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The formation of the cosmic ray energy spectrum by a photon field

S. Karakula and W. Tkaczyk
Institute of Physics, University of Lodz, ul. Pomorska 149/153, 90-236 Lodz, Poland

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The formation of the energy spectrum and mass composition of cosmic rays (CR) has been analyzed taking into consideration the model in which the nuclei (from hydrogen to iron) are accelerated by discrete sources. The spectra of produced nuclei are next modified due to their interactions with soft background UV photons in the source region. The photonuclear reactions (photodisintegration of nuclei) and proton energy losses due to photomeson production are considered.

The shape of the energy spectrum and mass composition of cosmic ray particles have been calculated and compared with the experimental data.

1. Introduction

The mass composition and energy spectrum of cosmic rays provide useful information for investigation of their acceleration and propagation. The mass composition, the energy spectra of different components, and the distribution of arrival directions are the basic data in the studies of the origin of cosmic rays and their propagation between sources and the observer. The studies of the mass composition are potentially the most incisive (because they relate to the source composition) but technically very difficult, since the flux of nuclei at high energy range is very low. To clarify the origin of cosmic rays it is important to exclude one of two extreme possibilities: that the primary cosmic rays particles are pure protons or very heavy nuclei (iron). The primary mass composition below about 10^{14} eV/nucleus can be measured directly using balloon and satellite exposures e.g. Burnett et al. [1]. Above 10^{14} eV/nucleus the information about the cosmic ray mass composition is indirect and can be drawn from underground muon experiments and extensive air shower (EAS) investigations at ground level and mountain altitudes (e.g. Nikolsky and Stamenov [2]). In the energy range 10^{15}–10^{16} eV the evidence about the mass composition of cosmic rays is very contradictory. Some results show a growing fraction of heavy nuclei (e.g. Amenomori et al. [3]), although other results do not confirm it (e.g. Stamenov et al. [4]; Muraki [5]). Moreover, on the basis of experimental data on muon and electron fluctuations in extensive air showers, Nikolsky and Stamenov [2] show the tendency of an increasing fraction of energetic protons in the cosmic rays. Earlier Walker and Watson [6] found results consistent with a pure proton primary composition above 2×10^{17} eV. On the basis of Yakutsk data, Doronina et al. [7] suggest that the proton component near 5×10^{17} eV is $(50 \pm 10)\%$ and increases to $(90 \pm 10)\%$ at 5×10^{19} eV. Summarizing, our knowledge concerning the cosmic ray mass composition above 10^{14} eV is not clear and is still a matter of investigations (see e.g. the review paper of Lloyd-Evans [8]).

The composition of cosmic rays and its energy dependence have been analysed in different models of cosmic ray propagation. Several explanations have been proposed to describe the observed steepening of

Correspondence to: S. Karakula, Institute of Physics, University of Lodz, ul. Pomorska 149/153, 90-236 Lodz, Poland.

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the all-particle cosmic ray spectrum around 3×10^{15} eV. The rigidity cut-off model predicts an iron-rich composition of cosmic rays near the "knee", because the spectrum of proton, and subsequently light nuclei, steepens due to leakage from the Galaxy (Peters [9]). The model suggested by Hillas [10] in which nuclei are removed from the beam due to photodisintegration processes near the sources, predicts an iron-poor composition of the cosmic rays.

In this paper we analyze the formation of the energy spectrum and the mass composition of cosmic rays in the model in which primary energy spectra of particles produced by discrete sources are modified by photodisintegration of nuclei and energy losses of protons due to photomeson production (Karakula et al. [11,12], Karakula and Tkaczyk [13]).

2. Analysis and results

2.1. Model description

We have considered the model of cosmic ray point sources with the following assumptions:

(i) point sources produce nuclei with mass number $A = 1$–56 (from hydrogen to iron) continuously with a power law type ($\sim E^{-\gamma}$) differential energy spectrum of the particular nuclei;

(ii) the background photon spectrum around sources can be thermal (Planckian) or a power law type $n(\epsilon) = (\rho/\rho_0)\epsilon^{-\alpha}$ ($\mathrm{cm}^{-3}\ \mathrm{eV}^{-1}$) for $\epsilon \leq \epsilon_m$ and zero for $\epsilon > \epsilon_m$;

(iii) the relative mass composition of produced nuclei by sources are the same as was obtained in low energy experiments: Tien Shan (Nikolsky [14]), NUSEX and Maryland (Aglietta et al. [15]). For Tien Shan normalization we assumed power index $\gamma = 2.6$ for all nuclei.

