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Solar and galactic cosmic-ray records of the Fermo (H) chondrite regolith breccia

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Abstract–We demonstrate the presence of solar flare as well as neutron capture effects in the isotopic composition of rare gases in the Fermo regolith breccia acquired on its parent body based on the measurements of tracks, rare gases and radionuclides. The track density along a 3.2 cm long core decreases by a factor of about 6 and by more than a factor of 13 within the meteorite, indicating small (2–9 cm) and asymmetrical ablation. Rare gases show a large trapped component; the isotopic ratios, particularly $^{20}Ne/^{22}Ne \simeq 11$ and $^{20}Ne/^{36}Ar = 10$ are indicative of a solar component. The galactic cosmic-ray exposure age is determined to be 8.8 Ma. Activities of a dozen radionuclides ranging in half-life from 16 day ^{48}V to 0.73 Ma ^{26}Al are consistent with their expected production rates. Track, rare gas and radionuclide data show that the meteoroid was a small body ($\leq$120 kg) and had a simple, one-stage exposure history to cosmic rays in the interplanetary space. However, ^{82}Kr and ^{128}Xe show an excess due to neutron irradiation on the parent body of the meteorite. The presence of solar gases and the neutron capture effects indicate several stages of irradiation on the parent asteroid. The chemical composition of Fermo confirms that it belongs to the H group of ordinary chondrites with lithic clasts having varying compositions. $\delta^{15}N$ is found to be 8.3 ± 1.2‰, close to the typical values observed in H chondrites.

INTRODUCTION AND SAMPLE DETAILS

The Fermo meteorite fell on 1996 September 25 at 15:30 U.T. in central Italy (13°45'12" E, 43°10'52" N). A fully crusted, single stone weighing 10.2 kg was recovered a few days later. Molin *et al.* (1997), based on mineral composition, classified it as H5 brecciated chondrite containing H3 and H4 lithic clasts. The conditions of fall and recovery and petrography have been described by Molin *et al.* (1997) and Cevolani *et al.* (1997). The meteorite was cut into two parts along I'R' (Fig. 1): the main mass (A) and the smaller (B), weighing about 800 g. The piece B was kindly made available to us by the Mayor of Fermo for the present study. We have made a series of studies which include major and trace element composition, track density profile, isotopic composition of rare gases and radioactivity. The radioactivity measurements were made on the whole piece B by nondestructive gamma counting. An interior sample from near the cut face (Z') was used for rare gas measurements whereas for tracks, a few near-surface samples from both the pieces and a core from stone B, were analyzed (Fig. 1).

We have also measured the major and trace element composition to confirm its chemical classification as well as to calculate the radionuclide production rates. These results are described here. Some of the preliminary results have been presented earlier (Murty *et al.*, 2001).

CHEMICAL ANALYSIS

Several small samples (typically 50 mg) were taken for chemical analysis. The concentrations of Fe, Mg, Al, Ni, Mn, Cr, K and Ti were measured by GF-AAS or inductively coupled plasma-mass spectrometry (ICP-MS) at the Joint Research Center of European Union, Ispra, Italy, in a clean room. Trace element analysis was carried out for five spot samples (40 to 76 mg) by neutron activation analysis using the procedure of Shukla *et al.*, 1997. The concentrations given in Table 1 are averages of all the measurements except two analyses discussed below. The concentration of various siderophile elements (Fe, Ni, Co, *etc.*) confirm that Fermo belongs to the H group of ordinary chondrites, in agreement with the classification based on petrography and mineralogical studies (Molin *et al.*, 1997). The average value of Fe (29%) appears to be higher than those observed for most of the H chondrites, but is similar to some meteorites like Allegan (H5), Mianchi (H5) and Richardton (H5) (Kallemeyn *et al.*, 1989). Various siderophile elements (Fe, Ni, Co, Ir and Os) show significant differences in their

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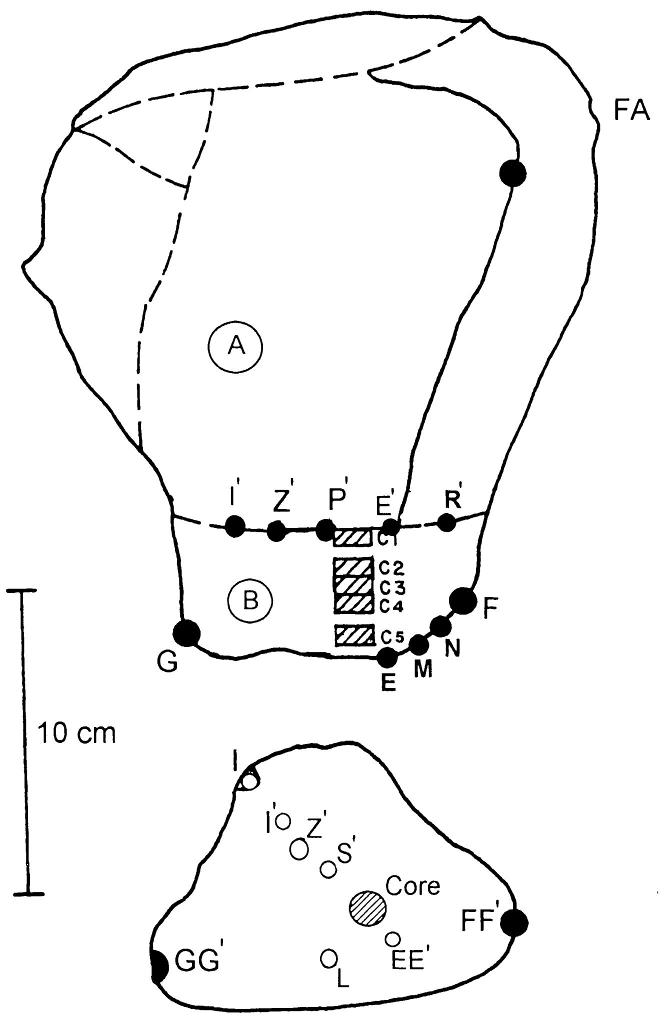

