\sigma(^{7}\mathrm{Be})$ (mb)	$\sigma_{exp}/\sigma_{calc}$	$\sigma(^{22}\mathrm{Na})$ (mb)	$\sigma_{exp}/\sigma_{calc}$	$\sigma(^{26}\mathrm{Al})$ (mb)	$\sigma_{exp}/\sigma_{calc}$
480(a)	1.1 ± 0.3	2.62	1.5 ± 0.3	1.20	1.9 ± 0.4	1.15
480(b)	1.2 ± 0.3	2.85	1.4 ± 0.3	1.12	1.8 ± 0.4	1.09
880	2.6 ± 0.7	1.96	2.8 ± 0.6	1.21	3.0 ± 0.6	1.23
2980	5.2 ± 1.4	0.83	2.8 ± 0.6	0.88	3.2 ± 0.7	1.08

TABLE 3

Spallation cross sections of ^{7}Be, and ^{10}Be from nitrogen

Energy	$\sigma(^{7}\mathrm{Be})$ (mb)	$\frac{\sigma_{exp}}{\sigma_{calc}}$	$\sigma(^{10}\mathrm{Be})$ (mb)	$\frac{\sigma_{exp}}{\sigma_{calc}}$
450	9.0 ± 2.1	2.00	1.5 ± 0.4	2.20
2950	9.3 ± 2.1	0.91	2.6 ± 0.6	1.37

cross sections and the calculated ones are given in Tables 2 and 3.

Figs. 1 to 5 show the calculated excitation functions (according to Silberberg and Tsao's formula) for production of ^{7}Be, ^{22}Na, ^{26}Al from argon and ^{10}Be from nitrogen. Experimental values from the literature and from the present work are also given.

4. Discussion

Our experimental values for production of ^{7}Be a ^{22}Na from argon at 480 MeV are in fairly good agre ment with the values reported by Brodzinski and Wogman [12]. Our measurements at 880 MeV and 2980 MeV complete the higher-energy part of the excitation functions of these reactions.

Concerning the production of ^{7}Be from nitrogen our experimental values at 450 MeV and 2950 MeV

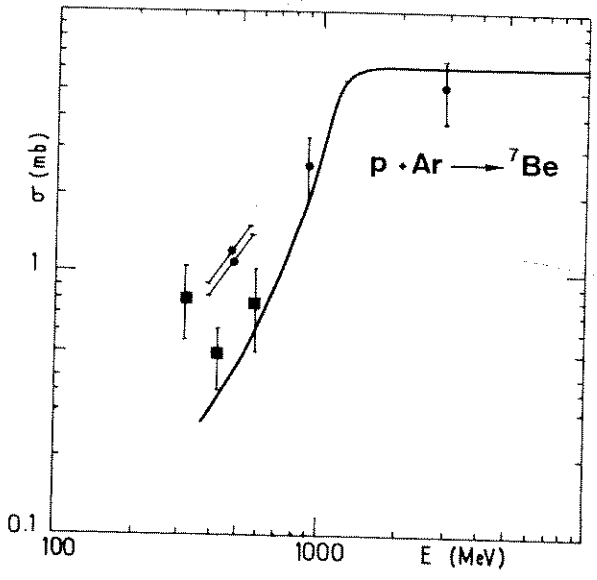


Fig. 1. Cross sections for production of ^{7}Be from argon. ■ = Brodzinski and Wogman [12]; ● = this work. The solid line has been calculated using the semi-empirical formula of Silberberg and Tsao [18].

