Research Article

FLUKA Monte Carlo Simulations about Cosmic Rays Interactions with Kaidun Meteorite

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An asteroid called Kaidun fell on December 3, 1980, in Yemen ($15^{\circ} 0'N$, $48^{\circ} 18'E$). Investigations on this large-sized meteorite are ongoing today. In this paper, interactions between cosmic rays-earth atmosphere and cosmic rays-Kaidun meteorite were modeled using a cosmic ray generator FLUKA Monte Carlo code. Isotope distributions and produced particles were given after these interactions. Also, simulation results were compared for these two types of interactions.

1. Introduction

Cosmic rays (CRs) are high-energy charged particles, coming from space which voyage at close to the speed of light and hit the Earth's atmosphere from anywhere. Essentially, all of the elements in the periodic table; about 89% of the nuclei are hydrogen (protons), 10% helium, and about 1% heavier elements, generate CRs. These heavier elements (such as carbon, oxygen, magnesium, silicon, and iron) are present in about the same relative abundance as in the solar system, but there are important differences in elemental and isotopic composition that provides information on the origin and history of galactic cosmic rays. For example, there is a significant excess of the rare elements (Li, Be, and B) produced when heavier CRs such as C, N, and O fragment into lighter nuclei during collisions with the interstellar gas. The isotope ^{22}Ne is also excessive, showing that the nucleosynthesis of cosmic rays and solar system material has differed. Electrons constitute about 1% of galactic cosmic rays. It is not known why electrons are apparently less efficiently accelerated than nuclei.

Kaidun meteorite fell in Yemen ($15^{\circ} 0'N$, $48^{\circ} 18'E$) on 3 December, 1980. It is in the carbonaceous chondrite meteorite class and its mass is about 2 kg. It holds a special place in the world meteorite collection. It is characterized by an unprecedentedly wide variety of meteorite material in its makeup. It is believed that Kaidun originated from Phobos, one of two Martian moons [1]. Two new minerals

called Andreyivanovite and Florenskyite were discovered after research on the meteorite. There are several studies about Kaidun meteorite and its minerals (Andreyivanovite and Florenskyite). These studies are generally focused on the chronology of meteorite [2–6], the geochemistry [7–16], mineralogy [17–19], and the space research [20–25].

FLUKA makes Monte Carlo estimations about particle-matter interactions. FLUKA Monte Carlo package has already been used to simulate CRs generation and interactions in several research papers [26–29]. Interactions between CRs-Kaidun meteorite and CRs-earth atmosphere were simulated in the present paper.

2. Methodology

FLUKA is a FORTRAN-based Monte Carlo tool used for calculations of particle transportations and interactions with different materials used in many different application areas such as calorimetry, activation, dosimetry, detector design, accelerators, cosmic rays, neutrino physics, and radiotherapy. In this code, 60 different subatomic particles are described and almost all of the materials used in many applications can be defined using suitable cards [30, 31]. In 2010, FLUKA Monte Carlo code was presented as a new high-energy cosmic ray generator. With this new release, FLUKA is able to simulate interactions between high-energy cosmic rays and Earth's atmosphere. In this code using the combinational

FIGURE 1: 100 layered FLUKA atmosphere model.

geometry package included into the general code, Earth atmosphere is modeled with a set of 100 concentric spherical shells (Figure 1). For the material components of Earth atmosphere, the same material at different pressure and temperature conditions for each layer was used. Composition of Kaidun meteorite was taken in the literature. Hadronic interactions were activated using DPMJET package [32]. As for primary cosmic ray beam primary mass composition model is used such as 90% of protons and 9% of alphas [33]. As for scores of simulations, we wanted primary proton fluency, produced radioisotopes, and secondary particles existing after interactions. The general FLUKA code exists on the website at <http://www.fluka.org/>.

3. Results

In terms of performance of FLUKA code about capability of cosmic ray-atmosphere interactions, we plotted primary proton fluency as a function of primary proton energies (Figure 2). As can be seen in this figure, proton energies can reach up to 10 TeV after interactions between CRs and Earth's atmosphere.

