MULTI-STAGE EXPOSURE HISTORY OF THE TORINO, H6, METEORITE; G.F. Herzog, S. Vogt, D. Aylmer, Dept. Chem., Rutgers Univ., New Brunswick, NJ 08903; P. Signer, Th. Graf, R. Wieler, NO C 61, ETH-Zentrum, CH-8092, Zürich, Switzerland; C. Tuniz, INFN, Dept. Phys., Univ. Trieste, Italy; J. Klein, D. Fink, R Middleton, Dept. Phys., Univ. Penn., Philadelphia, PA 19104; A.J.T. Jull, NSF Facility for Radioisotope Anal., Univ. Arizona, Tucson, AZ 85721.

All stony meteorites that contain solar-wind-implanted gases have been exposed to galactic cosmic rays (GCR) in two distinct episodes, first in the regolith of the parent body and later in a meteoroid. Evidence for multi-stage GCR exposures is scarce in ordinary chondrites that contain no solar-wind-implanted gases. Such meteorites are important because collectively they provide information about the evolution of asteroidal regoliths and/or the frequency of collisions between meteoroids; Jilin and Bur Gheluai [1] are two particularly well-documented examples. Bhandari et al. [2] investigated the recently fallen H4 chondrite Torino and found some evidence for a two-stage exposure. We decided to examine its exposure history in detail and for that purpose measured its concentrations of He, Ne, Ar, ^{14}C, ^{26}Al, and ^{10}Be.

Results - The light noble gases were determined by static mass spectrometry [3,4]. We used accelerator mass spectrometry to analyze for ^{26}Al and ^{10}Be [5] and ^{14}C [6]. Our new noble gas results (Table 1) agree with those of [2] except that we cannot confirm their exceptionally low $^{20}Ne/^{22}Ne$ ratio of 0.70 or their low ^{4}He concentration. The constancy of the noble gas concentrations in the Aeritalia and Leuman fragments indicates that they experienced similar shielding conditions. The low $^{20}Ne/^{22}Ne$ ratios show that the measured Ne consists of essentially pure cosmogenic Ne. The $^{22}Ne/^{21}Ne$ ratios, ~1.067, are among the lowest observed in chondrites and signal a well shielded position in a rather large meteoroid. The (cosmogenic) ^{21}Ne concentrations, which are among the highest known, require an unusually long exposure to cosmic rays. In sum, a qualitative look at the cosmogenic gases indicates that Torino suffered a long exposure to cosmic rays at considerable depth in a large meteoroid. This conclusion tends to conflict with the observations that 1) the recovered mass of all fragments is only about 1 kg; 2) the observed ^{60}Co [2] concentration is typical of a small parent meteoroid or a surface location in a larger one; 3) the cosmic ray track densities of 4-5 x 10^5 t/cm^2 in pyroxenes [2] are rather low. On the other hand, the radionuclide activities (Table 2) are comparable to those observed at saturation in typical H-chondrites [7]. These contradictory indications support the idea that Torino had a complex history. A more quantitative treatment follows.

Single-stage exposure history? - The conventional [8], one-stage ^{3}He, ^{21}Ne, and ^{38}Ar ages of 59, 56, and 56 Ma agree within errors; their average, 53.8 ± 1.8 Ma, is clearly lower than a *minimum* age of 67 Ma obtained by using the $^{22}Ne/^{21}Ne$ ratio in conjunction with the model of Graf et al. [4]. More detailed modeling based on ref. [4] that also includes the ^{26}Al and ^{10}Be activities leads to an even higher one-stage exposure age of 81 Ma, a sample depth of 30 cm, and a meteoroid radius of ~80 cm. However, this reconstruction fails to explain not only the low ^{60}Co concentration, only 2.8 dpm/kg, but also the observed track densities [2]. Under the specified exposure conditions, the ^{60}Co activity should be substantially higher [9] and the track density much lower [10]. As a one-stage exposure history cannot explain the whole data set, we try next a two-stage history.