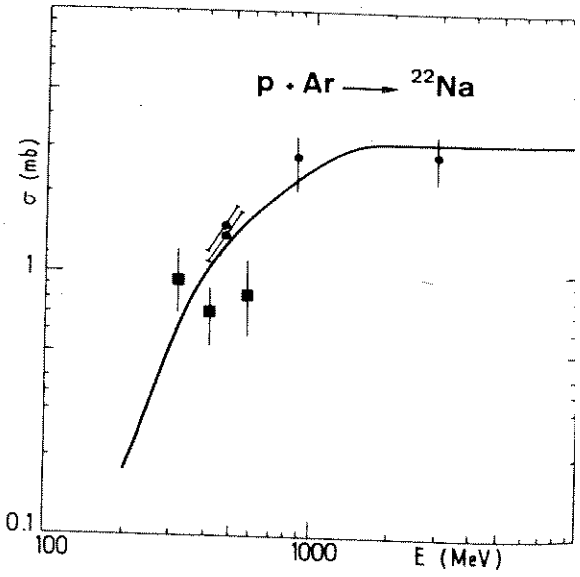
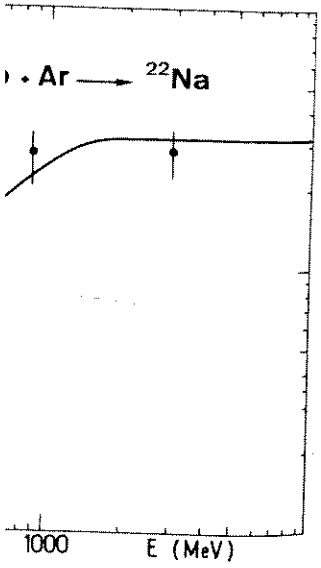


Fig. 2. Cross sections for production of ^{22}Na from argon. Symbols as in Fig. 1.

$\sigma(^{26}Al)$ (mb)	$\sigma_{exp}/\sigma_{calc}$
1.9 ± 0.4	1.15
1.8 ± 0.4	1.09
3.0 ± 0.6	1.23
3.2 ± 0.7	1.08

mental values from the litera-
ent work are also given.

alues for production of ^{7}Be and
0 MeV are in fairly good agree-
eported by Brodzinski and
asu ments at 880 MeV and
e er-energy part of the
these reactions.
luction of ^{7}Be from nitrogen,
s at 450 MeV and 2950 MeV



d of ^{22}Na from argon.

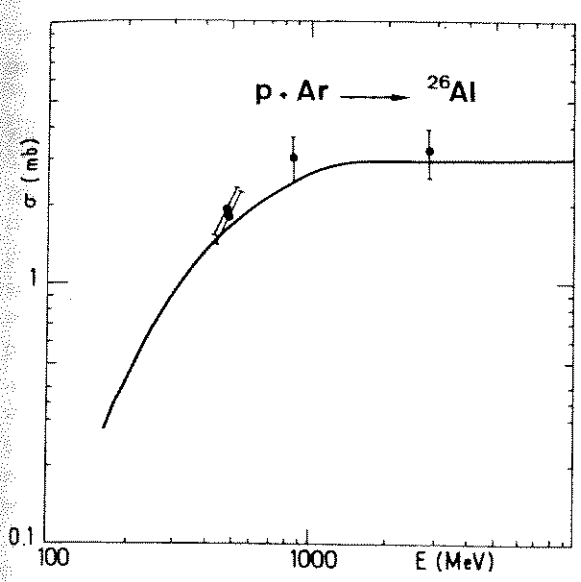


Fig. 3. Cross sections for production of ^{26}Al from argon. Symbols as in Fig. 1.

are in reasonable agreement with the excitation function proposed by Radin et al. [19].