In Table 1, radioisotopes produced after interactions between CRs and Earth's atmosphere are seen. 66 different cosmogenic isotopes were produced as atomic number range from 1 to 20. Abundance of ^4He , ^{14}C , and ^{14}N isotopes is remarkable. Trace isotopes are ^{37}S , ^{18}O , and ^{34}P .

In Table 2, isotope products derived from CRs-Kaidun meteorite interactions were given. A wide range of isotope

FIGURE 2: The differential primary proton fluence spectra.

distribution (atomic number from 1 to 79) is seen unlike Table 1. In these products, the most abundance is ^{56}Fe because of Kaidun's high Fe content. Other important isotopes are ^{55}Fe , ^{55}Mn , and ^{54}Mn . Small amounts of ^{49}Ca , ^{82}Br , and ^{108}Ag are also produced.

Table 3 shows number of particles produced after CRs-atmosphere and CRs-Kaidun. In this table, neutrons and protons are outstanding. Antisigma (+), antisigma (-), xi (0), anti-xi (0), and anti-xi (+) are trace particles. Looking at the relative differences, it is seen that the biggest changes occur

TABLE 1: Isotope distribution after interactions between CR and Earth's atmosphere.

Isotope	Number of nuclei
H-1	$4,63E + 02$
H-2	$6,84E + 01$
H-3	$2,24E + 01$
He-3	$2,12E + 01$
He-4	$4,62E + 02$
He-6	$4,53E - 02$
Li-6	$2,27E + 01$
Li-7	$1,60E + 01$
Be-7	$6,78E + 00$
He-8	$3,25E - 04$
Li-8	$3,51E + 00$
B-8	$1,10E - 01$
Li-9	$6,16E - 03$
Be-9	$2,10E + 01$
C-9	$4,01E - 02$
Be-10	$1,49E + 01$
B-10	$1,99E + 01$
C-10	$1,03E + 00$
Be-11	$2,83E - 01$
B-11	$6,93E + 01$
C-11	$1,22E + 01$
B-12	$3,64E + 00$
C-12	$7,27E + 01$
N-12	$3,11E - 04$
B-13	$5,01E - 01$
C-13	$9,50E + 01$
N-13	$1,73E + 01$
C-14	$1,10E + 02$
N-14	$2,19E + 02$
O-14	$3,97E - 01$
C-15	$7,48E - 04$
N-15	$2,40E + 01$
O-15	$8,70E + 00$
N-16	$7,91E - 01$
O-16	$5,42E + 01$
O-17	$1,99E - 03$
O-18	$6,53E - 05$
Ne-20	$1,25E - 04$
Ne-21	$9,71E - 01$
Na-22	$1,53E - 04$
Al-28	$2,52E - 01$
Si-28	$1,81E - 01$
Si-30	$3,50E - 04$
Si-31	$4,01E - 01$
S-32	$3,22E - 04$
P-33	$8,92E - 04$
S-33	$1,86E - 02$
P-34	$7,41E - 05$
S-34	$5,15E - 03$
S-35	$5,42E - 02$

TABLE 1: Continued.

Isotope	Number of nuclei
Cl-35	$1,42E - 03$
S-36	$6,77E - 02$
Cl-36	$1,13E - 02$
Ar-36	$9,21E - 05$
S-37	$5,74E - 05$
Cl-37	$1,64E - 02$
Ar-37	$4,41E - 02$
Cl-38	$7,48E - 02$
Ar-38	$1,72E + 00$
Cl-39	$5,60E - 03$
Ar-39	$8,78E - 01$
Cl-40	$5,99E - 04$
Ar-40	$1,32E + 00$
K-40	$1,10E - 01$
Ar-41	$1,36E - 01$
Ca-42	$2,44E - 04$

for xi (0), sigma (-), and antilambda. The amount of ^3He has not changed.