2.2. The photodisintegration process

The interactions between photons and high energy nuclei have important consequences both for the mass composition and for the energy spectrum of cosmic rays. The nuclei lose their energy due to e^+e^--pair production or can be removed from the beam completely and appear as lighter nuclei by photodisintegration (photonuclear) processes (see, e.g., Berezinskii et al. [16]). The energy losses of nuclei, in the considered energy region, due to pair creation are much less than via photodisintegration, so we include only the latter.

The reciprocal mean free path for a nucleus of mass A for photodisintegration is given by the expression

$$\lambda_A^{-1} = \frac{1}{2\gamma_A^2} \int_{\epsilon_1}^{2\gamma_A \epsilon_m} \epsilon^* \sigma_A(\epsilon^*)\, \mathrm{d}\epsilon^* \int_{\epsilon^*/2\gamma_A}^{\epsilon_m} n(\epsilon) \frac{\mathrm{d}\epsilon}{\epsilon^2}, \tag{1}$$

where $n(\epsilon)$ is the density of ambient photons with energy ϵ in the observer's system, ϵ^* is the energy of the photon in the rest system of the nucleus, γ_A is the Lorentz factor of the nucleus, $\sigma_A(\epsilon^*)$ is the photodisintegration cross section.

The photodisintegration cross section for losing one nucleon by a nucleus of mass number A was obtained by approximation of the experimental data (Bishop and Wilson [17]; Kinsey [18]) and is expressed by

$$\sigma_A(\epsilon^*) = \begin{cases} \sigma_0(A) \dfrac{(\epsilon^* T)^2}{(\epsilon^{*2} - \epsilon_0^2)^2 + (\epsilon^* T)^2}, & \text{for } \epsilon^* \leq 30 \text{ MeV}, \\ A/8 \text{ mb}, & \text{for } \epsilon^* > 30 \text{ MeV}, \end{cases} \tag{2}$$

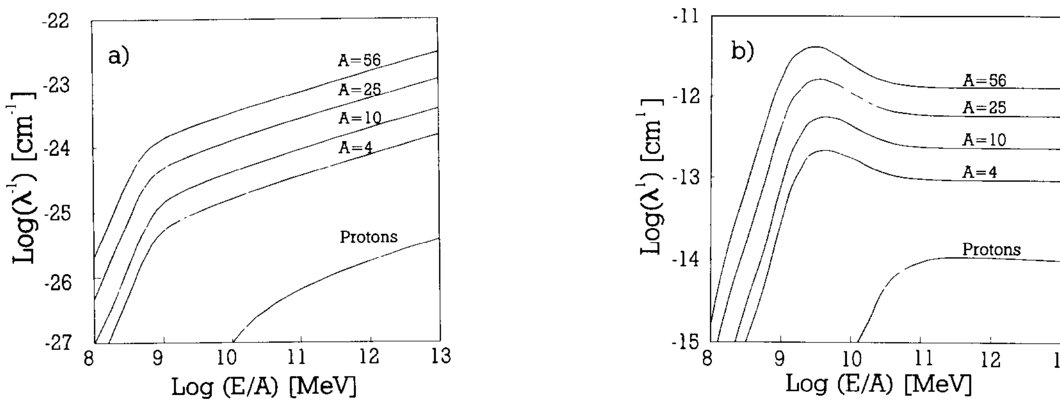

Fig. 1. The reciprocal mean free path for photodisintegration of nuclei and the reciprocal mean interaction length of protons for photomeson production calculated for a background photon spectrum of power law (a) and Planckian (b) type.

where $\sigma_0(A) = 1.45 \times 10^{-27} \times A$ cm^2, $T = 8$ MeV is the energy bandwidth of the giant resonance, $\epsilon_0 = 42.65 \times A^{-0.21}$ MeV for $A > 4$ and $\epsilon_0 = 0.925 \times A^{2.433}$ MeV for $A \leq 4$, the peak energy of the giant resonance.