FIG. 1. Locations of surface and core samples in the Fermo chondrite. The sketch at the bottom shows top view of piece B which was counted for gamma-radioactivity.

TABLE 1. Chemical composition of the Fermo meteorite.*

Element	Average composition
Fe (%)	29.0
Mg (%)	11.3
Ni (%)	1.82
Ca (%)	1.57
Al (%)	1.08
Cr (μg/g)	3546
Na (μg/g)	5738
Mn (μg/g)	2267
K (μg/g)	660
Ti (μg/g)	553
Co (μg/g)	1081
Sc (μg/g)	7.1
La (μg/g)	0.48
Sm (μg/g)	0.17
Eu (μg/g)	0.08
Ir (ng/g)	904
Os (ng/g)	1082
Au (ng/g)	213

*Allende and Dhajala meteorites and USGS terrestrial reference materials W2 and BCR-1 were used as standards for INAA and ICPAES/AAS analyses. For ICPMS and GF-AAS, the concentrations and reproducibility of results were verified by NIST standards. The errors in concentration for the elements are ≤5% except for Os where it is ~10%.

concentrations among various samples. However, samples with higher concentrations of Fe and Ni show higher values for other siderophiles (Co, Ir, Os) as well. In particular, samples taken from below the crustal and cut faces of piece B (Fig. 1) show these large variations. This may be due, in part, to the brecciated nature of the rock containing different lithic clasts, although we must bear in mind that the small amount of each sample used may not be representative of the bulk composition. In two of the analyses, we found Fe (21.8% and 22.3%), Ni (1.24% and 1.27%) and Co (570 and 580 ppm), which are almost identical to the average L chondrite composition (Fe = 21.6%, Ni = 1.23% and Co = 600 ppm; Kallemeyn *et al.*, 1989), thus indicating the presence of an L type clast in this H chondrite. These values have not been included in computing the average composition given in Table 1.

TRACK DENSITY MEASUREMENTS

Five near-surface samples, below the crust from several locations of piece A (FA) and B and one interior piece from the cut face (Z') were studied for tracks (Fig. 1). Track densities were measured in olivine and pyroxene grains using standard procedures (Bhandari *et al.*, 1980). For revelation of tracks, we used boiling WN solution (40% EDTA+1% oxalic acid and orthophosphoric acid, made to pH 8 by adding NaOH; Krishnaswami *et al.*, 1971) for 4.5 h for olivines and 30 M boiling NaOH solution for 90 min for pyroxenes. The preliminary results showed a factor of 13 gradient in track density within the meteorite. Therefore, it was considered desirable to take a core along the direction of the steepest gradient from stone B. For this purpose a 6 mm diameter, 32 mm long core was taken as shown in Fig. 1. The core was divided in five sections (C1 to C5) and the depth profile of the tracks was obtained. The results are given in Table 2. Differing track recording sensitivity of the pyroxenes and olivines typically result in a factor of 2 higher track density in pyroxenes. We adopt an exposure age of 8.8 Ma for Fermo based on cosmogenic rare gas data, as discussed later. The track production rates and ablation calculated using the procedure of Bhandari *et al.* (1980) are given in Table 2. These track production rates are calculated from the track densities in pyroxenes, and where they are not available, from the track densities measured in olivines, after they have been corrected for their sensitivity. The track density profile in the core and along the measured samples is shown in Fig. 2, along with the track production profiles, given by Bhandari *et al.* (1980). The

TABLE 2. Track densities in surface and core samples in olivines and pyroxenes of the Fermo meteorite.

Sample	Depth* (cm)	Track density (# of tracks) (cm^{-2})		Track production rate (cm^{-2} Ma^{-1})	Mean shielding depth (cm)
		Olivines	Pyroxenes		
FA	21.5	2.5×10^5 (84)	4.1×10^5 (26)	4.7×10^4	8.7 ± 1.3
Z'	4.5	–	1.1×10^5 (76)	1.3×10^4	13.2 ± 2.4
C1	3.15 ± 0.15	0.4×10^6 (79)	–	9.1×10^4	6.2 ± 0.6
C2	2.15 ± 0.25	0.48×10^6 (217)	–	1.1×10^5	5.8 ± 0.7
C3	1.5 ± 0.4	0.65×10^6 (78)	–	1.5×10^5	4.9 ± 0.5
C4	0.95 ± 0.15	1.3×10^6 (436)	–	2.9×10^5	3.5 ± 0.4
C5	0.15 ± 0.15	1.9×10^6 (341)	–	4.3×10^5	2.8 ± 0.2
E	~0.3	2.7×10^6 (136)	5.12×10^6 (789)	5.8×10^5	2.2 ± 0.2
F	~0.3	2.2×10^6 (200)	4.73×10^6 (1835)	5.4×10^5	2.2 ± 0.2
G	~0.3	–	3.8×10^6 (697)	4.3×10^5	2.8 ± 0.2
I	~0.3	0.7×10^6 (NR)	–	1.6×10^5	4.8 ± 0.3

*Measured from the crustal face of piece B.
NR = not recorded.