In Table 4, numbers of secondary particles generated in inelastic interactions were given. 47 different particles for atmosphere and 50 for Kaidun meteorite were detected by simulations. After each two interactions with CRs, produced maximum particle is neutrons as up to three millions. Also, a small amount of D mesons (D^+) was produced. Judging by the relative differences, maximum changes occur for D-meson (D^+), delta baryon ($D^0\text{BAR}$), and omega baryon. Charmed omega baryons (OMEGAC), tau neutrinos (NEU-TRIT), and their antiparticles (ANEUTRIT) were formed only after CRs-Kaidun interactions.

Finally in Table 5, numbers of decay products have been shown. 26 different decay products for atmosphere and 31 of Kaidun interactions were detected. In these products, there are many photons, electrons, positrons, muons, and neutrinos (electron and tau). Relative difference of anti-xi (+), xi (0), and negative kaon particles is higher than that of other products.

4. Conclusions

Recently, the interest in dark matter investigations, Mars mission studies, and actual cosmological studies is increasing rapidly. On these issues, meteorites, cosmic dust, and cosmogenic subatomic particles from outer space give some hints for researchers. In this paper, we simulated CRs interactions with Earth's atmosphere and Kaidun meteorite by FLUKA code which is a popular CR generator. For this aim, Earth's atmosphere, Kaidun sample, and primary cosmic rays consisting of protons, alphas, and a small amount of other particles were modeled. As for outputs of simulations, produced isotopes and subatomic particles by atmosphere and Kaidun were obtained. Looking at the isotope distributions, 185 types of isotopes were produced after CRs-Kaidun

TABLE 2: Isotope distribution after interactions between CR and Kaidun meteorite.

Isotope	Number of nuclei
H-1	$2,89E + 01$
H-2	$1,41E + 00$
H-3	$3,34E - 01$
He-3	$5,62E - 02$
He-4	$5,41E + 00$
He-6	$4,09E - 02$
Li-6	$2,37E - 04$
Li-7	$3,73E - 04$
Be-7	$1,85E - 05$
Li-9	$2,43E - 06$
Be-9	$4,22E - 06$
B-10	$8,91E - 06$
B-11	$2,66E - 04$
C-11	$4,70E - 04$
B-12	$2,70E - 05$
C-12	$5,41E - 04$
C-13	$2,60E - 04$
N-13	$3,94E - 06$
C-14	$1,09E - 02$
N-14	$2,16E - 03$
C-15	$1,09E - 05$
N-15	$8,53E - 02$
O-15	$1,20E - 05$
N-16	$3,86E - 05$
O-16	$5,72E - 02$
O-17	$6,20E - 02$
F-17	$3,64E - 05$
O-18	$2,04E - 02$
F-18	$8,53E - 04$
F-19	$1,58E - 02$
O-20	$3,72E - 06$
F-20	$1,30E - 03$
Ne-20	$2,39E - 02$
F-21	$2,99E - 04$
Ne-21	$3,12E - 01$
Ne-22	$4,22E - 01$
Ne-23	$2,40E - 02$
Na-21	$5,72E - 05$
Na-22	$8,06E - 02$
Na-23	$2,09E + 00$
Mg-23	$6,04E - 06$
Na-24	$3,09E - 02$
Mg-24	$1,99E - 04$
Al-26	$4,17E - 05$
Mg-27	$4,05E - 08$
Al-27	$2,21E - 02$
Al-28	$1,24E - 03$
Si-28	$5,30E - 03$
Al-29	$1,30E - 05$
Si-29	$5,07E - 03$
Al-30	$3,38E - 03$
Si-30	$6,41E - 02$
P-30	$5,35E - 04$

TABLE 2: Continued.