For numerical calculation we have taken a threshold energy of $\epsilon_1 = 2$ MeV in the rest system of the nucleus.

Figure 1 shows the reciprocal mean free path of various nuclei for photodisintegration and the reciprocal mean interaction length of protons for photomeson production, calculated for the background photon spectrum: power law with parameters $\epsilon_m = 20$ eV, $\alpha = 1.3$, $\rho/\rho_0 = 1$ (fig. 1a) and Planckian with $kT = 1.8$ eV (fig. 1b). We note that such large differences between the mean free path lengths in the cases of Planckian and power-law spectra are because of different normalizations of the spectra.

2.3. The energy spectra of cosmic nuclei

During propagation in a space filled by low energy photons nuclei lose nucleons one by one due to photodisintegration processes. Proton energy losses due to photomeson production are also included.

The energy spectra of nuclei with mass number A at the propagation distance x have been obtained by solving the appropriate diffusion equations:

$$\frac{\partial N_i}{\partial x}(E, x) = -a_i(E)\, N_i(E, x) + a_{i-1}(E)\, N_{i-1}(E, x), \quad \text{for } i = 1, 2, \ldots, 54, \tag{3}$$

$$\frac{\partial N_0}{\partial x}(E, x) = -a_0(E)\, N_0(E, x), \quad \text{for } i = 0. \tag{4}$$

Here $i = 56 - A$, A is the mass number of the nucleus, E is the energy per nucleon of the nucleus; $N_i(E, x)$ is the differential flux of nuclei with mass number $A = 56 - i$ and energy E at the propagation distance x from the source; and $a_i(E)$ is the reciprocal mean free path of nuclei with mass number $A = 56 - i$ for photodisintegration.

In general form, the solution of eqs. (3) and (4) (obtained jointly with I.V. Moskalenko) is given by

$$N_i(E, x) = \sum_{j=0}^{i} b_{ij}(E) \exp(-a_j(E)\, x), \tag{5}$$

where

$$b_{00}(E) = N_0(E, 0) \tag{6}$$

and other coefficients one finds by the recurrence formula:

$$\begin{aligned} b_{ik}(E) &= \frac{a_{i-1}(E)\, b_{i-1k}(E)}{a_i(E) - a_k(E)}, && \text{for } k < i, \\ b_{ii}(E) &= N_i(E, 0) - \sum_{n=0}^{i-1} b_{in}(E), && \text{for } k = i. \end{aligned} \tag{7}$$

We note that the above solution is the same as that obtained by Karakula et al. [11], but in a form more convenient for the following applications.

We have started to solve the diffusion equation from iron ($i = 0$), and the spectra of nuclei with mass number $A < 56$ were evaluated subsequentially.

The composition of nuclei at the propagation distance x was calculated versus energy per nucleon and then recalculated to energy per nucleus. Nuclei were then collected into groups: p, primary protons (produced by source); p_A, secondary protons (from photodisintegration); α ($A = 2$–4); L ($A = 5$–9); M ($A = 10$–16); H ($A = 17$–40); VH ($A > 40$).

2.4. *The secondary protons – from photodisintegration*

The energy spectrum of the secondary protons (from photodisintegration) have been obtained by solving the equation,

$$\frac{\partial P_i(E, x)}{\partial x} = a_i(E)\, N_i(E, x), \tag{8}$$

where $i = 56 - A$, $P_i(E, x)$ is the differential flux of protons of energy E from fragmentation of nuclei with mass number $A = 56 - i$ at distance x from the source, and $a_i(E)$ and $N_i(E, x)$ are as above.