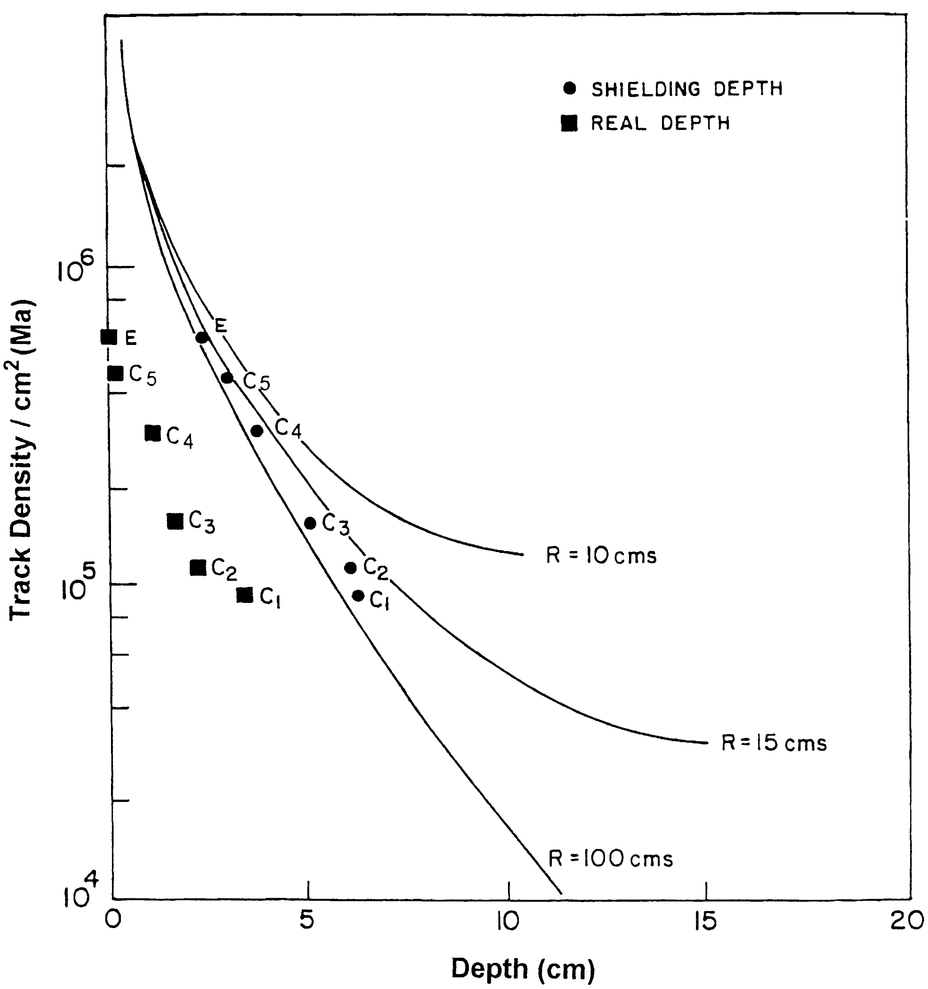

FIG. 2. Track density profile in Fermo. Squares represent actual depth along the core and circles represent deduced shielding depth in the interplanetary space. Theoretical profiles for spherical bodies (10, 15 and 100 cm radii) are shown for comparison (after Bhandari *et al.*, 1980).

profiles indicate an ablation of about 2 cm on face of the fragment B. The shielding depths are small, indicating that the crustal face of fragment B did not suffer much ablation. It was probably located on the rear of the meteorite while it was passing through the atmosphere. The crustal face of piece A, opposite to the piece B, had the highest ablation, about 8.7 cm and must have been the leading face. The meteorite belongs to ablation class I of Bhandari *et al.* (1980). The mass ablation of the meteorite is calculated to be about 92%, indicating that it entered the Earth's atmosphere with a velocity of about 19 km/s, as calculated from the ablation models of Potdar (1981).

COSMOGENIC RADIONUCLIDES

Piece B of Fermo was made available to us for nondestructive measurement of radioactivity about three weeks after the fall. Although the radionuclides of a few days half-life had decayed by that time, ^{48}V ($t_{½}$ = 16 days) and other gamma-emitting radioisotopes of longer half-life could be measured using a large volume (248 cm^3) hyperpure Ge-NaI(Tl) coincidence spectrometer in the underground Laboratory of Monte dei Cappuccini in Torino (Bonino *et al.*, 1992). Procedures of Bhandari *et al.* (1989) using inherent ^{40}K as an internal gamma ray standard for determining the counting efficiency were followed for estimating the radioactivity level of each radioisotope.