Model two-stage histories - The high track densities (and the low ^{60}Co activity), but not the $^{22}Ne/^{21}Ne$ ratio, can be explained by a relatively short recent exposure in a small body. At fixed depth, the highest track production rates, and hence the shortest estimates for the duration of the second-stage exposure, pertain to the smallest meteoroids. On impact, the radius of Torino was certainly > 4 cm and probably > 7 cm. If the samples came from close to the center of a 7-cm meteoroid, then Torino's second stage must have lasted > 1 Ma, long enough to influence appreciably both the ^{26}Al and ^{10}Be activities. We favor a longer second stage because the 1-Ma value implies a first-stage ^{26}Al production rate of over 80 dpm/kg, albeit with a large uncertainty. If the second stage lasted 4-12 Ma, then a second-stage radius of ~13 cm would be consistent with the observed ^{26}Al and ^{10}Be activities and with the track densities. By applying mass balance, we obtain a first-stage $^{22}Ne/^{21}Ne$ ratio of 1.054, which in turn suggests a radius, R_I, > 85 cm and a duration, t_I, > 83 Ma. In the limit of a very large first-stage radius, i.e., irradiation in a parent-body regolith, we find t_I ~ 270 Ma and a depth of 70 cm. Neither the K/Ar age nor the U/Th/He age of Torino hints at any very recent disturbance. Thus if Torino came from a regolith, the impact that launched it evidently did not completely reset the isotopic clocks.

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Cosmogenic argon - The decay of ^{36}Cl produces ^{36}Ar. As the conditions deduced for Torino's first-stage exposure correspond to substantial production rates of ^{36}Cl [9], we expected but did not find enhanced $^{36}Ar/^{38}Ar$ ratios.

Summary - Torino belongs to the small group of solar-gas-free ordinary chondrites now recognized as having experienced two-stage irradiations. Its atypically long (for a chondrite) total exposure and first stage and its relatively long second stage distinguish Torino from Jilin and Bur Gheluai. The study of such meteorites has just begun; nonetheless, the absence to date of evidence for first-stage exposure ages greater than 1,000 Ma suggests that the precursors of the meteoroids in this group had short lifetimes in space and were small compared to asteroids.

Table 1. Noble gas concentrations (10^{-8} cm^3 STP/g) and ratios in Torino.

Sample	Mass (mg)	^3He	^4He	^{21}Ne	$^{22}Ne/^{21}Ne$	$^{20}Ne/^{22}Ne$	^{38}Ar	^{40}Ar	$^{36}Ar/^{38}Ar$
Leuman									
9/1	214.75	80.7	1700	21.8	1.0675	0.837	2.88	5210	0.946
9/3	98.65	83.3	1790	21.0	1.0652	0.842	2.98	5230	1.081
9/4	261.10	78.0	1540	20.9	1.0680	0.842	2.82	4810	0.951
9/5	5180	77.1	1520	20.6	1.0680	0.842	2.85	4940	0.979
Aeritalia									
10/51	212.15	85.0	1780	21.2	1.0658	0.895	2.82	5470	0.969
Mean[1]		83.0	1755	21.3	1.0669	0.852	2.873	5300	0.985
±		3%	10%	2%	0.0013	0.024	2%	10%	0.055
Lit. [2]	27.15	76.0	1140	20.3	1.062	0.70			
±		1.6	90	0.6	0.010	0.10			

Notes: 9/4 is a sample taken from about 3 mm below the fusion crust. 9/5 is a 5.10 % split of the gas from a sample of 5.18 g used for other purposes.

1) Means of concentrations are determined from runs 9/1 and 9/3 only; for isotope ratios, all four determinations are used.

Table 2. Activities (dpm/kg) of long-lived cosmogenic radionuclides in Torino.

Isotope	Half-life	Aeritalia	Leuman	Pianezza
^{10}Be	1.5 My	18.3±0.9 19.1±0.9	19.6±0.8	19.0±0.8
^{26}Al	0.7 My	53.0±3.7 54±1 [2]	59.7±2.5	59.2±2.9
^{14}C	5.7 ky		42.2±2.1	

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