Investigations of Cosmic-Ray-Produced Nuclides in Iron Meteorites:
5. More Data on the Nuclides of Potassium and Noble Gases, on Exposure Ages and Meteoroid Sizes

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Dedicated to Professor Alfred Klemm on the occasion of his 70th birthday

The concentrations of the cosmic-ray-produced He-, Ne-, and Ar-nuclides in samples of 31 iron meteorites have been determined by mass spectrometry. Thereby, the number of samples analyzed in this laboratory has grown to 83. A critical examination of all these results was performed. The data of at least 52 samples prove to be useful to describe the "normal" abundance patterns of cosmogenic noble gases in iron meteorites; the description is accomplished by a new system of equations that correlate some properly selected abundance ratios with one another. The correlations serve as an instrument to recognize and diagnose certain abundance anomalies (^{3}He- or ^{38}Ar-deficiencies) which occur in about 25% of all samples analyzed. They allow to select those data which may unhesitatingly be applied in calculations concerning the irradiation histories of the respective meteorites. Another matter of concern for establishing these histories are the cosmic-ray-exposure ages. Mass spectrometric abundance analyses on meteoritic potassium have provided new data on the ^{41}K/^{40}K exposure ages of about 10 iron meteorites as well as on meteoroid sizes and sample depths. For two meteorites of the chemical group IIIAB, Joe Wright Mountains and Picacho, the age values obtained are 685 and 635 Ma, respectively. The results confirm our previous conclusion that the IIIAB-irons resided originally within a more or less contiguous partial volume (metallic core?) of their parent body and were ejected in consequence of a single impact event that happened about 670 Ma ago. Another motive for the present investigation was to measure the exposure ages for meteorites of the chemical groups IIICD and IIIE. However, the new information obtained on their age distributions is still inadequate to answer some old questions concerning a possible relationship to the event that produced the IIIAB-meteoroids 670 Ma ago.

1. Introduction

The interaction of cosmic rays with iron meteoroids in the interplanetary space has been the topic of our preceding papers [1–6] and is also treated here. The irradiation history of a sample of iron meteorite may essentially be characterized by three physical quantities: (1) the exposure age T, (2) the size S of the irradiated body, i.e. its pre-atmospheric mass, and (3) the depth D of the sample within that body. They define the contents of "cosmogenic" nuclides in the sample. For a given specimen, the analysis of some of these nuclides may provide information on T, S, and D. Mass spectrometric analyses of potassium and of the noble gases He, Ne, and Ar have so far delivered such data for about 60 specimens of different iron meteorites [4, 5]. We report here experiments on further samples.

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The samples are listed in Table 1. They were mainly selected with regard to the fact that most of the various "chemical groups" [7] of iron meteorites exhibit their own characteristic distributions of exposure ages, but that our previous studies of that topic [1, 3] were incomplete, particularly with regard to the small groups IIB, IIICD, IIIE, and others.

2. New noble gas measurements and new correlations between noble gas abundances

The experimental procedures applied to determine the He-, Ne-, and Ar-nuclides in iron meteorites have been described elsewhere [2, 4]. The new results are presented in Table 2; however, the data on ^{20}Ne/^{21}Ne, ^{22}Ne/^{21}Ne, and ^{40}Ar/^{38}Ar are so similar to those obtained previously and of no particular significance that they are neglected in this report. The noble gases of Unter-Mässing have been analysed in Zürich by Schultz [5], those of Bella Roca

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Table 1. Meteorites investigated: Classification[a] and sample identification[b]