The activities, decay corrected to the time of fall, are listed in Table 3. These activities can be compared with the depth and size-dependent production rates calculated in stony meteoroids using a variety of models (*e.g.*, Reedy and Arnold, 1972; Bhandari, 1986; Graf *et al.*, 1990; Michel *et al.*, 1991; Masarik and Reedy, 1994). Comparison of the measured activities with the production rates calculated using a physical model for ^{22}Na and ^{26}Al (Bhandari *et al.*, 1993; Leya *et al.*, 2000), ^{44}Ti (Michel and Neumann, 1998), ^{54}Mn and ^{60}Co (Michel and Leya, pers. commun., 1999) are consistent with a spherical meteoroid of radius R = 15–25 cm and a shielding depth of 5–10 cm. In Table 3, we also compare the activities with that measured in the Torino H6 meteorite that fell in 1988, nearly 10 years before Fermo and during a similar rising phase of the previous solar cycle (cycle 21). Activities of most of the radioisotopes in Fermo and Torino are generally similar, except for the neutron capture isotope, ^{60}Co. The low activity of ^{60}Co in Fermo is consistent with the track data discussed above and the conclusion that the piece B had suffered a small ablation of 2 or 3 cm, as compared to Torino which had similar preatmospheric size but larger ablation of about 14 cm. The ratio of $^{22}Na/^{26}Al$ of 1.52, which is nearly independent of shielding depth but depends on the phase of the solar cycle at the time of fall is again close to the expected value as well as to the value observed in Torino (1.47). The ^{44}Ti (1.26 dpm/kg) is also in agreement with the expected value calculated on the basis of the century scale modulation of galactic cosmic rays (GCR) (Bonino *et al.*, 1995).

RARE GASES

The isotopic composition of rare gases He, Ne, Ar, Kr and Xe as well as nitrogen were measured in the interior piece (Z') of the meteorite (Fig. 1). The shielding depth of this sample is

TABLE 3. Cosmogenic radionuclides in the Fermo meteorite at the time of fall.

Isotope	E_γ (keV)	Half-life	Main target elements	Counts per minute*	Activity	
					Fermo (dpm/kg)	Torino† (dpm/kg)
^{48}V	983.50	15.97 d	Ti, Fe, Ni	0.068 ± 0.003	28 ± 2	20.8 ± 1.5
	1312.10	–	–	0.059 ± 0.003	–	–
^{51}Cr	320.07	27.70 d	Fe, Ni, Co	0.047 ± 0.002	88 ± 7	76 ± 7
^{7}Be	477.59	53.29 d	O, Mg, Si, Al	0.075 ± 0.002	79 ± 2	59 ± 6
^{58}Co	810.77	70.86 d	Fe, Ni	0.090 ± 0.002	10.9 ± 0.2	11 ± 0.7
^{56}Co	846.70	77.27 d	Fe, Ni	0.060 ± 0.001	7.9 ± 0.2	7.7 ± 0.8
^{46}Sc	889.26	83.79 d	Ti, Fe, Ni	0.097 ± 0.002	11.8 ± 0.2	10 ± 2
^{57}Co	122.06	271.74 d	Fe, Ni	0.296 ± 0.004	13.6 ± 0.2	16 ± 1
^{54}Mn	834.83	312.30 d	Fe, Ni, Mn	1.689 ± 0.004	114.6 ± 0.3	121 ± 2
^{22}Na	1274.51	2.61 y	Mg, Al, Si	0.855 ± 0.003	86.7 ± 0.3	78.3 ± 0.9
^{60}Co	1173.23	5.27 y	Co, Ni	0.0102 ± 0.008	0.82 ± 0.06	2.8 ± 0.3
	1332.51	–	–	0.0106 ± 0.008	0.89 ± 0.06	–
$^{44}Ti(^{44}Sc)$	1157.0	59.2 y	Fe, Ni, Ti	0.0034 ± 0.0003	1.26 ± 0.11	1.2 ± 0.2
^{26}Al	1808.65	7.4×10^5 y	Mg, Al, Si	0.487 ± 0.002	57.0 ± 0.3	53.1 ± 0.5

*At the time of measurement.
†Bhandari *et al.* (1989).

estimated to be ~13 cm (Table 2). The measurements were made on a VG1200 mass spectrometer following the standard procedures described in Murty *et al.* (1998). Briefly, the sample was combusted at 400 °C in 2 torr of O_2, primarily to release surficial contaminants. Gases were then extracted at 1000 °C and 1600 °C by pyrolysis. The data reported here have been corrected for blanks (<5% in all cases), instrumental mass discrimination and interferences as detailed in Murty *et al.* (1998). In the case of Kr, we could not get meaningful data for ^{78}Kr (due to background interference at mass 78 in the mass spectrometer) and ^{80}Kr (due to large contribution from $^{40}Ar_2^+$, as a result of inefficient Ar/Kr separation).