Although the productions of ^{7}Be and ^{22}Na are important in the study of air masses, our discussion will

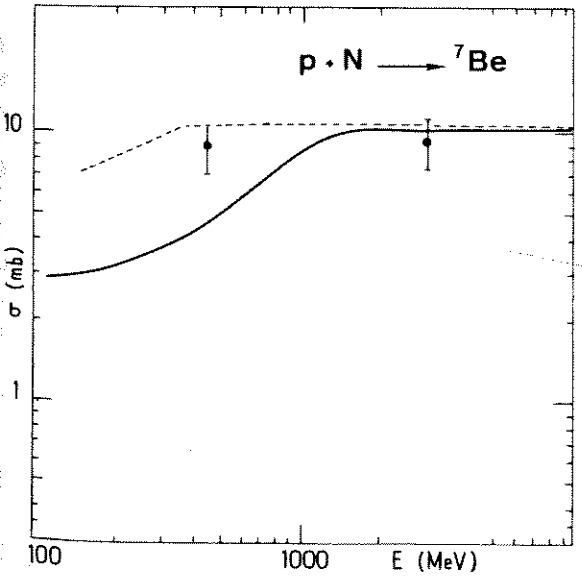


Fig. 4. Cross sections for production of ^{7}Be from nitrogen. Solid line as in Fig. 1; dashed line was proposed by Radin et al. [19] from numerous experimental results.

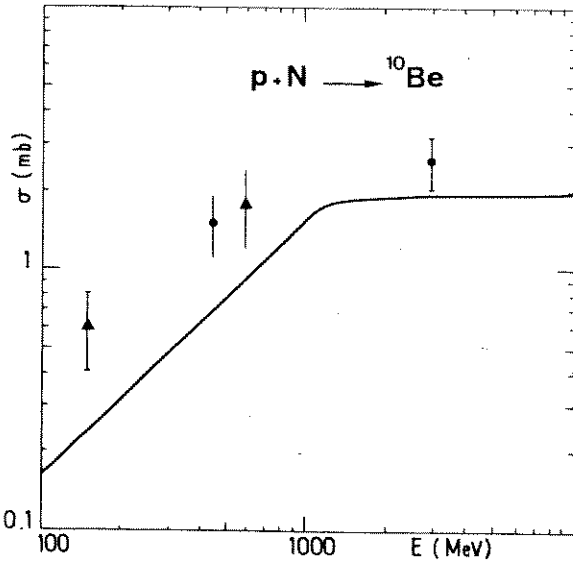


Fig. 5. Cross sections for production of ^{10}Be from nitrogen. ▲ = Raisbeck and Yiou [23,24]; ● = this work; solid line as in Fig. 1.

focus on the production of long-lived nuclides ^{10}Be and ^{26}Al.

4.1. Production of ^{10}Be from nitrogen

Our measurement of the cross section for $^{14}N(p,x)^{10}Be$ at 450 MeV is in good agreement with the results of Raisbeck and Yiou [23,24] (Fig. 5). For this reaction, we also measured the cross section at 2950 MeV, which completes the higher-energy par of the excitation function. The experimentally measured cross sections of this reaction are somewhat larger than the calculated cross sections according to Silberberg and Tsao's formula, especially at the lower energies.

We calculated the production rate of ^{10}Be in the atmosphere with Yokoyama et al.'s model [21] by provisionally adopting the experimentally measured cross sections for $^{14}N(p,x)^{10}Be$ and $^{16}O(p,x)^{10}Be$ reactions.

A value of $(2.1 \pm 0.5) \times 10^{-2}$ atoms cm^{-2} s^{-1} is obtained. To this value should be added an uncertainty in the half-life of ^{10}Be (about 10–20%): $(1.5 \pm 0.3) \times 10^{6}$ years by Yiou and Raisbeck [26] and $(1.48 \pm 0.15) \times 10^{6}$ years by Makino et al. [28].