No.	Meteorite	Classification		Sample identification	
1	Altonah	Of	IVA	ASU	168ax
2	Ballinger	Og	IIICD	FMNH	2110
3	Bella Roca	Om	IIIB	ASU	266a
4	Billings	Om	IIIA	ASU	151a
5	Bishop Canyon	Of	IVA	FMNH	1948
6	Calico Rock	H	IIA	AML	70.2
7	Chihuahua City	An	An	ASU	27ax
8	Chinautla	Of	IVA-An	BMNH	1913.434
9	Colfax	Om	IB	FMNH	1961
10	Coopertown	Og	IIIE	USNM	1003
11	Edmonton (KY)	Of	IIICD-An	USNM	1413
12	Elyria	Om	IIIA	AML	124.11
13	Hassi-Jekna	Of	IIICD	MNP	2996
14	Joe Wright Mts.	Om	IIIB	NHMW	2166K
15	Kokstad	Og	IIIE	FMNH	1015
16	La Grange	Of	IVA	ASU	291a
17	Lombard	H	IIA	AML	658.20
18	Navajo	Ogg	IIB	FMNH	2099
19	Needles	Of	IID	UCLA	
20	Ogallala	Og	IA	ASU	90.1x
21	Paneth's Iron	Og	IIIE	MPIM	103/13
22	Para de Minas	Of	IVA	ASU	604.1
23	Picacho	Om	IIIA	AML	237.5
24	Rhine Villa	Og	IIIE	FMNH	869
25	Santa Luzia	Ogg	IIB	USNM	772
26	Silver Bell	Ogg	IIB	ASU	793
27	Surprise Springs	Og	IA	FMNH	854
28	Tanakami Mts.	Og	IIIE	FMNH	1150
29	Unter-Mässing	Opl	IIC	NHMN	
30	Wichita County	Og	IA	FMNH	41
31	Willow Creek	Og	IIIE	ASU	227.14

[a] Classification after Wasson [7]; Elyria and Picacho: Scott et al. [8]; Ballinger, Edmonton (KY); Hassi-Jekna: Wasson et al. [9].
[b] AML = American Meteorite Laboratory, Denver; ASU = Arizona State University, Tempe; BMNH = British Museum of Natural History, London; FMNH = Field Museum of Natural History, Chicago; MNP = Muséum National d'Histoire Naturelle, Paris; MPIM = Max-Planck-Institut für Chemie, Mainz; NHMN = Naturhistorisches Museum, Nürnberg; NHMW = Naturhistorisches Museum, Wien; UCLA = University of California, Los Angeles; USNM = U.S. National Museum of Natural History, Washington.

and Hassi-Jekna in the laboratory of H. Hintenberger in this institute.

The relative abundances of cosmic-ray-produced noble gas nuclides in a sample of iron meteorite depend almost solely on the effective irradiation hardness, i.e. on the shielding of the sample by the surrounding meteoroid mass. The different abundance ratios in different samples from different iron meteorites can, therefore, almost perfectly be described by a set of equations which correlate some properly selected abundance ratios with one another. A particular set which provides with a minimum number of equations a complete description of all abundance patterns, was called a "primary correlation system". A wealth of other – "secondary" – correlations may be deduced from a primary system by algebraic operations [2].

In the preceding paper [6] of this series, a new partial system of secondary correlations between the cosmogenic species ^{3}He, ^{4}He, ^{21}Ne, and ^{38}Ar was introduced. It is particularly well suited to test the "normality" of measured ratios, i.e. to recognize and diagnose abundance anomalies. As a rule, all experimental data should be tested prior to their application in calculations on the irradiation history. For that purpose, they must be compared with predictions which are provided by a suitably selected set of "normal" test correlations.

The particular test correlations chosen in the preceding paper [6] are based on the data of only 12 of the first suite of 16 samples measured at this laboratory; the data of 4 samples proved to be anomalous, cf. Figs. 2 and 3 in [2]. In the meantime, the number of analyses published from this laboratory has grown to 83, see Table 1 in [4] and Table 2 of the present work. Consequently, test correlations should henceforth be used which are based on the normal data from all these 83 analyses. Therefore, we have now performed a critical examination of these data sets by application of the principles described in [6].