Solar Components in the Light Noble Gases

The He, Ne and Ar data are presented in Table 4. Whereas He is predominantly composed of radiogenic (^{4}He) and cosmogenic (^{3}He) components, the isotopic ratios of ^{20}Ne/^{22}Ne and ^{38}Ar/^{36}Ar indicate the presence of both the trapped as well as cosmogenic components. On a three isotope diagram the Ne data fall in the enclosure bound by the three components, solar wind (SW), solar energetic particles (SEP) and GCR-spallation (Fig. 3) indicating that the composition of trapped Ne in Fermo is close to solar but much above Ne-Q or Ne-A (planetary Ne), usually observed in ordinary chondrites. The 400 °C fraction might have a small air contribution (as clearly seen in Kr and Xe isotopic data), lowering the ^{20}Ne/^{22}Ne. The 1000 and 1600 °C points scatter within the triangle enclosed by SW, SEP and spallation end members indicating a variable admixture of these components in each temperature fraction. On correcting for spallation Ne, we derive (^{20}Ne/^{22}Ne) ≈ 11 which is typical of solar component. The ratio $(^{20}Ne/^{36}Ar)_T$ turns out to be ~10, which is different from the planetary ($(^{20}Ne/^{36}Ar)_T < 1$) or solar ($(^{20}Ne/^{36}Ar)_T \approx 36$) ratio, indicating that Ne and Ar are a mixture of both solar and planetary components. However, it may be noted that the solar component in (^{4}He/^{20}Ne) is not clearly identifiable. The measured (^{4}He/^{20}Ne) ≈ 100 and most or all of ^{4}He can be accounted for by the radiogenic production. Absence of a solar component in ^{4}He, therefore, indicates loss of trapped ^{4}He shortly after the solar irradiation. Considering the fact that Fermo is a regolith breccia and contains H3–H6 and possibly L clasts, the presence of solar gases acquired in certain clasts on the parent body would be expected. The amount of trapped ^{20}Ne in Fermo is 13.6 × 10^{-8} cc STP/g which is three orders of magnitude smaller compared to the most gas-rich H-chondrite Fayetteville which had a few million years regolith exposure (Wieler *et al.*, 1989). Hence the period of surface exposure of Fermo on its parent body must be rather small (<10^4 years) which also accounts for the fact that no irradiated track-rich grains were found.

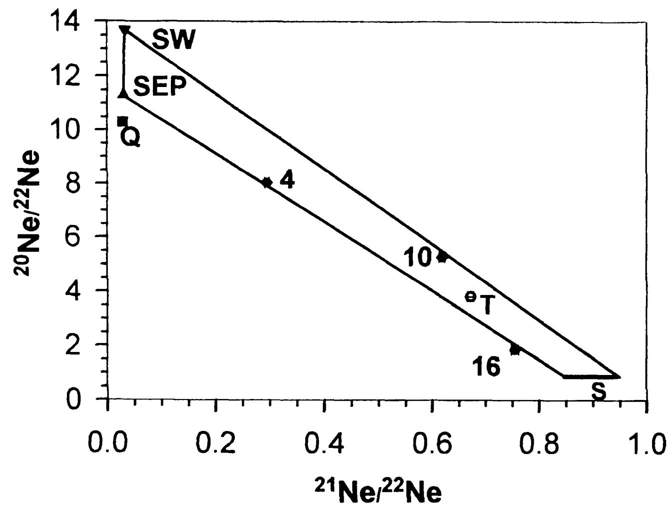

FIG. 3. Neon isotopic ratios for various temperature steps as well as the total are plotted for the Fermo meteorite. Numbers near each point indicate the corresponding extraction temperature in 100 °C. T represents total. Points for solar wind (SW), solar energetic particles (SEP), Q component as well as the range for GCR-produced Ne (S) are indicated. The data fall in the triangle enclosed by SW, SEP and S indicating the presence of solar Ne in Fermo. The 400 °C point might have a small air component (due to surface adsorption), while 1000 and 1600 °C points might have different proportions of SW/SEP components.

Cosmogenic Components, Cosmic-Ray Exposure Ages and Exposure History

The cosmogenic and radiogenic components have been estimated using the end member compositions suggested by Eugster (1988). Due to the presence of a large amount of noncosmogenic Ne, it is difficult to get a reliable value of cosmogenic $(^{22}Ne/^{21}Ne)_c$. We, therefore, use production rates

TABLE 4. Light noble gases and nitrogen content of the Fermo meteorite.*

Temp. (°C)	^{4}He (10^{-8} cc STP/g)	^{22}Ne	^{36}Ar	^{3}He/^{4}He (×10^4)	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar	N (ppm)	δ^{15}N (‰)
400	464.7	0.087	0.097	34.51 ± 2.92	8.035 ± 0.014	0.2947 ± 0.0038	0.2315 ± 0.0003	8631 ± 85	0.272	16.49 ± 1.20
1000	1156.7	2.28	0.307	62.44 ± 5.28	5.262 ± 0.019	0.6191 ± 0.0055	0.4923 ± 0.0026	7776 ± 78	0.282	22.45 ± 0.79
1600	17.5	1.84	1.202	384.9 ± 32.6	1.850 ± 0.009	0.7552 ± 0.0068	0.4043 ± 0.0003	473.5 ± 4.8	0.438	40.85 ± 0.55
Total	1639	4.21	1.606	57.96 ± 4.91	3.829 ± 0.014	0.6722 ± 0.0060	0.4107 ± 0.0007	2363 ± 24	0.992	28.94 ± 0.79

*Errors in concentrations are ±10%. Errors in isotopic ratios represent 95% C.L.