The production rates of ^{10}Be from other sources

than that of atmospheric production were estimated to be negligible: less than 1.7×10^{-4} atoms cm^{-2} s^{-1} for the sum of non-atmospheric productions [15]. Therefore we can compare the atmospheric production rate of ^{10}Be with results of ^{10}Be measurements in marine sediments, ices and rain water. Most of the results available until now were obtained from marine sediments. A compilation of the literature values on the distribution of ^{10}Be fluxes as a function of latitude for 18 oceanic cores is given in Fig. 6. The obtained distribution does not show clear evidence of the variation of ^{10}Be fluxes with latitude. Such a variation would be expected if the ^{10}Be fluxes at the bottom of ocean reflect the pattern of radioactive fallout from stratospheric origin [22]. Two points in Fig. 6 (points *16* and *17*) which indicate very low flux at high latitudes were obtained in Arctic Ocean and this anomalously low flux can be explained by other effects than that of latitude [31]. When ^{10}Be enters in ocean water, the behaviour of this nuclide is controled by chemical and biological effects and therefore the ^{10}Be precipitation rates to the bottom of ocean can be modified by these effects during the residence time of ^{10}Be in the oceans. The estimation of this residence time [10,11] has yet a large uncertainty but suggests a sufficiently long time to erase the atmospheric fallout distribution.

The average ^{10}Be flux in 18 oceanic cores is 2.6×10^{-2} atoms cm^{-2} s^{-1} which is comparable to our calculated flux.

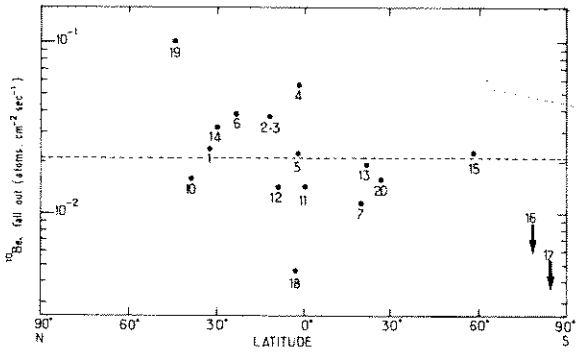


Fig. 6. Measured and calculated deposition rate of ^{10}Be in marine sediments. *1–10*, nomenclature used in Tanaka and Inoue [7]; *11–17*, as in Finkel et al. [31]; *18* = core Nova IV 13 calculated by Guichard [15]; *19* = Raisbeck et al. [6]; *20* = Guichard [15]. Dashed line is the average calculated production rate from measured cross section.

Two measurements of ^{10}Be in ice were carried at very different locations. The result of McCorke al. [4] at Greenland, 2×10^{-2} atoms cm^{-2} s^{-1}, is agreement with our calculated flux. However, the obtained by Raisbeck et al. [5] at an Antarctic sta tion, 3.1×10^{-3} atoms cm^{-2} s^{-1} is musch lower. R beck et al. attribute this low flux to the very low precipitation rate at the Antarctic station.

In regard to rain water, only one series of meas ments is available [25]. The average ^{10}Be flux was 4.2×10^{-2} atoms cm^{-2} s^{-1}, which is in agreemen with our estimation within a factor of two. The ra active fallout rate can vary with a factor of two, o more, according to local meteorological condition

Yiou and Raisbeck [26] suggested that in the p ticular case of ^{10}Be formed from ^{16}O and ^{14}N, the neutron induced reactions have quite possibly larg cross sections than those induced by protons. Sinc the neutron-induced reactions are important for t ^{10}Be production in the atmosphere, they conclude that the calculations based on proton cross section were underestimated.

In meteorites, however, the calculations based proton cross sections are in excellent agreement w measured activities of ^{10}Be (to be published else- where), although neutron-induced reactions for ^{16} are important in meteorites. This fact suggests tha least for ^{16}O, neutron-induced reactions do not ha different cross sections from those induced by pro tons. Concerning neutron-induced production of ^{1} from nitrogen, however, we cannot arrive at a con sion because we lack such a comparison. Therefore we consider the calculated ^{10}Be production rate b on proton cross sections as a lower limit.