The solution of eq. (8) is

$$P_i(E, x) = \sum_{j=0}^{i} \frac{a_i(E)\, b_{ij}(E)}{a_j(E)} \big(1 - \exp(-a_j(E)\, x)\big). \tag{9}$$

The total flux of protons of energy E at the propagation distance x (from photodisintegration of nuclei from iron to deuterium) is given by:

$$P(E, x) = \sum_{i=0}^{54} P_i(E, x). \tag{10}$$

2.5. *Propagation of the high energy protons – photomeson production process*

During propagation in a space filled by background photons the high energy protons suffer considerable energy losses due to photomeson production. These energy losses influence significantly the energy spectrum of protons in the high energy region.

The energy spectrum of protons at the propagation distance x have been obtained by solving the diffusion equation:

$$\frac{\partial P(E, x)}{\partial x} = -g(E)\, P(E, x) + g\left(\frac{E}{1-K}\right) P\left(\frac{E}{1-K}, x\right) \frac{1}{(1-K)}, \tag{11}$$

where $P(E, x)$ is the differential flux of protons with energy E at the propagation distance x from the source, K is the coefficient of inelasticity for the pγ-reaction, $g(E)$ is the reciprocal mean free path of protons for photomeson production. In calculations we have assumed that K is the same for all energies of protons ($K = 0.3$).

The solution of this equation (obtained by method of successive generation) is

$$P(E, x) = \sum_{l=0}^{\infty} P_l(E, x), \tag{12}$$

where:

$$P_l(E, x) = \begin{cases} P(E, 0)\exp(-g(E)x), & \text{for } l = 0 \\ \dfrac{P\left(\dfrac{E}{(1-K)^l}, 0\right)}{(1-K)^l} \displaystyle\prod_{j=1}^{l} g\left(\frac{E}{(1-K)^j}\right) \sum_{n=0}^{l} \frac{\exp\left\{-g\left(\dfrac{E}{(1-K)^n}\right) x\right\}}{\displaystyle\prod_{\substack{m=0 \\ m\neq n}}^{l} \left[g\left(\dfrac{E}{(1-K)^m}\right) - g\left(\dfrac{E}{(1-K)^n}\right)\right]}, & \\ \text{for } l > 0 & \end{cases} \tag{13}$$

and $P(E, 0)$ is the flux of protons at $x = 0$.

2.6. Comparison with experimental data

The spectra of particular nuclei with mass number A have been calculated by solving the propagation equations. The calculated spectra of the nuclei were collected into groups: p, α, L, M, H, VH. The propagation distance x was found from the best fit of the calculated spectrum to the observed one. Table 1 contains parameters of the best fit in the case of a power law ($\alpha = 1.3$) and a Planckian background photon spectra for Tien Shan (Nikolsky [14]), NUSEX and Maryland (Aglietta et al. [15]) normalizations. We note that the solution of the propagation equation is the same for the constant product $x\rho$ (propagation distance and photon energy density). Figure 2 shows the comparison of the cosmic ray energy spectrum (the data, collected by Hillas [19], coming from different experiments: Proton-4, Tien Shan, Haverah Park, Yakutsk and Akeno) with the spectrum expected from our model, calculated for the case of a mass composition taken from the Tien Shan EAS experiment at energy

Table 1

	Planck			Power law		
	kT (eV)	log x (cm)	ρx (eV/cm^2)	ϵ_m (eV)	log x (cm)	ρx (eV/cm^2)
Tien Shan	1.8	14.4	2.25×10^{29}	20	26.4	1.84×10^{29}
NUSEX	0.6	15.6	4.41×10^{28}	8	26.2	6.12×10^{28}
Maryland	1.4	14.5	1.04×10^{29}	8	26.3	7.71×10^{28}