TABLE 5. Concentrations of cosmogenic and radiogenic gases and calculated exposure ages.

Concentration (10^{-8} cc STP/g)					Ages (Ma)*				
Cosmogenic			Radiogenic		Cosmic-ray exposure			Gas retention	
^{3}He	^{21}Ne	^{38}Ar	^{4}He	^{40}Ar	T_3	T_{21}	T_{38}	T_4	T_{40}
9.5	2.68	0.409	1590	3795	6.0	8.6	8.9	4000	4000

*Error in ages are estimated to be ±12%, which includes ±10% error in absolute concentration.

corresponding to the shielding depth of the sample as determined by track density discussed above. Using a value of $(^{22}Ne/^{21}Ne)_c = 1.15$ (Bhandari and Potdar, 1982; Leya *et al.*, 2000), and following the method of Eugster (1988), we determine the production rates of ^{3}He and ^{21}Ne, while for ^{38}Ar, we follow the modified procedure suggested by Marti and Graf (1992). The deduced cosmogenic contents and the estimated exposure ages are given in Table 5. While the exposure ages based on ^{21}Ne (8.6 Ma) and ^{38}Ar (8.9 Ma) are in close agreement, the ^{3}He exposure age of 6 Ma is about 25% lower, indicating partial ^{3}He loss during its cosmic-ray exposure history in the interplanetary space. We adopt the average value of ^{21}Ne and ^{38}Ar exposure ages of 8.8 Ma for Fermo in the following discussion. The isotope pair $^{26}Al/^{21}Ne$ can be used to determine whether the meteorite had a simple or a complex exposure history. The measured ratio of 0.37 is close to the expected production value (0.38; Leya *et al.*, 2000) indicating that the meteorite had a simple exposure history.

Radiogenic Components and Radiogenic Ages

Adopting the values of U = 12 ppb and Th = 42 ppb, the average concentration observed in H chondrites (Wasson and Kallemeyn, 1988), we calculate U-Th-^{4}He age of 4.0 Ga. The measured K = 660 ppm (Table 1) yields K-Ar age of 4.0 Ga for Fermo in close agreement with U-Th-^{4}He age. These values are lower than the expected age of the meteorite (4.56 Ga) indicating ^{4}He and ^{40}Ar loss early in its history, probably during the impact-induced thermal event which led to the formation of the breccia. The radiogenic ages thus indicate that the breccia must have been formed about 4 Ga ago.

Primordial Krypton and Xenon

Kr and Xe data are presented in Tables 6 and 7, respectively. The 400 °C fraction shows a dominant air contribution, probably adsorbed on the surface. Cosmogenic and radiogenic (for ^{129}Xe) components are visible in 1000 and 1600 °C fractions, although the dominant component is the primordial trapped component. The ratios $(^{84}Kr/^{132}Xe)_{trap} = 0.85$ and $(^{36}Ar/^{132}Xe)_{trap} = 85$ are within the range of values observed for primordial components. This indicates that contribution from solar gases is negligible for Kr and Xe, as also suggested by the small amount of solar ^{20}Ne ($\sim 13 \times 10^{-8}$ cc STP/g). The trapped amount of ^{84}Kr and ^{132}Xe are consistent with Fermo being classified as an H5 chondrite (Schultz *et al.*, 1990).

Neutron Effects in Krypton and Xenon

The $^{82}Kr/^{84}Kr$ ratio for the 1000 °C step is greater than the ratio $^{83}Kr/^{84}Kr$ indicating that there is excess ^{82}Kr at this temperature, over and above the expected cosmogenic $^{82}Kr_c$. From $^{83}Kr_c = 0.609 \times 10^{-12}$ cc STP/g at 1000 °C and the cosmogenic $(^{82}Kr/^{83}Kr)_c = 0.766 \pm 0.022$ as determined in the H6 San Juan Capistrano (Lavielle and Marti, 1988), we estimate the excess ^{82}Kr to be 0.484×10^{-12} cc STP/g. Similarly, the 1000 °C step of Xe also shows elevated ratio of $^{128}Xe/^{132}Xe$, accompanied by a high ratio of $^{129}Xe/^{132}Xe$, indicating that excess of ^{128}Xe is most likely related to ^{127}I. From $^{126}Xe_c = 3.7 \times 10^{-14}$ cc STP/g at 1000 °C and the ratio $(^{128}Xe/^{126}Xe)_c = 1.56 \pm 0.10$ (Hohenberg *et al.*, 1981), we derive an excess ^{128}Xe of 19.7×10^{-14} cc STP/g. As this excess ^{128}Xe is accompanied by an elevated ratio of $^{129}Xe/^{132}Xe$, due to ^{129}I decay, we attribute it to *in situ* production by ^{127}I (n,γ,β^-) ^{128}Xe. The

TABLE 6. Isotopic composition of krypton in the Fermo meteorite.