4.2. Production of ^{26}Al from argon

We report here first experimental measurement of the excitation function of ^{26}Al production fro argon. We compared our experimental results to th calculated values according to Silberberg and Tsao formula [18]. They used interpolated parameters i their formula for the atomic numbers of targets (Z between 17 and 20 because of the scarcity of expe mental results in this region. The calculated cross s tions for the products of argon might therefore ha a large uncertainty. Our experimental results, how- ever, show a good agreement with the calculated

f ^{10}Be in ice were carried out
ns. The result of McCorkell et
10^{-2} atoms cm^{-2} s^{-1}, is in
ulated flux. However, the flux
al. [5] at an Antarctic sta-
m^{-2} s^{-1} is musch lower. Rais-
low flux to the very low
Antarctic station.
r, only one series of measure-
The average ^{10}Be flux was
s^{-1}, which is in agreement
in a factor of two. The radio-
ry with a factor of two, or
meteorological conditions.
6] suggested that in the par-
ed from ^{16}O and ^{14}N, the
is have quite possibly larger
induced by protons. Since
tions are important for the
tmosphere, they concluded
d proton cross sections

r, the calculations based on
in excellent agreement with
Be (to be published else-
-induced reactions for ^{16}O
tes. This fact suggests that at
duced reactions do not have
om those induced by pro-
-induced production of ^{10}Be
we cannot arrive at a conclu-
a comparison. Therefore
d ^{10}Be production rate based
as a lower limit.

rom argon

perimental measurements
of ^{26}Al production from
experimental results to the
g to Silberberg and Tsao's
interpolated parameters in
nic numbers of targets (Z)
se of the scarcity of experi-
on. The calculated cross sec-
argon might therefore have
mental results, how-
ent with the calculated

cross sections (Table 2 and Fig. 3). Nevertheless, it should be noted that ^{26}Al has a short-lived isomer, ^{26m}Al ($T_{1/2}$ = 6.4 seconds), which decays directly to ^{26}Mg without contributing to the production of ^{26}Al. The experimental cross sections correspond to the production of ^{26}Al alone, whereas the calculated cross sections correspond to the sum of ^{26}Al + ^{26m}Al productions, as it was pointed out by Raisbeck et al. [20]. Therefore, agreement between the experiment and the calculation cannot be confirmed unless the cross sections for production of ^{26m}Al are negligible.

As concerns the production of ^{26}Al in the atmosphere, the estimated production rates based on the calculated cross sections according to Rudstam's formula or the improved version of Silberberg and Tsao are not free from the uncertainty due to ^{26m}Al. It should therefore be emphasized that the present measurements of ^{26}Al production cross section completely eliminate this uncertainty.

We applied our experimental cross sections to Yokoyama et al.'s model [21] which describes the interaction of GCR with matter, and calculated the production rate of ^{26}Al in the atmosphere: $(1.1 \pm 0.3) \times 10^{-4}$ atoms cm^{-2} s^{-1}. This value is slightly lower than the value estimated from Rudstam's formula by Lal and Peters [22]: 1.4×10^{-4} atoms cm^{-2} s^{-1}.

This production rate is lower by two orders than that of ^{10}Be. Therefore the contribution of other sources than the atmospheric production could be non-negligible for the production of ^{26}Al. For example, Lal and Venkatavaradan [29] calculated an influx of 1.2×10^{-3} atoms cm^{-2} s^{-1} due to cosmic dust-bearing ^{26}Al, assuming a cosmic dust flux of 1000 tons per day on the earth surface. However, our calculation based on the present cosmic dust flux measured by Apollo window programme, gave much les ^{26}Al influx with cosmic dust: 10^{-5} atoms cm^{-2} s^{-1} [3]. The measurement of the ^{26}Al/^{10}Be ratio in marine sediments is therefore useful to evaluate the cosmic dust flux in the past million years.

4.3. Production ratio ^{26}Al/^{10}Be

We obtained a ratio of $(5.2 \pm 1.9) \times 10^{-3}$ for the atmospheric production from the fluxes calculated in the preceding chapter. This ratio corresponds to a lower limit because of the reasons discussed in section 4.1.