During examination of the 83 data sets, no "pecularities" were found for 52 of them. From these 52 data sets we have deduced the following equations describing new primary correlations:

$$^3\mathrm{He}/^4\mathrm{He} = (0.151 \pm 0.003) + (34.3 \pm 0.9)\,(^4\mathrm{He}/^{21}\mathrm{Ne})^{-1}\,, \quad s = 0.0037 \mathrel{\widehat{=}} 1.4\%\,; \tag{1}$$

$$^4\mathrm{He}/^{38}\mathrm{Ar} = (35.9 \pm 0.8) + (0.089 \pm 0.003)\,^4\mathrm{He}/^{21}\mathrm{Ne}\,, \quad s = 1.0 \mathrel{\widehat{=}} 1.7\%\,. \tag{2}$$

They represent linear approximations of relationships reported previously [2, 6]. In the computations of the regression lines, the effective irradiation hardness, i.e. ^{4}He/^{21}Ne, was treated as an independent variable; s designates the square root of the mean sample variance. From (1) and (2) the following secondary correlations are deduced:

$$^3\mathrm{He}/^4\mathrm{He} = 0.1506 + 3.040\,(^4\mathrm{He}/^{38}\mathrm{Ar} - 35.9)^{-1}, \quad s = 0.005 \mathrel{\widehat{=}} 1.8\%\,; \tag{3}$$

Table 2. Concentrations and abundance ratios of noble gas nuclides in 31 samples of different iron meteorites.

1 No.	2 Meteorite	3 Ni %	4 ^{4}He [a]	5 ^{21}Ne [a]	6 ^{38}Ar [a]	7 $^{3}He/^{4}He$	8 $^{4}He/^{21}Ne$	9 $^{4}He/^{38}Ar$	10 $^{36}Ar/^{38}Ar$	11 Remarks [b]
1	Altonah	8.2	972	4.09	16.9	0.282	238	57.4	0.646	$d_3 = 4\%$
2	Ballinger	6.2	1299	5.09	22.2	0.270	255	58.6	0.635	$d_3 = 5\%$
3	Bella Roca	9.9	303	0.90	4.6	0.246	338	65.8	0.620	A
4	Billings	7.8	1418	4.98	23.5	0.268	285	60.4	0.630	
5	Bishop Canyon	7.6	987	3.72	17.2	0.287	265	57.3	0.636	
6	Calico Rock	5.5	1502	5.92	25.5	0.289	254	59.0	0.638	ave 2
7	Chihuahua City	6.7	91	0.25	1.3	0.241	362	68.4	0.614	
8	Chinautla	9.5	154	0.34	2.1	0.233	449	74.6	0.607	
9	Colfax	10.8	1123	5.14	20.1	0.301	219	55.9	0.654	
10	Coopertown	8.5	1504	5.87	25.0	0.286	256	60.1	0.640	
11	Edmonton (KY)	12.7	2166	8.16	34.8	0.281	265	62.2	0.639	d_{36}(Ni) = 5%
12	Elyria	8.6	1850	7.67	32.5	0.294	241	56.9	0.641	
13	Hassi-Jekna	10.5	1361	6.83	25.0	0.310	199	54.4	0.665	A; ave 2
14	Joe Wright Mts.	9.1	1672	6.20	27.0	0.275	270	62.0	0.636	ave 2
15	Kokstad	8.3	163	0.38	2.1	0.222	428	76.6	0.602	
16	La Grange	7.4	1169	4.51	20.1	0.282	259	58.3	0.638	
17	Lombard	5.6	318	0.81	4.4	0.239	393	71.9	0.604	ave 2
18	Navajo	5.5	133	0.31	1.8	0.235	436	73.1	0.603	
19	Needles	10.7	1100	4.46	18.8	0.288	246	58.6	0.644	
20	Ogallala	7.9	1360	4.18	20.7	0.258	326	65.6	0.619	
21	Paneth's Iron	8.9	1526	4.95	23.9	0.256	308	63.9	0.623	
22	Para de Minas	8.0	1130	3.79	18.1	0.270	298	62.5	0.628	
23	Picacho	7.1	2049	7.24	34.0	0.273	283	60.3	0.630	
24	Rhine Villa	8.6	775	2.77	12.4	0.267	280	62.4	0.632	
25	Santa Luzia	6.3	106	0.25	1.4	0.228	423	76.8	0.599	
26	Silver Bell	6.4	802	2.85	13.3	0.274	281	60.5	0.628	
27	Surprise Springs	8.1	605	3.15	11.5	0.328	192	54.6	0.659	
28	Tanakami Mts.	8.9	1223	3.84	18.4	0.257	318	66.5	0.624	
29	Unter-Mässing	9.8	3810	14.35	62.2	0.281	266	61.3	0.638	B
30	Wichita County	6.8	955	2.53	13.7	0.240	377	69.7	0.608	ave 2
31	Willow Creek	8.8	1505	4.92	23.4	0.262	306	64.4	0.625	