Isotope	Number of nuclei
Si-31	$2,43E - 06$
P-31	$2,05E - 02$
P-32	$4,95E - 02$
S-32	$1,06E - 01$
P-33	$1,66E - 04$
S-33	$6,57E - 02$
S-34	$1,07E - 01$
Cl-34	$1,18E - 03$
S-35	$3,28E - 05$
Cl-35	$5,72E - 02$
S-36	$3,15E - 04$
Cl-36	$8,91E - 02$
Ar-36	$7,90E - 02$
Cl-37	$6,31E - 02$
Ar-37	$3,54E - 01$
K-37	$4,75E - 06$
Cl-38	$1,30E - 04$
Ar-38	$1,20E - 01$
K-38	$5,57E - 03$
Ca-38	$4,01E - 06$
Cl-39	$1,22E - 03$
Ar-39	$2,31E - 02$
K-39	$3,78E - 01$
Ca-39	$3,47E - 02$
Cl-40	$4,40E - 06$
Ar-40	$5,99E - 05$
K-40	$4,53E - 01$
Ca-40	$3,61E - 01$
K-41	$1,13E - 01$
Ca-41	$1,57E - 02$
Sc-41	$1,51E - 05$
K-42	$1,16E - 03$
Ca-42	$8,91E - 02$
Sc-42	$9,01E - 05$
K-43	$1,08E - 04$
Ca-43	$2,50E - 02$
Sc-43	$4,28E - 04$
Ca-44	$5,46E - 02$
Sc-44	$8,85E - 02$
Ca-45	$1,22E - 03$
Sc-45	$5,30E - 02$
Ca-46	$8,53E - 06$
Sc-46	$2,51E - 02$
Ca-47	$4,37E - 04$
Sc-47	$1,28E - 03$
Sc-48	$6,73E - 05$
Ca-49	$5,88E - 09$
Sc-49	$1,17E - 05$
Ti-44	$3,27E - 03$
Ti-45	$2,85E - 02$
Ti-46	$3,60E - 01$
V-46	$7,42E - 06$
Ti-47	$3,41E - 01$
V-47	$2,82E - 03$

TABLE 2: Continued.

Isotope	Number of nuclei
Ti-48	$2,99E-01$
V-48	$2,24E-01$
Cr-48	$5,46E-02$
Ti-49	$6,89E-02$
V-49	$5,99E-01$
Cr-49	$1,25E-01$
Ti-50	$7,63E-02$
V-50	$6,63E-01$
Cr-50	$7,95E-01$
Mn-50	$1,23E-01$
V-51	$2,11E-01$
Cr-51	$8,80E-01$
Mn-51	$3,54E-01$
V-52	$8,06E-02$
Cr-52	$1,72E+00$
Mn-52	$6,52E-01$
Fe-52	$8,80E-02$
V-53	$1,26E-05$
Cr-53	$7,00E-01$
Mn-53	$1,58E+00$
Fe-53	$4,64E-01$
Cr-54	$2,06E-01$
Mn-54	$2,83E+00$
Fe-54	$2,48E+00$
Co-54	$1,11E-05$
Cr-55	$1,13E-02$
Mn-55	$3,07E+00$
Fe-55	$3,75E+00$
Co-55	$1,23E-01$
Mn-56	$1,02E+00$
Fe-56	$2,46E+01$
Co-56	$2,03E-01$
Ni-56	$3,50E-05$
Mn-57	$3,11E-03$
Fe-57	$2,60E+00$
Co-57	$2,88E-01$
Ni-57	$7,05E-02$
Mn-58	$5,72E-06$
Fe-58	$7,74E-02$
Co-58	$3,33E-01$
Ni-58	$7,32E-01$
Fe-59	$2,25E-03$
Co-59	$9,75E-02$
Ni-59	$2,91E-01$
Co-60	$2,43E-01$
Ni-60	$5,41E-01$
Cu-60	$5,08E-06$
Co-61	$2,13E-03$
Ni-61	$7,32E-02$
Cu-61	$2,34E-02$
Co-62	$2,34E-02$
Ni-62	$2,90E-02$
Ni-63	$2,93E-02$
Cu-63	$2,85E-04$

TABLE 2: Continued.

Isotope	Number of nuclei
Ni-64	$2,49E-02$
Cu-64	$6,52E-06$
Zn-64	$2,98E-04$
Ni-65	$1,08E-04$
Cu-65	$2,99E-04$
Zn-65	$5,99E-04$
Zn-66	$5,94E-04$
Zn-67	$8,53E-04$
Zn-68	$1,81E-03$
Zn-69	$2,60E-04$
Ga-69	$5,62E-06$
Ga-72	$2,75E-05$
As-74	$2,82E-04$
As-75	$4,13E-06$
As-76	$4,62E-05$
Br-82	$7,74E-07$
Kr-83	$6,89E-05$
Kr-84	$1,85E-04$
Rb-84	$8,69E-02$
Ag-108	$8,11E-07$
Ag-110	$2,16E-05$
Cd-114	$3,57E-05$
Ir-192	$5,09E-06$
Au-197	$2,33E-06$

TABLE 3: Number of particles generated by interactions.