Lal [30] proposed the use of ^{26}Al/^{10}Be ratio to the dating of marine sediments, because by taking the ratio of two nuclides, one can eliminate the uncertainties due to the variations of cosmic ray flux in the past and to the variations of the physico-chemical and biological conditions which control the precipitation of these cosmonuclides. His proposition can be valid only if the two nuclides have their origin principally in the atmospheric production. The measured ratios in marine sediments $(6.7 \pm 3.3) \times 10^{-3}$ [3,14], $(5.2 \pm 1.9) \times 10^{-3}$ [14], and in Greenland ice $(5.2 \pm 2.8) \times 10^{-3}$ [4,14] are in good agreement with the production ratio in the atmosphere and show that the contribution of the atmospheric production dominates over those from other sources. The measured ratio in manganese crusts $(6.7 \pm 3.8) \times 10^{-3}$ [9,15], in agreement with the ratio in marine sediments, indicates that the two nuclides show a similar behaviour in marine environments, which is also a necessary condition to the use of ^{26}Al/^{10}Be ratio for dating. In this regard, the progress of new and much more sensitive techniques to detect these nuclides [32] will promote the development of the use of ^{26}Al/^{10}Be ratio.

Acknowledgements

We thank M. Lefort who motivated us to carry out this work, J. Labeyrie for his encouragement, G.M. Raisbeck and F. Yiou for helpful discussions, G. Valladas and the synchroton crew at Centre d'Etudes Nucléaires de Saclay for irradiation facilities.

References

1 J.R. Arnold, ^{10}Be produced by cosmic rays, Science 124 (1956) 584.
2 P.S. Goel, D.P. Kharkar, D. Lal, A. Narsappaya, B. Peters and V. Yatirajam, The ^{10}Be concentration in deep-sea sediments, Deep-Sea Res. 4 (1957) 202.
3 J.-L. Reyss, Y. Yokoyama and S. Tanaka, ^{26}Al in deep-sea sediment, Science 193 (1976) 1119.
4 R. McCorkell, E.L. Fireman and C.C. Langway, Jr., ^{26}Al and ^{10}Be in Greenland ice, Science 158 (1967) 1690.
5 G.M. Raisbeck, F. Yiou, M. Fruneau, M. Lieuvin and J.-M. Loiseaux, Measurement of ^{10}Be in 1000 and 5000 year old Antarctic ice, Nature 275 (1978) 731.
6 G.M. Raisbeck, F. Yiou, M. Fruneau, J.-M. Loiseaux, M.