[a] Unit: 10^{-8} cm³ STP/g.
[b] Remarks: ave 2: average of two analyses. A: analyses performed in H. Hintenberger's laboratory by O. Braun. B: analysis by L. Schultz, cf. [5]. $d_3 = 4\%$: Relative ^{3}He-deficiency of 4% presumably owing to diffusion loss of its radioactive precursor tritium, cf. [6]. $d_{38} = 5\%$: Relative ^{38}Ar-deficiency of 5% owing to the high nickel content of the sample, cf. [6].

$$^{38}Ar/^{21}Ne = (^{3}He/^{21}Ne - 34.28) \cdot (2.369 + 0.0887\ ^{3}He/^{21}Ne)^{-1}, \quad s = 0.08 \mathrel{\widehat{=}} 1.7\% . \tag{4}$$

The four Eqs. (1)–(4) are equivalent to the partial system of test correlations presented in the preceding paper, cf. Figs. 1A–D in [6]. They are consistent and equivalent with the $^{3}He/^{4}He-^{4}He/^{21}Ne$- and $^{3}He/^{38}Ar-^{4}He/^{21}Ne$-correlations used previously [2] as primary correlations. From (1) and (4) a secondary $^{4}He/^{38}Ar-^{3}He/^{21}Ne$-correlation may be derived which turns out to be linear, cf. Fig. 7 in [2].

Of the 83 samples, the other 31 data sets proved to be not or less appropriate for at least one of the following reasons:

(a) in 10 samples, the measured concentrations are rather low ($^{21}Ne < 10^{-8}$ cm³ STP/g); the results for a few of them are less precise.

(b) All 13 samples with nickel contents > 11% exhibit a ^{38}Ar-deficiency of about 4%, cf. [6].

(c) A significant ^{3}He-deficiency was found in 11 samples.

(d) Slight anomalies, probably owing to a two-stage irradiation history, are found for Yanhuitlan, cf. [4].

If the results of this "anomaly hunting" are summarized one notes that no case of a ^{4}He-excess was found. The number of cases with a significant ^{3}He-deficiency is considerable (11 of 83) although this more critical examination does not substantiate our previous conjectures [4] on the occurrence of anomalies in Arispe, Bendego, Cowra, Mount Edith, and Sanderson. The most important result is that all ^{21}Ne- and $^{4}He/^{21}Ne$-data in Table 2 refer, indeed, to the cosmogenic component and can, therefore, immediately be used for the calculations in Sect. 3 and 4. A prominent detail in Table 2 are the extreme abundance ratios for Surprise Springs, for example $^3He/^4He = 0.328$ and $^4He/^{21}Ne = 192$. This sample was obviously situated closer to the meteoroid surface than any other sample so far analysed, cf. Figs. 1 and 7 in [4].

3. Determination of cosmic-ray exposure ages

Frequently, the $^{41}K/^{40}K$-method is most appropriate to determine exposure ages [1, 3–5]. The temporal development of the cosmogenic (c) potassium nuclides in a sample of iron meteorite yields, after a time period T of irradiation, the concentrations

$$^{39}K_c = P_{39}\,T\,, \tag{5}$$

$$^{40}K_c = P_{40}\,\lambda^{-1}(1 - e^{-\lambda T})\,, \tag{6}$$

$$^{41}K_c = P_{41}\,T\,. \tag{7}$$

The P's and λ are the production rates and the decay constant of ^{40}K, respectively. The mass spectra of potassium extracted from irons are superpositions of those of cosmogenic potassium and of an accessory (a) component originating from terrestrial contamination and from the primordial component in the meteoritic material:

$$^{39}K = {}^{39}K_c + {}^{39}K_a\,, \tag{8}$$

$$^{40}K = {}^{40}K_c\,, \tag{9}$$

$$^{41}K = {}^{41}K_c + {}^{41}K_a\,. \tag{10}$$

In the present context, the accessory contribution to ^{40}K can be neglected. With the abbreviations

$$a =: (^{41}K/^{39}K)_a\,, \tag{11}$$

$$M =: {}^{41}K/^{40}K - a\,^{39}K/^{40}K\,, \tag{12}$$

$$N =: P_{41}/P_{40} - a\,P_{39}/P_{40}\,, \tag{13}$$

one derives from (5)–(10) the relationship

$$\lambda T/(1 - e^{-\lambda T}) = M/N \tag{14}$$

for the calculation of the age T.

Melting of the meteorite sample in high vacuum, fractional volatilization, thermal surface ionization, and ion transport by electrostatic fields are the techniques employed to extract the alkali elements and to load them selectively for mass spectrometric analysis onto a clean Pt-filament [1, 3, 5]. However, the procedure is preceded by an important 1-hour period during which the sample is glowed in a high vacuum at about 1200 °C, so that selective loss of the accessory alkali elements from the sample surface as well as from grain boundaries is achieved. The cosmogenic component is not released until the sample is melting in the final extraction stage. Considering the extremely small concentrations of cosmogenic potassium of the order of ng/g or less, it is understandable that even with these sophisticated procedures a good state of sample preservation is a prerequisite of success. Spectra with ^{40}K-abundances $\lesssim 4\%$ can barely provide useful information. With the samples of Table 1 the outcome was relatively poor. The results of the successful experiments are summarized in Table 3.

In the present context, "quality" means, first of all, the relative contribution of the cosmogenic component which is essentially characterized by the relative abundance of ^{40}K given in column 4. The data in column 3 provide further information on the "quality". In the first instance, the number of recorded spectra is given; it presents a relative measure of the time period during which stable ion currents were obtained before the potassium reserve on the filament was exhausted. As, for the first time in our K-laboratory, a computer was used for data acquisition, the data collecting rate was roughly three times that of our previous measurements. A supplementary quality criterion is provided by observation of the isotope fractionation behaviour during the run, as characterized by one or a combination of two of the letters A–D (cf. [1, 3]).

As an example, we discuss the case of No. 6 in Table 3, Calico Rock. A total of 764 spectra were recorded in the course of four working-days, until the potassium sample on the filament was exhausted. The ion current was held nearly constant and the spectra were taken in constant time intervals. The data in column 4 are the uncorrected means from all spectra. As cosmogenic and accessory components are never perfectly mixed on a filament, slight and slow variations of the relative abundances occurred with, for example, ^{40}K-abundances between 11 and 14%. These variations do not affect the M-values. Isotope fractionation occurred, however, producing a slight temporal increase of the uncorrected (see below) M-value from about 1.675 to 1.695 (mean 1.687). In column 3 of Table 3 such behaviour is denoted by the letter B. The

Table 3. Potassium isotopes, cosmic-ray exposure ages, meteoroid sizes, and sample depths.

1 No.	2 Meteorite	3 Quality[a]	4 Rel. abundances[b] (%) ^{39}K	 ^{40}K	 ^{41}K	5 M-value[c]	6 Exposure age, Ma	7 P_{21}[d]	8 Size 10^3 kg	9 Depth cm
6	Calico Rock	764 B	61.62	12.59	25.80	1.710 ± 0.024	545 ± 55	1.09	2	14
10	Coopertown	394 A	80.41	5.08	14.51	1.722 ± 0.041	575 ± 90	1.02	3	13
11	Edmonton (KY)	385 A	65.61	10.54	23.84	1.827 ± 0.028	795 ± 60	1.03	2	16
14	Joe Wright Mts.	582 A	72.70	7.97	19.33	1.779 ± 0.031	685 ± 70	0.90	5	15
15	Kokstad	500 DA	71.87	8.30	19.83	1.776 ± 0.032	470 ± 70	0.08	L[e]	L[e]
23	Picacho	505 AB	47.09	18.01	34.90	1.766 ± 0.021	635 ± 50	1.14	0.8	28
24	Rhine Villa	495 B	74.28	7.80	17.92	1.620 ± 0.030	310 ± 70	0.85	6	17
		128 A	75.09	7.43	17.48	1.632 ± 0.031	340 ± 70			
27	Surprise Springs	345 C	85.79	3.22	10.99	1.490 ± 0.070	130 ± 170	–	–	5–10
29	Unter-Mässing[f]	450 B	73.63	6.80	19.57	2.113 ± 0.037	1385 ± 70	1.04	2	16
31	Willow Creek	100 A	60.45	12.91	26.64	1.741 ± 0.024	550 ± 55	0.88	2	25
		350 A	67.20	10.21	22.58	1.750 ± 0.027	570 ± 60			