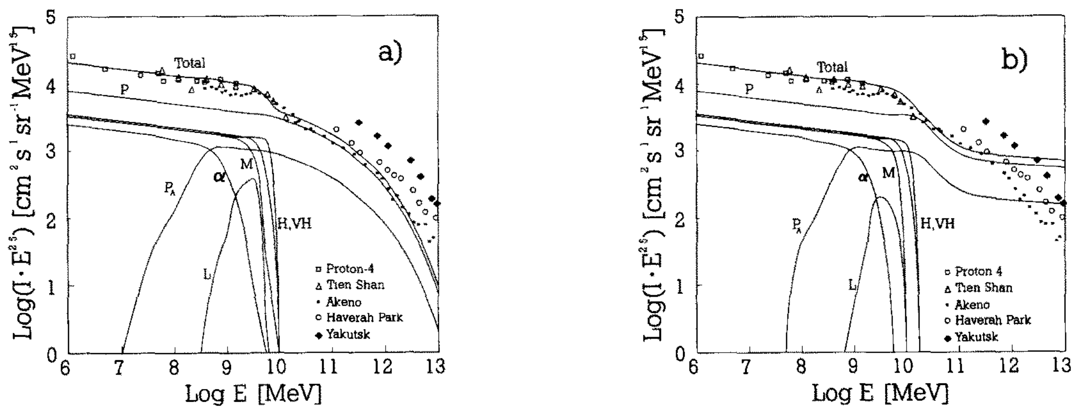

Fig. 2. Comparison of the cosmic ray energy spectrum with the spectrum obtained in our model calculated for Tien Shan normalization and a background photon spectrum of power law (a) and Planckian (b) type.

1.5×10^{15} eV (Nikolsky [14]) and the background photon spectra of power law or and Planckian type. The best fit of the experimental data with the calculation was obtained for a power law photon spectrum with power index $\alpha = 1.3$, cut-off at energy $\epsilon_m = 20$ eV (fig. 2a), and for a Planckian distribution with $kT = 1.8$ eV (fig. 2b). In fig. 2 we also show the spectra of particular groups of nuclei. The curves are labeled by p for primary protons, p_A for secondary protons and groups of nuclei α, L, M, H, VH.

The sensitivity of our model to input parameters, such as relative mass composition below the "knee" and background soft photon spectra, is shown in fig. 3. Figure 3 shows the comparison of the cosmic ray energy spectrum (the experimental data, collected by Hillas [19]) with the one expected from our model calculated for Tien Shan (TS), NUSEX (N) and Maryland (M) relative mass composition and background photon spectrum power-law (p-l) and black-body (b-b). In fig. 4 is shown the cosmic ray mass composition as a function of energy predicted by our model. On the vertical axis is the mean value of the logarithm of mass number A ($\langle \ln A \rangle$). The experimental data come from several experiments: the black circles are from the direct observations by balloon and satellite (see Watson [20]), the black diamonds from the JACEE experiment (Burnett et al. [1]), the open diamond from the JACEE experiment (Asakimori et al.

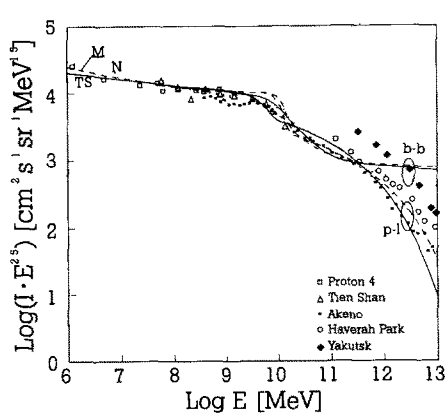

Fig. 3. Comparison of the cosmic ray energy spectrum with that expected from our model calculated for Tien Shan (TS), NUSEX (N) and Maryland (M) normalization and a background photon spectrum of power law (p-l) and Planckian (b-b) type.

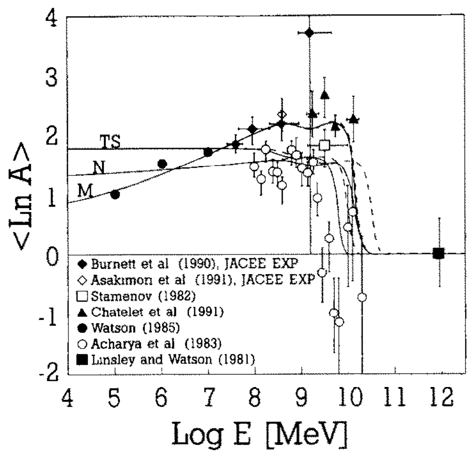

Fig. 4. The comparison of the mean mass composition ($\langle \ln A \rangle$) of cosmic rays calculated in our model for Tien Shan (TS), NUSEX (N), Maryland (M) composition and a background photon spectrum of power law (solid lines) and Planckian (dotted lines) type with experimental data.

