Study of primary nuclei composition in the knee region using the Cronin effect

C.E. Navia[1], C.R.A. Augusto[1], V. Kopenkin[1,2], Y.Fujimoto[3], M. Moriya[3], A.Ohsawa[4], A.K. Managadze[2], I.V. Rakobolskaya[6], T.M.Roganova[2], L.G.Sveshnikova[2], E.H.Shibuya[5], and S.L.C. Barroso[5]

[1]*Instituto de Física, Universidade Federal Fluminense, 24210-130, Niterói, RJ, Brazil*
[2]*Institute of Nuclear Physics, Moscow State University, Moscow, 119899, Russia*
[3]*Advanced Research Center for Science and Engineering,Waseda University, Tokyo 169, Japan*
[4] *Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan*
[5]*Instituto de Fisica, Gleb Wataghin, UNICAMP, 13083-970, Campinas, Sao Paulo, Brazil*
[6]*Physical department of Moscow State University, Moscow, 119899, Russia*

Abstract

It is shown that the Cronin effect in nucleus-nucleus collision leads to an efficient and compact way to obtain the fraction high energy hadron-gamma families ($\Sigma E_{vis} > 100$ TeV) induced by primary heavy nuclei. The cosmic ray families are detected by thick lead X-ray emulsion chambers at high mountain altitudes at Pamir (4300 m, $595 g/cm^2$). The comparison of simulation calculations (UA5 model) and experiment shows that the fraction of families induced by heavy primaries in the energy region $100 TeV \leq \Sigma E_{vis} \leq 700 TeV$ is about $2-3\%$. However, in the high energy region $\Sigma E_{vis} \geq 1000 TeV$ this fraction is $(27 \pm 10\%)$.

1 Introduction:

The primary cosmic ray composition plays a crucial role in the knowledge of astrophysics, the problems of the origin and propagation of the cosmic particles into and out of the galaxy. Direct measurements have been done using balloons, aircrafts and satellites (Grigorov, 1971, JACEE ,1990, Ichimura et al.,1993). However, these measurements are limited to energies below 10^{14} eV by the low fluxes and the limited exposure time in space or on balloons. Thus, the primary flux composition in the very high energy region (above 10^{14} eV) can be obtained using only indirect methods such as ground based detectors. An air shower is a result of atmospheric nuclear electromagnetic cascade phenomena with repetition of several nuclear collisions and many electromagnetic processes, originated by single primary particle of high energy entering the atmosphere. The high energy particles are concentrating very near the air shower core and can be observed in the lead chamber as a bundle of high energy showers, called a 'γ-hadron family', propagating in the same direction , with mean lateral spread of a few cm. The emulsion chambers at mountain altitudes used for their detection are a multilayer sandwich of lead plates and photosensitive layers (X-ray films and nuclear emulsion plates)(Arisawa et al., 1994). The global characteristics of gamma-hadron families are affected by the primary cosmic ray chemical composition. In this work we use MSU-Waseda experimental data (500 m^2 $year$) from thick lead chambers (40-60 cm Pb) of homogeneous structure exposed at the Pamirs in 1977-1991 (Arisawa et al., 1994, Kopenkin & Fujimoto, 1997).

2 The Cronin Effect:

It has been shown that the cross section in pA and AA collisions shows a very strong A dependence at high P_T. The atomic number dependence is close to $A^{\alpha(P_T)}$, where the index $\alpha(P_T)$ increases with increase of P_T. This means that the nucleons in the nucleus appear to act collectively in the production of high-P_T hadrons. This effect is called the Cronin effect (Cronin, 1975).

The changes in the transverse momentum distributions from p-p to p-A collisions are represented in the form $E\frac{d^3\sigma^{p-A}}{d^3p} = A^{\alpha(P_T)} E\frac{d^3\sigma^{p-p}}{d^3p}$, or in alternative form as $E\frac{d^3\sigma^{p-A}}{d^3p} = \sigma^{p-A} E \frac{d^3 \langle n^{p-A} \rangle}{d^3p}$. In superposition like models the increase of the multiplicity n_{p-A} in p-A collisions relative to n_{p-p} collisions is given by $\frac{<n_{p-A}>}{<n_{p-p}>} = \frac{1}{2}(<\nu> + 1)$, where $<\nu> = A\sigma^{p-p}/\sigma^{p-A}$ is the average number of participating target nucleons (wounded nucleons) per inelastic interaction. This means that the source of the Cronin effect is the multiple particle scattering which changes (increases) transverse momenta. The other sources (the intrinsic parton transverse momentum in the hadrons and the one from the Fermi motion of the nucleons inside of the nucleus) can be ignored in the fragmentation region that is covered by γ-hadron families produced by cosmic rays in the atmosphere. These ideas are applied for study of nucleus-nucleus collisions observed in cosmic ray experiments. The Monte Carlo event generator used in our work includes the UA5 algorithm (Alner, 1987).