[a] See text.
[b] Uncorrected abundances.
[c] Corrected M-values, Equation (17).
[d] ^{21}Ne-production rate $P_{21} = C_{21}/T$; unit: 10^{-10} cm^3 STP/g Ma.
[e] "Low-P-sample", cf. Sect. 4.2 in [4].
[f] Already published: [5].

character A refers to the more favourable case of constant M-values, whereas C and D indicate occurrences of certain instabilities as described elsewhere [1, 3].

With equation (12) and with the abundances in column 4, an uncorrected value M_0 is calculated. Owing to the mass dependence of the ion-electron conversion in the multiplier used, a correction has to be applied. With an estimated mass discrimination of 1% u^{-1} the following relationships are obtained [1, 3]:

$$M = M_0 + m\,, \tag{15}$$

$$m = 0.01\,(^{41}K/^{40}K + a\ ^{39}K/^{40}K)\,. \tag{16}$$

The uncertainty of the M-value depends, of course, on the contribution of the accessory component in the spectrum; a good measure for it is the value of m itself. Therefore, and according to the practice adopted before, we present in column 5 the values of

$$M = (M_0 + m) \pm m\,. \tag{17}$$

With regard to the N-values – cf. (13) – we recall that the ratios between any two production rates depend almost solely on the effective irradiation hardness. N must, therefore, be a function of $^4He/^{21}Ne$. Previous studies [1, 10] have demonstrated that the equation

$$N = 1.346 + 0.515\ 10^{-3}\ ^4He/^{21}Ne \tag{18}$$

is appropriate. The exposure ages which finally follow are shown in column 6.

4. Meteoroid sizes and sample depths

We refer here to the P_{21}–$^4He/^{21}Ne$-diagram shown in Figure 1. It predicts how the production rate of cosmogenic ^{21}Ne ($P_{21} = C_{21}/T$) and the ratio $^4He/^{21}Ne$ depend on the meteoroid size S and sample depth ; a detailed account is given elsewhere [4]. The diagram, in connection with results in Tables 2 and 3, enables us to ascertain the meteoroid sizes and the sample depths listed in columns 8 and 9 of Table 3. The distribution of the data points in the P_{21}–$^4He/^{21}Ne$-diagram is essentially similar to that of our earlier results [4]. For Surprise Springs an estimate of the size cannot be made owing to the large uncertainty of the age value; however, according to its $^4He/^{21}Ne$-ratio of 192, the sample depth must be somewhere between 5 and 10 cm. The sample of Kokstad, with the "co-ordinates" $^4He/^{21}Ne = 428$ and $P_{21} = 0.08 \cdot 10^{-10}$ cm^3 STP/g, falls distinctly below the allowed field of the P_{21}–$^4He/^{21}Ne$-diagram and belongs, therefore, to the group of "low-P-samples" [4]; it had probably experienced a