Temp. (°C)	^{84}Kr (10^{-12} cc STP/g)	^{82}Kr	^{83}Kr (^{84}Kr = 100)	^{86}Kr
400	27.2	20.06 ± 0.30	20.38 ± 0.30	30.60 ± 0.46
1000	33.2	22.59 ± 0.09	21.79 ± 0.12	31.81 ± 0.13
1600	72.7	20.55 ± 0.30	20.97 ± 0.05	30.40 ± 0.39
Total	133.1	20.96 ± 0.25	21.06 ± 0.12	30.79 ± 0.34

TABLE 7. Isotopic composition of Xenon in the Fermo meteorite.

Temp. (°C)	^{132}Xe (10^{-12} cc STP/g)	^{124}Xe (^{132}Xe = 100)	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{134}Xe	^{136}Xe
400	14.1	0.346 ± 0.017	0.469 ± 0.023	7.07 ± 0.11	98.26 ± 1.47	15.16 ± 0.23	78.07 ± 1.17	40.88 ± 0.61	33.30 ± 0.50
1000	35.9	0.674 ± 0.035	0.517 ± 0.014	8.97 ± 0.13	133.2 ± 0.5	16.36 ± 0.32	79.20 ± 0.39	39.38 ± 0.09	33.51 ± 0.24
1600	106.2	0.517 ± 0.043	0.459 ± 0.021	8.43 ± 0.07	118.2 ± 0.5	16.15 ± 0.06	81.71 ± 0.12	38.19 ± 0.09	32.70 ± 0.28
Total	156.2	0.538 ± 0.039	0.473 ± 0.020	8.43 ± 0.09	119.9 ± 0.6	16.11 ± 0.14	80.80 ± 0.28	38.71 ± 0.14	32.94 ± 0.29

^{82}Kr excess ($^{82}Kr_{exc}$) also can be similarly attributed to ^{81}Br (n,γ,β^-) ^{82}Kr. The ratio $(^{82}Kr/^{128}Xe)_{exc}$ = 2.4 is in good agreement with the expected value of 2 for the average elemental ratio of $(Br/I)_{atom}$ = 6 for H chondrites (Mason, 1979) and thermal neutron cross sections (Goebel *et al.*, 1982), further supporting the possibility that these excesses are produced by neutron capture effects. Taking the average Br (0.26 ppm) and I (68 ppb) concentration of H chondrites (Mason, 1979), and the observed excesses of ^{82}Kr and ^{128}Xe, we estimate an integrated thermal neutron density of (11 ± 4) × 10^{13} n cm^{-3}. If the production is due to epithermal neutrons (30–300 eV), the neutron density will be an order of magnitude lower. However, it may be noted that the observed ratio of $(^{82}Kr/^{128}Xe)_n$ is closer to the value expected for thermal neutrons (~2) than for epithermal neutrons (~1). It is difficult to visualise the production of excess ^{36}Ar in the reaction ^{35}Cl (n,γ,β^-) ^{36}Ar, since the expected neutron capture $^{36}Ar_{Cl}$ = 0.14 × 10^{-8} cc STP/g for $(Cl/Br)_{atom}$ = 700 (Mason, 1979) is only about 10% of the observed trapped ^{36}Ar in Fermo. However, this value appears to be consistent with the data. In view of the above discussion, we conclude that the excess ^{82}Kr and ^{128}Xe in 1000 °C step are consistent with (n,γ) effects on Br and I respectively.

Parent Body Irradiation and Neutron Exposure Ages

^{60}Co is mainly produced by thermal neutron capture in the reaction ^{59}Co(n,γ)^{60}Co. The value for ^{60}Co for Fermo is low (0.87 ± 0.02 dpm/kg; Table 3). Some of the observed activity should be due to spallation of Ni; but even if it is assumed to be entirely due to (n, γ) reaction, the corresponding neutron density in the past decade of meteorite exposure to cosmic rays is estimated to be 6 × 10^{-4} n $cm^{-3}s^{-1}$. On the other hand, to produce the observed neutron capture excess at ^{82}Kr and ^{128}Xe, during the cosmic-ray exposure in space (8.8 Ma), a neutron density of about 0.5 n $cm^{-3}s^{-1}$ is required. Such a high density of slow neutrons is possible only in a large meteoroid of >50 cm radius and not in the Fermo meteoroid, estimated to have a preatmospheric size of ~20 cm as determined from the track density data. It therefore appears that the neutron effects in rare gases were produced either on the parent body or during an earlier stage of exposure in space if the meteorite had a complex exposure history. These alternatives can be easily resolved by using isotope pairs ^{22}Na/^{26}Al/^{21}Ne. The relative values of these three isotopes is (1:0.65:1.79) close to their production ratios as discussed above. We therefore infer that the meteoroid had a simple exposure history and did not undergo any fragmentation during its interplanetary exposure. These considerations indicate that the intense neutron irradiation required to produce the ^{82}Kr and ^{128}Xe excesses occurred on the parent body under some overburden, adequate to generate slow neutrons. If the neutron irradiation occurred at a depth of peak neutron intensity in a large body (Lingenfelter *et al.*, 1972), a minimum exposure of about 10 Ma would be required to generate the observed ^{82}Kr and ^{128}Xe excesses. So far no clear evidence of neutron irradiation records for Kr and Xe on the parent body regolith have been reported in any meteorite. The only exception is the acid residue of meteorite Inman where neutron effects are most likely due to presolar irradiation (Nichols *et al.*, 1991). There is also an unexplained neutron irradiation component of early solar system era in the trapped Xe from Forest Vale Metal (FVMXe) (Kim and Marti, 1992). In conclusion, the absence of neutron produced ^{60}Co in Fermo indicates that the neutron effects at stable isotopes ^{82}Kr and ^{128}Xe are likely to have occurred on its parent body. Study of Sm and Gd isotopic systematics of Fermo will be useful in confirming these neutron effects. ^{150}Sm excesses due to parent body regolith irradiation have been demonstrated for the solar gas rich meteorites Kapoeta and Fayetteville (Rajan and Lugmair, 1988).