[21]), the black triangles from (Chatelet et al. [22], the open square from (Stamenov [23]), the open circles are the data by Acharya et al. [24], the black square is from Linsley and Watson [25]. The mean mass predicted by our model was calculated for Tien Shan (TS), NUSEX (N) and Maryland (M) normalization and background photon spectrum of power law (solid lines) and Planckian (dotted lines) type.

3. Discussion and conclusions

The shape of the cosmic ray energy spectrum in a wide energy region as well as the observed "knee" at an energy of about 3×10^{15} eV can be very well described by our model. The agreement between the energy spectrum expected from our model and experimental data is good up to about 3×10^{17} eV for both power law and Planckian background photon spectra (see fig. 3). Above 3×10^{17} eV the better description of the experimental data is obtained for the nonthermal soft photon spectrum with power index $\alpha = 1.3$ and cut-off at energy $\epsilon_m = 20$ eV. This is because the thermal spectrum suppresses protons in a narrow energy range, which corresponds to its maximum. This effect appears in fig. 4 and is caused by the difference in the interaction lengths (figs. 1a and 1b). The same shape of the cosmic ray energy spectrum can be obtained for the thermal background photon spectrum if protons are lost through an additional process, for example leakage from the storage region. In order to describe the observed CR energy spectrum in the energy range from "knee" up to 10^{19} eV in the case of a cosmic ray source with a thermal soft photon spectrum, the source should be linked with a leakage effect of CR from the Galaxy. In that case significant leakage of protons from the Galaxy can give a heavier mass composition of CR in the UHE range.

Our results for mass composition are shown in fig. 4. The calculated mean mass composition of CR ($\langle \ln A \rangle$) as a function of energy for both Tien Shan and NUSEX normalizations, remains almost constant up to an energy of a few times 10^{16} eV and at higher energies falls quickly to zero (only protons). For the Maryland normalization, the situation is a little different at low energy, but is the same at high energy. The comparison between the mean mass composition of CR expected from our model with experimental data shows good agreement for the case of Maryland normalization as well as for power law and Planckian soft background photon spectra.

The analysis of the world's EAS data made by Chi et al. [26–28] shows some indications that CR sources are of Galactic origin and suggests a large flux of heavy nuclei at energy above 10^{19} eV. If these indications are confirmed our model should be modified in order to describe such features. The modification would involve the energy spectrum of soft photons and/or include such effects as leakage of particles and different propagation distances of particular nuclei in the source region.

Taking into account that the luminosity of a source in ultraviolet band is $L_{\mathrm{UV}} = 4\pi R^2 \rho c$ and $R \leq x$, one can find inequality $L_{\mathrm{UV}} \leq 4\pi R x \rho c \leq L_{\mathrm{Edd}}$, where L_{Edd} is the Eddington luminosity ($L_{\mathrm{Edd}} = 4\pi G M m_{\mathrm{p}} c/\sigma_{\mathrm{T}}$), R is the radius of the source. For a mass of a source equal to the solar mass and $x\rho = 1.2 \times 10^{29}$ eV/cm^2 (as above, see table 1; the solution of the propagation equation is the same for the constant product $x\rho$) it is possible to estimate a radius of the source R as equal or less than $\sim 10^9$ cm. This is a strong evidence of the compactness of the CR sources. We note that the linear dimension of the source region R can be smaller than the propagation distance of particles x if magnetic field confinement of particles in the source region takes place.

The secondary products of interactions of nuclei and protons with the background photons are the photons created due to deexcitation of nuclei and due to π^0 decay from photopion production. In the case of a thin, soft photon field around the CR source, deexcitation of nuclei and photopion production give the main contributions in the VHE (TeV) and UHE (PeV) energy regions, respectively. If the CR source is surrounded by an extended soft photon field, the VHE gamma rays will be absorbed by $\gamma\gamma \to e^+e^-$. In this case an electromagnetic cascade will be developed, and the object will be seen as a high energy (GeV) gamma ray source. In our forthcoming paper we analyze the processes of generation of VHE gamma rays during the propagation CR through a soft photon field.

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