Particle name	Number of particle		
	Atmosphere	Kaidun	Relative difference (%)
4-HELIUM	$8,84E+03$	$9,03E+03$	2,13
3-HELIUM	$1,60E+03$	$1,60E+03$	—
TRITON	$2,13E+03$	$2,14E+03$	0,47
DEUTERON	$3,20E+03$	$3,26E+03$	1,86
HEAVYION	$1,03E+03$	$1,09E+03$	5,66
PROTON	$4,57E+05$	$4,61E+05$	0,87
APROTON	$1,56E+03$	$1,60E+03$	2,53
NEUTRON	$1,67E+06$	$1,69E+06$	1,19
ANEUTRON	$1,55E+03$	$1,57E+03$	1,28
MUON+	$4,48E+01$	$4,52E+01$	0,89
MUON-	$4,18E+03$	$4,43E+03$	5,81
PION+	$3,32E+03$	$3,27E+03$	1,52
PION-	$3,22E+03$	$3,20E+03$	0,62
KAON+	$2,47E+01$	$2,18E+01$	12,5
KAON-	$1,24E+01$	$1,39E+01$	11,4
LAMBDA	$6,10E-01$	$3,83E-01$	45,72
ALAMBDA	$3,95E-03$	$7,26E-03$	59,05
SIGMA-	$1,12E-03$	$2,99E-03$	91,00
SIGMA+	$2,51E-03$	$3,24E-03$	25,39
KAONZERO	$2,97E+01$	$3,43E+01$	14,38
AKAONZER	$3,82E+01$	$4,33E+01$	12,52
ASIGMA-	$1,51E-04$	$2,09E-04$	32,22
ASIGMA+	$2,75E-04$	$1,71E-04$	46,64
XSIZERO	$1,18E-04$	$4,48E-04$	116,61
AXSIZERO	$1,09E-04$	$1,88E-04$	53,20
AXSI+	$1,25E-04$		

TABLE 4: Number of secondaries generated in inelastic interactions.

