Mechanisms of the production of leading neutral pions

O A Novolodskaya, T Kh Sadykov, N N Zastrozhnova and M K Zhunusbekov
Institute for Physics and Technology, Almaty, Kazakhstan
E-mail:sadykov@sci.kz

Abstract. This work analyzes the most probable mechanisms of the production of leading π^0-mesons in gamma families. It was shown that major contribution to the generation of leading neutral mesons is made by the process of non-elastic recharging of an incident pion.

1. Introduction
Over a long period of time at Tien Shan high-altitude cosmic rays station, located at the height of 3340 m above the sea level, an experiment of studying cosmic radiation hadrons in the field of energy $E \geq 10^{13}$ eV has been carried out. These studies were carried out at the complex units «Hadron-9» and «Hadron-44» [1] that consist of ionizing calorimeters, X-ray emulsion chambers and special targets.

During the generation of families of $\gamma$-rays the essential role is played by the interaction of primary pions with atomic target nuclei [2]. It has been found out that the share of energy, transferred into the neutral component - $K\pi^0$ during the pions collisions is higher than during the interaction of nucleons. Besides, experiments on accelerators show that in p-p interactions, unlike π-p interactions $\gamma$ - rays with $U > 0.2$, where $U=E_\gamma/E_0$ are actually unavailable. For example, under the radiation of a stack of nuclear emulsions, alternating with the layers of lead filters, in the proton beam at $E=303$ GeV it was found that the share of interactions with the $\gamma$ - ray with energy $U > 0.1$ does not exceed 1.5 % [3]. According to the data [4], obtained from the coming beams at $E=1500$ GeV, energy spectrum of $\gamma$ - rays actually fall to zero at $U \sim 0.15$. At the same time, according to the results of the research in [5] the spectrum of $\gamma$ - rays from π- p interactions at $E=205$ GeV stretches to the values of $U=0.7$-0.8, which indicates the difference in the mechanisms of the generation of energetic $\gamma$ - rays in π- p and p-p interactions.

It is known that in the mountains the flow of nuclear active particles consists of the mixture of nucleons and pions; moreover, the share of pions in the hadron flow, according to various estimates, varies from 30 to 50 % [6]. Thus, it may be suggested that the advent of leading $\pi^0$-mesions in the mountains, generating the family of $\gamma$-rays, occurs, mostly, in the interaction of attacking pions with atomic nuclei of the matter.

There are many approaches in cosmic rays physics to the explanation of the mechanism of the generation of leading secondary particles, e.g., production of fireballs, isobars, different resonance states. However, the most adequate interpretation of the advent of leading, i.e. energy releasing $\pi^0$-mesons, in our opinion, lies in two processes – diffraction dissociation and non-elastic recharging of an incident pion [7].

2. Experimental data
We have analysed 1157 interactions in the carbonic target ($x~0.15 \lambda_m$) and 1209 interactions that occurred in iron target ($x~0.18 \lambda_m$), recorded on complex units «Hardon-9» and «Hardon-44». The
analysis results show that the share of the interactions, generating the leading neutral pions with the relative energy \( U_{\pi^0} = \frac{E_{\pi^0}}{E_0} \) in collisions of hadrons with nuclei, of both carbon and iron, does not depend on the primary energy and the atomic number of the target nucleus.

Experimental data on the probability of non-elastic recharging of charged pions into neutral during their interaction with carbon nuclei in the range of primary energies \( E = 10-50 \text{ TeV} \) and with the iron nuclei in the range of primary energies \( E = 10-70 \text{ TeV} \), expressed in the share of the leading \( \pi^0 \)-mesions with different relative energies \( U_{\pi^0} \) are shown in table 1, table 2.

**Table 1.** Relative number of \( \pi^0 \)-mesions depending on \( E_0 \) and \( U_{\pi^0} \) for carbon target.

| \( U_{\pi^0} \) | \( E_0 \), TeV | 10-15 | 15-30 | 30-50 |
|----------------|---------------|-------|-------|-------|
| \( \geq 0.2 \) | \( 0.22\pm0.04 \) | \( 0.20\pm0.05 \) | \( 0.20\pm0.06 \) |
| \( \geq 0.3 \) | \( 0.14\pm0.03 \) | \( 0.09\pm0.05 \) | \( 0.11\pm0.07 \) |
| \( \geq 0.4 \) | \( 0.09\pm0.03 \) | \( 0.10\pm0.05 \) | \( 0.08\pm0.06 \) |
| \( \geq 0.5 \) | \( 0.06\pm0.02 \) | \( 0.06\pm0.03 \) | \( 0.05\pm0.06 \) |