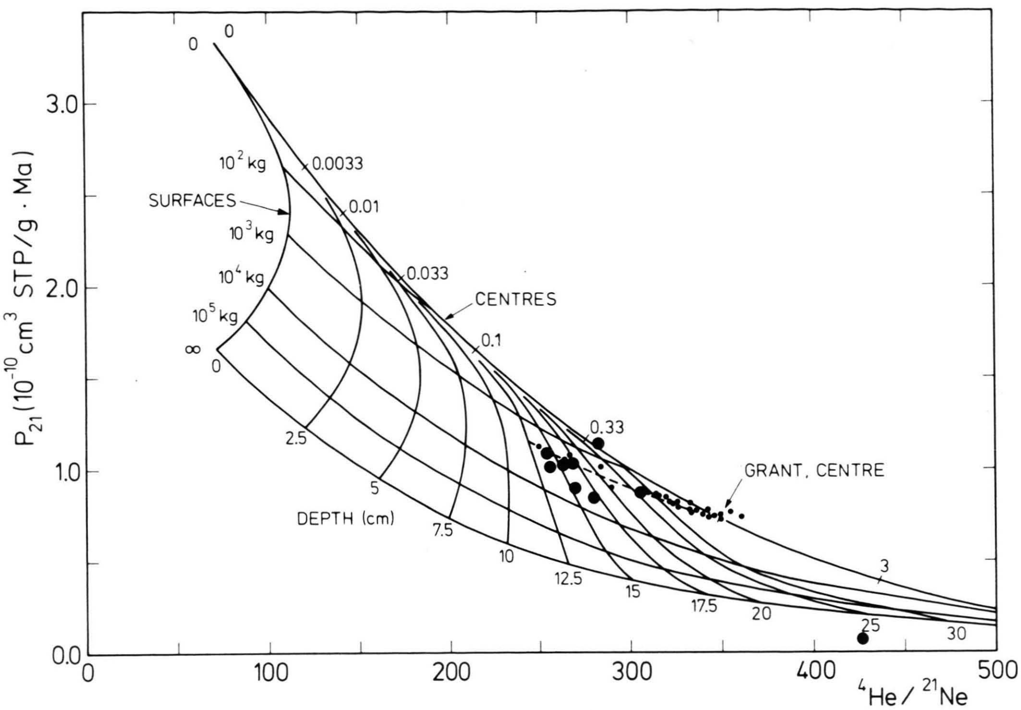

Fig. 1. Variation of the ^{21}Ne production rate P_{21} with ^{4}He/^{21}Ne as a function of depth in spherical meteoroids of various sizes, as derived from Signer and Nier's [11] analysis of the noble gas distribution in Grant and an exposure age of Grant of 695 Ma. The "allowed field" of the diagram is limited by the "centre limit" (top) for the centres of meteoroids of various sizes, by the "infinite-mass limit" (bottom) for the depth dependence of P_{21} and ^{4}He/^{21}Ne in a meteoroid of "infinite" mass, and by the "surface limit" (left) reflecting the P_{21}–^{4}He/^{21}Ne-relationship for surface samples from meteoroids of variable sizes. The numbers at the centre curve give the meteoroid mass in units of that of Grant. The small dots and the broken line refer to data on the Grant meteorite as measured by Signer and Nier [11], the large dots to the results of the present work (Tables 2 and 3).

two- or more-stage irradiation history. The meaning of the value of 470 Ma for its exposure age is, therefore, problematic.

5. Discussion: Exposure ages

The ^{41}K/^{40}K-ages from the present and previous work are summarized in Figure 2. The partition into several histograms is based on Wasson's classification [7] with some minor modifications [9]. The observation of characteristic age distributions supports the belief that almost each of the different chemical groups originated in a single discrete parent body. An interesting motive to measure the age distribution for a group of homologous meteorites is based on the expectation that it would somehow reflect the temporal progress of the collision-induced destruction of the respective parent body and that it could, perhaps, reveal its stratigraphic structure, see e.g. [12, 13].

According to the new analyses, the IIIAB-irons Joe Wright Mountains and Picacho are members of the age cluster at 670 Ma which were obviously ejected in consequence of a single impact event on their parent body. The total number of meteoroids released may have gone into the hundreds of millions. The existence of this age cluster implies that the IIIAB-material originally resided within a more or less contiguous partial volume of the parent body, perhaps in a metallic core. The same explanation may hold for the 450 Ma age clustering of the IVA-irons.