Lieuvin and J.-C. Ravel, Search in a marine sediment core for ^{10}Be concentration variations during a geomagnetic field reversal, Geophys. Res. Lett. 6 (1979) 717.
7 S. Tanaka and T. Inoue, ^{10}Be dating of North Pacific sediment cores up to 2.5 million years B.P., Earth Planet. Sci. Lett. 45 (1979) 181.
8 B.L.K. Somayajulu, ^{10}Be in a manganese nodule, Science 156 (1967) 1219.
9 F. Guichard, J.-L. Reyss and Y. Yokoyama, Growth rate of manganese nodule measured with ^{10}Be and ^{26}Al, Nature 272 (1978) 155.
10 Y. Yokoyama, F. Guichard, J.-L. Reyss and Nguyen Huu Van, Oceanic residence times of dissolved beryllium and aluminium deduced from cosmogenic tracers ^{10}Be and ^{26}Al, Science 201 (1978) 1016.
11 G.M. Raisbeck, F. Yiou, M. Fruneau, J.-M. Loiseaux and M. Lieuvin, ^{10}Be concentration and residence time in the oceans, Earth Planet. Sci. Lett. 43 (1979) 237.
12 R.L. Brodzinski and N.A. Wogman, High energy proton spallation of argon, Phys. Rev. C I (1970) 1955.
13 N. Bourelly and N. Deschamps, Etude du comportement des métaux alcalins sur pentoxyde d'antimoine hydraté, J. Radioanal. Chem. 8 (1971) 303.
14 J.-L. Reyss, L'aluminium 26 empreinte du rayonnement cosmique pour le million d'années passées, Thesis, Université d'Orsay Paris-Sud (1977); Note CEA N2018 (1978).
15 F. Guichard, De l'utilisation du ^{10}Be à des fins de datation dans des matériaux marins, Thesis, Université de Paris VII (1980).
16 J. Tobailem, C.H. Lassus St. Genies and L. Leveque, Sections efficaces des réactions nucléaires induites par protons, deutons, particules α, I. Réactions nucléaires moniteurs, Commissariat à l'Energie Atomique (France), Note CEA N1466 (1971).
17 H.R. Heydegger, A.L. Turkevich, A. Van Ginneken and P.H. Walpole, Production of ^{7}Be, ^{22}Na and ^{28}Mg from Mg, Al and SiO_2 by protons between 82 and 800 MeV, Phys. Rev. C 14 (1976) 1506.
18 R. Silberberg and C.H. Tsao, Partial cross sections in high energy nuclear reactions and astrophysical applications: targets with $Z \leqslant 28$, Astrophys. J. Suppl. Ser. 220 (I), 25 (1973) 315.
19 J.R. Radin, E. Gradsztajn and A.R. Smith, ^{7}Be production cross section in N, C, ^{11}B and ^{10}B with 740 MeV protons, Phys. Rev. C 20 (1979) 787.
20 G.M. Raisbeck, C. Meninga, R. Brodzinski and N. Wogman, Cross section for the production of ^{26}Al from targets of Si, Al and Fe irradiated by protons of 600 MeV 15th Int. Cosmic Ray Conf., Plovdiv 1977, O.G. 143 (in press).
21 Y. Yokoyama, J. Sato, J.-L. Reyss and F. Guichard, Variation of solar cosmic ray flux deduced from ^{22}Na-^{26}Al data in lunar samples, Proc. 4th Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4 (1973) 2209.
22 D. Lal and B. Peters, Cosmic ray produced radioactivity on the Earth, in: Handbuch der Physik, K. Sitte, ed. (Springer, Berlin, 1967) 46, 2, 551.
23 G.M. Raisbeck and F. Yiou, Cross sections for the spallation production of ^{10}Be in targets of N, Mg and Si and their astrophysical applications, Phys. Rev. C 9, 4 (1974) 1385.
24 G.M. Raisbeck and F. Yiou, in: Spallation Nuclear Reactions and Their Applications (Reidel, Dordrecht, 1976) 83.
25 G.M. Raisbeck, F. Yiou, M. Fruneau, J.-M. Loiseaux, M. Lieuvin and J.-C. Ravel, Deposition and seasonal variations in precipitation of cosmogenic ^{10}Be, Nature 282 (1979) 279.
26 F. Yiou and G.M. Raisbeck, Half-life of ^{10}Be, Phys. Rev. Lett. 29 (1972) 372.
27 V.S. Venkatavaradan, Isotopic changes induced by cosmic rays interplanetary matter, Thesis, Bombay (1970).
28 T. Makino, R. Gensho and M. Honda, Preparation of ^{10}Be and the measurement of the isotopic ratio of beryllium, Mass Spectrosc. 23 (1975) 33.
29 D. Lal and V.S. Venkatavaradan, Activation of cosmic dust by cosmic ray particles, Earth Planet. Sci. Lett. 3 (1967) 299.
30 D. Lal, Cosmic ray produced radionuclides in the sea, J. Oceanogr. Soc. Japan, 20th Anniv. (1962) 600.
31 R. Finkel, S. Krishnaswami and D.L. Clark, ^{10}Be in Arctic Ocean sediment, Earth Planet. Sci. Lett. 35 (1977) 199.
32 G.M. Raisbeck, F. Yiou and C. Stephan, ^{26}Al measurement with a cyclotron, J. Phys. Lett. 40 (1979) 241.