Particle name	Number of particle		
	Atmosphere	Kaidun	Relative difference (%)
4-HELIUM	1,80E + 06	1,82E + 06	1,10
3-HELIUM	1,31E + 05	1,33E + 05	1,52
TRITON	1,30E + 05	1,31E + 05	0,77
DEUTERON	3,00E + 05	3,02E + 05	0,66
PROTON	2,41E + 06	2,44E + 06	1,24
APROTON	1,44E + 03	1,47E + 03	2,06
ELECTRON	1,38E + 02	1,35E + 02	2,20
POSITRON	1,38E + 02	1,34E + 02	2,94
NEUTRIE	2,89E - 02	7,12E - 02	84,52
ANEUTRIE	4,89E - 01	9,96E - 01	68,28
PHOTON	7,90E + 05	8,03E + 05	1,63
NEUTRON	3,09E + 06	3,13E + 06	1,29
ANEUTRON	1,44E + 03	1,46E + 03	1,38
MUON+	5,68E + 01	5,16E + 01	9,59
MUON-	4,26E + 01	4,12E + 01	3,34
KAONLONG	2,04E + 02	1,74E + 02	15,87
PION+	2,92E + 05	2,94E + 05	0,68
PION-	2,77E + 05	2,79E + 05	0,72
KAON+	1,19E + 04	1,20E + 04	0,84
KAON-	4,32E + 03	4,37E + 03	1,15
LAMBDA	6,70E + 03	6,86E + 03	2,36
ALAMBDA	1,41E + 02	1,39E + 02	1,43
KAONSHRT	2,03E + 02	1,79E + 02	12,57
SIGMA-	2,01E + 03	1,98E + 03	1,50
SIGMA+	2,35E + 03	2,34E + 03	0,43
SIGMAZER	3,55E + 03	3,53E + 03	0,56
PIZERO	3,64E + 05	3,67E + 05	0,82
KAONZERO	1,14E + 04	1,14E + 04	—
AKAONZER	4,11E + 03	4,16E + 03	1,21
NEUTRIM	4,15E + 03	4,39E + 03	5,62
ANEUTRIM	2,97E - 01	3,08E - 01	3,64
ASIGMA-	4,62E + 01	4,46E + 01	3,52
ASIGMAZE	4,26E + 01	4,25E + 01	0,24
ASIGMA+	4,15E + 01	4,68E + 01	12,00
XSIZERO	1,28E + 02	1,26E + 02	1,57
AXSIZERO	8,77E + 00	1,08E + 01	20,75
XSI-	1,09E + 02	1,09E + 02	—
AXSI+	8,21E + 00	8,82E + 00	7,16
OMEGA-	3,93E - 01	6,92E - 02	140,11
AOMEGA+	8,51E - 01	1,10E + 00	25,53
D+	1,34E - 04	2,40E - 03	178,85
D-	2,29E - 04	2,35E - 04	2,59
D0	6,17E - 04	3,45E - 04	56,55
D0BAR	3,51E - 04	2,98E - 03	157,85
DS+	6,74E - 05	1,45E - 04	73,07
DS-	2,54E - 04	8,29E - 05	101,57
LAMBDA+	1,34E - 04	3,17E - 04	81,15
NEUTRIT		2,30E - 03	
ANEUTRIT		2,30E - 03	
OMEGAC0		9,17E - 05	

TABLE 5: Decay products generated in inelastic interactions.

Particle name	Number of particle		
	Atmosphere	Kaidun	Relative difference (%)
PROTON	7,96E + 03	8,05E + 03	1,12
APROTON	1,55E + 02	1,52E + 02	1,95
ELECTRON	2,92E + 05	2,94E + 05	0,68
POSITRON	3,10E + 05	3,12E + 05	0,64
NEUTRIE	3,05E + 05	3,07E + 05	0,65
ANEUTRIE	2,87E + 05	2,89E + 05	0,69
PHOTON	7,70E + 05	7,75E + 05	0,65
NEUTRON	6,90E + 03	6,89E + 03	0,15
ANEUTRON	1,34E + 02	1,41E + 02	5,09
MUON+	3,13E + 05	3,15E + 05	0,64
MUON-	2,97E + 05	3,00E + 05	1,01
PION+	1,48E + 04	1,47E + 04	0,68
PION-	2,01E + 04	2,02E + 04	0,50
KAON+	5,43E - 01	7,37E - 01	30,31
KAON-	2,30E - 01	4,76E - 02	131,41
LAMBDA	3,79E + 03	3,76E + 03	0,79
ALAMBDA	6,04E + 01	6,32E + 01	4,53
SIGMA+	6,47E - 05	—	
PIZERO	2,16E + 04	2,14E + 04	0,93
KAONZERO	2,33E - 04	5,30E - 04	77,85
AKAONZER	4,09E - 04	7,94E - 04	64,01
NEUTRIM	5,98E + 05	6,02E + 05	0,66
ANEUTRIM	6,01E + 05	6,05E + 05	0,66
XSIZERO	1,64E - 01	8,05E - 04	198,05
AXSIZERO	3,08E - 01	1,96E - 01	44,44
AXSI+	1,54E - 04	1,67E - 01	199,63
KAONLONG	—	5,74E - 05	
KAONSHRT	—	5,74E - 05	
XSI-	—	2,35E - 02	
TAU-	—	8,29E - 05	
NEUTRIT	—	8,29E - 05	
ANEUTRIT	—	8,29E - 05	

interactions. Also, differences in the number of particles produced from atmosphere and Kaidun interactions are outstanding. For example, tau neutrinos which do not occur after CRs-atmosphere interactions have been observed after CRs-Kaidun interactions. Given results as a result of this paper may be useful for space and particle researchers.

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