The value for neutron density (6×10^{-4} n cm^{-3}s^{-1}) based on ^{60}Co for Fermo can be compared with that observed in other meteorites. For example in Torino (Co = 690 ppm), the neutron density is estimated to be 3×10^{-3} n cm^{-3}s^{-1}. Torino, however, is a meteorite with very long exposure age (~50 to 80 Ma) and complex interplanetary, fragmentation history in space (Bhandari *et al.*, 1989). The complex exposure history of Torino has also been subsequently confirmed by Wieler *et al.* (1996). However, in case of Torino the neutron records refer to the exposure in the interplanetary space whereas in case of Fermo, the neutron exposure refers to irradiation on the parent body.

ISOTOPIC COMPOSITION OF NITROGEN

The isotopic composition of nitrogen is given in Table 4 and its release pattern is plotted in Fig. 4. The N content of Fermo is 1 ppm. The $\delta^{15}N$ progressively increases, starting at 16.5‰ at 400 °C, going up to 41‰ at 1600 °C due to release of cosmogenic nitrogen. Using the relation $(^{15}N/^{21}Ne)_c = 4.5 \pm 0.5$ for the average shielding depth of the sample Z' (Mathew and Murty, 1993), we estimate the cosmogenic nitrogen and correct the measured $\delta^{15}N$ to derive the composition of trapped nitrogen. Following this procedure, we deduce $\delta^{15}N_{trap} = 8.3 \pm 1.2$‰ which falls in the range of typical values observed in bulk H chondrites (Hashizume and Sugiura, 1995). The $\delta^{15}N$ in the 400 °C combustion step is much higher than the average trapped $\delta^{15}N$. As cosmogenic nitrogen can not be generally released at such low temperatures it is likely to be a trapped component from a combustible phase. Organic matter with $\delta^{15}N = 15 \pm 15$‰ is generally observed at low temperatures in ordinary chondrites (Hashizume and Sugiura, 1995). At present, it is difficult to ascertain whether this organic matter in Fermo is indigenous or terrestrial contamination but when C and H isotopic data become available, the source of organic matter can be identified.

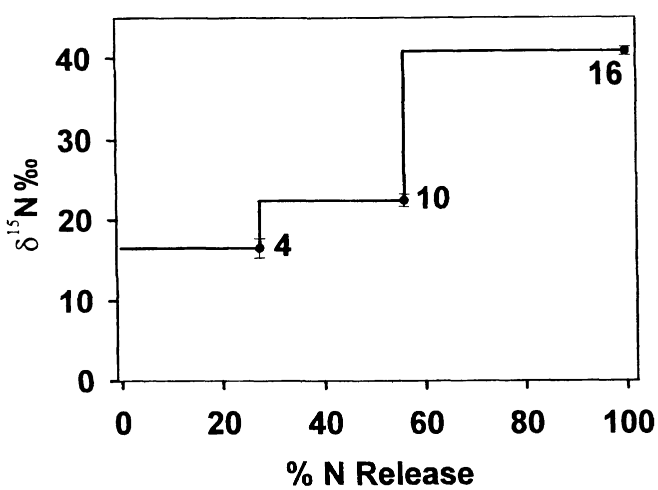

FIG. 4. $\delta^{15}N$ is plotted against the cumulative nitrogen release for the stepped temperature data of Fermo. Numbers against each point indicate temperatures in 100 °C.

SUMMARY

Radioactive as well as stable cosmic-ray spallation products (*e.g.*, ^{22}Na, ^{26}Al and ^{21}Ne) and track density measurements indicate that Fermo meteorite had a simple exposure history in interplanetary space for 8.8 Ma. However, excess of ^{82}Kr and ^{128}Xe show that the meteorite body was previously irradiated with a flux of slow neutrons. Since this flux is about 600× higher than that deduced by ^{60}Co, it implies an irradiation on the parent body shielded with suitable overburden to provide adequate flux of thermalised neutrons. In addition, the presence of a solar component ($^{20}Ne/^{22}Ne \approx 11$ and $^{20}Ne/^{36}Ar = 10$) suggest irradiation on the surface of the parent body. This is consistent with the presence of lithic clasts of different lithologies in this meteorite. Thus three stages of irradiation to cosmic rays can be envisaged for the Fermo meteorite: deep exposure (>10 Ma) on the parent body, followed by a short (~10^4 years) surface exposure on the parent body wherein solar gases were acquired and a final 8.8 Ma exposure in the interplanetary space, before it was captured by the Earth.

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