**Table 2.** Relative number of \( \pi^0 \)-mesions depending on \( E_0 \) and \( U_{\pi^0} \) for iron target.

| \( U_{\pi^0} \) | \( E_0 \), TeV | 10-15 | 15-30 | 30-70 |
|----------------|---------------|-------|-------|-------|
| \( \geq 0.2 \) | \( 0.22\pm0.04 \) | \( 0.23\pm0.04 \) | \( 0.25\pm0.05 \) |
| \( \geq 0.3 \) | \( 0.17\pm0.03 \) | \( 0.17\pm0.03 \) | \( 0.14\pm0.04 \) |
| \( \geq 0.4 \) | \( 0.13\pm0.03 \) | \( 0.10\pm0.03 \) | \( 0.13\pm0.04 \) |
| \( \geq 0.5 \) | \( 0.07\pm0.03 \) | \( 0.13\pm0.04 \) | \( 0.08\pm0.04 \) |

From the data, given in tables 1, 2 it may be concluded that the share of interactions with the generation of leading \( \pi^0 \)-mesions with different relative energies \( U_{\pi^0} \) does not change within experiment errors with the growth of \( E_0 \) and for the meanings of \( U_{\pi^0} \geq 0.2 \) is \( \eta = 0.23 \pm 0.02 \).

The process of nucleon diffraction dissociation may clarify a large share of observed interactions with the production of superthreshold \( \gamma \)-rays. For example, at the energy of 30 TeV-up to 25\% interactions with the production of superthreshold \( \gamma \)-rays and about 6\% all interactions may represent the same processes [8].

Figure 1 shows an estimated differential spectrum of \( \pi^0 \)-mesons, from the decay of diffraction excitation of a heavy cluster.

The range of \( \pi^0 \)-mesons from diffraction processes, given in fig. 1 shows that in the processes of nucleon diffraction dissociation \( \pi^0 \)-mesons with the energy of more than 0.3 \( E_0 \) may not be produced. Theoretical assessments [9] for the considered energy region demonstrate that jointly the processes of incident nucleon and pion diffraction dissociation may explain 3-5\% of the number of the observed leading \( \pi^0 \)-mesons, selected by criterion \( U > 0.2 \).

Therefore, it is possible to state that the processes of diffraction dissociation of incident hadrons, included into cosmic radiation in the mountainous areas, enable to explain generation of neutral pions (\( \gamma \)-rays) with high energy up to the values of parameter \( U = 0.2 \). At the same time, diffraction mechanism cannot ensure the required share of \( \pi^0 \)-meson generation with the energies \( E_{\pi^0} \geq 0.2E_0 \); these leading \( \pi^0 \)-mesons are produced in the process of recharging an incident charged pion.

Basing on the above results it is possible to evaluate the probability of non-elastic recharging -W, giving the share of pions in the flow of hadrons in the mountains.
Supposing that in the mountains the flow of nuclear active particles consists of the mixture of nucleons and pions, where the share of pions in the flow of hadrons is from 30 to 50 %, the probability of recharging \( \pi^\pm \rightarrow \pi^0 \) at \( U \geq 0.2 \) is \( W(U > 0.2) = 0.47 \pm 0.08 \). The found value of the probability of non-elastic recharge under the interaction with the nuclei of iron in fact coincides with the \( W \) value for the carbon target, mean probability value of the non-elastic recharge for interactions with carbon and iron target is \( W = 0.46 \pm 0.05 \).

Conclusion
Summarizing the aforesaid, it can be concluded that the main mechanism leading to the production of leading neutral pions under the interaction of cosmic ray hadrons is the process of non-elastic recharging of an incident pion.

References
[1] Novolodskaya O A 2004 Tashkent The collected papers of the Second International Conference Fundamental and applied questions of physics p 41.
[2] Murzin V S 1974 Multiple processes at high energy (Moscow: Atomizdat) p 366.
[3] Fuchi 1977 Proceedings of the 15th ICRC (Plovdiv) vol 7 p 73.
[4] Neuhoffer G 1972 Phys. Lett. B 38 51.
[5] Ljung D 1976 Multiplicities of charged and neutral particles in \( \pi p \) interactions at 205 GeV/c (Fermilab Pub) p 76.
[6] Yakovlev I 1979 Kyoto Proceedings of the 16th ICRC vol 7 p 94.
[7] Kuchin I A 1984 Diffraction dissociation (Almaty: Nauka) p 150.
[8] Yuldashbaev T S, et al. 2001 Proceedings of the 27th ICRC (Hamburg ) p 1432.