The age clustering of the IIIAB-meteorites presents the extreme counter-example to the almost continuous age distribution of the IA-meteorites. The total cross section against collision-induced disruption and release of the material which contains the IA-metal appears to be substantially larger than that of the material which contains the IIIAB-metal. On the other hand, each single impact on the IA-

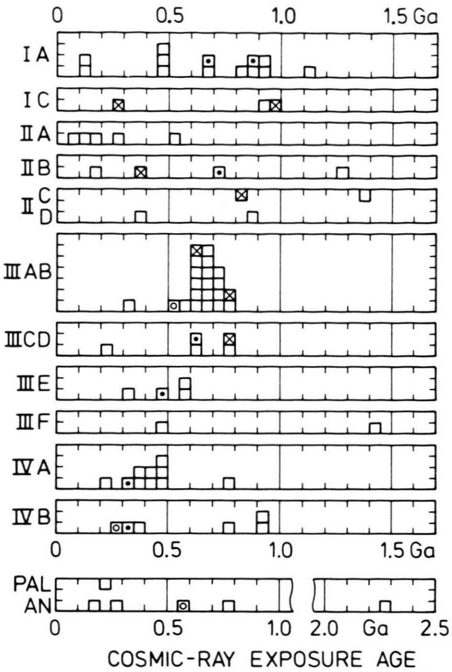

Fig. 2. $^{41}K/^{40}K$-exposure age histograms for various chemical groups of iron meteorites. With regard to the classification, see [7, 9]; AN = anomalous irons, PAL = pallasite. Crossed bars represent anomalous members of the respective group. Bars with open circles represent less certain age values, bars with dots represent ages that do possibly not reflect the time of the primary ejection of the respective meteoroids from their parent bodies, cf. [4].

parent-body has been less effective in producing irons that found their way to Earth. This observation is consistent with the explanation that the IA-irons are derived from a relatively big parent body where metal boulders are widely dispersed within chondritic mantle or crustal material. These general ideas have already been discussed in previous publications [1, 3].

Studies on the "geochemistry" of iron meteorites have provided evidence for the existence of two different major classes of meteoritic nickel-iron, see e.g. [9]: first, the "igneous" or "magmatic" groups of irons (among them the IIIAB-irons) which formed by fractional crystallization of a metallic magma; and second, groups (among them the IA-irons) in which iron formed in small pools of impact melt. The igneous metal may occur in form of very massive conglomerates or of an asteroidal core, whereas the pools solidified rapidly and remained isolated from each other, widely dispersed within unfractionated chondritic material. It is remarkable that these geochemical considerations and the discussion of age distributions have independently produced quite similar conceptions on the different modes of formation of the IA- and IIIAB-meteorites.

It appears, however, that these arguments cannot be generalized. The existence of more or less completely fractionated magmatic metal in form of veins which remain widely dispersed within fractionated silicate material of a parent body is, at the currently poor state of our understanding, perhaps conceivable. On the other hand, circumstances are conceivable allowing the gradual destruction of more or less massive conglomerates of igneous metal and a quasi continuous release of igneous iron meteoroids.

The IIA- and IIB-irons, for example, belong to be igneous groups [14] and exhibit, nevertheless, quasi continuous age distributions (Figure 2). Although the IIICD-irons consist of impact metal [9] and the IIIE-irons of igneous metal [15], their age distributions appear very similar in character. We observe even a certain quantitative similarity of the age distribution of the IIICD's with that of the IIIAB's; yet we do not deduce from them that it was one single event that produced the majority of the IIICD-meteoroids as well as that of the IIIAB-irons. The groups IIIE and IIIAB differ only slightly in their chemical compositions and it has been an open question whether or not the two groups formed in different parent bodies [8]. Comparison of their age distributions does not provide much help to decide this question, all the more so as the meaning of the value of 470 Ma for the exposure age of the IIIE-member Kokstad is problematic.

It is obvious that certain problems remain unsolved and that for their solution two requirements should be realized as much as possible: (1) that more irons of the groups IIB, IIICD, IIIE, and IIIF are dated and the statistical significance of their age distributions is thereby improved; and (2) that the time resolution of the analyses, i.e. the precision of the age determination is substantially improved. However, we do not see a possibility for a decisive progress in these affairs at the present time.

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