3 Analysis of γ-hadron families

The characteristics of the energy weighthed lateral spread,(ER), (where E is the energy and R is the lateral distance from family center of a gamma ray or hadron) in a γ-hadron family is governed by the P_t distribution of the hadronic collisions and by the multiple scattering which changes (increases) their transverse momenta. In order to reduce the degradation effect from electromagnetic cascade processes, the energy weighted lateral spread of gamma rays and hadrons in a γ-hadron family is obtained only after the application of decascading procedure with parameter $Z_{dec} = <E_\gamma R_\gamma> \sim 11$ TeV mm at Pamir, that permits to trace back the electromagnetic cascade to reconstruct the original gamma quanta at the point of their production . The Cronin effect sensitivity to the primary composition can be seen in FIG.1 where we present comparison between calculations and experiment (MSU-Waseda) for families with visible energy above 1000 TeV and $E_c R_c \geq 500$ TeV mm. The simulated set consists of proton-induced families and of heavy ($A \geq 24$)-induced families. The minimum of χ^2 from correlation plot in FIG.2 yields the $27\% \pm 10\%$ of heavy fraction, that is the ratio between heavy primary induced families with $A \geq 24$ and all nuclei induced families. FIG.3 is similar to FIG.1 and shows $E_c R_c$ distribution from families in the energy region above 100 TeV and below 700 TeV. In this case the best value for heavy fraction is about 2%. It has been shown (Kawasumi et al., 1996, Saito et al., 1993, Tamada, 1994) that cosmic ray families with $<\Sigma E_0> > 1000$ TeV are accompanied by air showers of size $N_e > 10^7$ (that corresponds to the primary energy $E_0 > 2\ 10^{16}$) eV. Monte Carlo simulations show (FIG.4) that our results on fraction of heavy nuclei induced families detected at mountain level are consistent with normal chemical composition in primary cosmic ray spectrum ($\sim 25\%$ of $A \geq 24$)at energies $\sim 2 \times 10^{16}$ eV and heavy primary composition ($\sim 61\%$ of $A \geq 24$) at higher energies. This research was supported partly by FAPERJ (Rio de Janeiro State Agency).

References

Alner, G. L. et al. 1987, UA5 Collaboration, Nucl. Phys. B 291, 445

Arisawa, T. et al. 1994, Nucl. Phys. B 424, 241

Cronin, J. et al. 1975, Phys. Rev. D 11, 3105

Grigorov, N. L. et al. 1971, Proc. 12th Int. Cosmic Ray Conf., Hobart-Tasmania, Vol. 5,1746

Ichimura, M. et al. 1993, Phys. Rev. D 48, 1949

JACEE Collaboration 1990, ApJ 349, L25

Kawasumi, N. et al. 1996, Phys. Rev. D 53, 3534

Kopenkin, V., & Fujimoto, Y. 1997, Il Nuovo Cimento, Vol.19C, 1017

Saito, T. et al. 1993, Astroparticle Physics 1, 257

Tamada, M. 1994, J. Phys. G20, 487

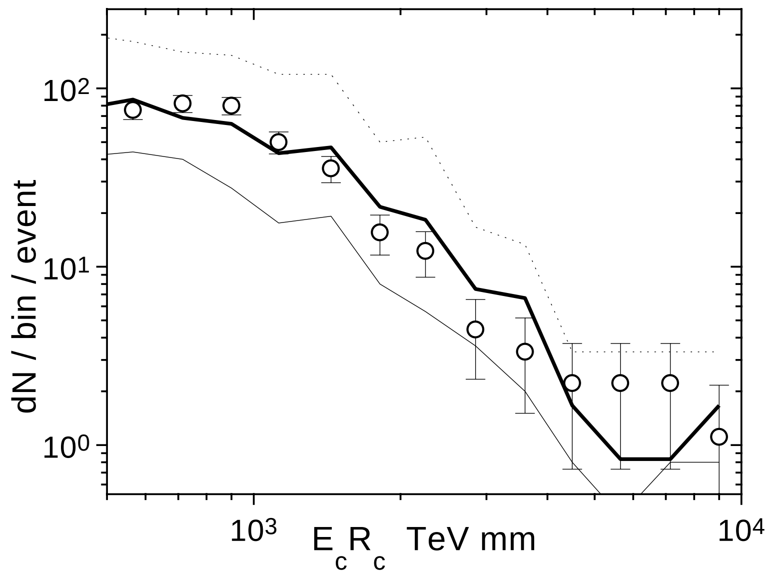

Fig. 1. Energy weighted lateral spread (E_cR_c) distribution of gamma-rays and hadrons in families of $\Sigma E_{vis} > 1000$ TeV and $E_cR_c > 500$ TeV mm at Pamir level. The marks are: circles - experiment, solid line - proton induced families, dashed line - heavy induced famlies, bold line - 27% of heavy induced families.

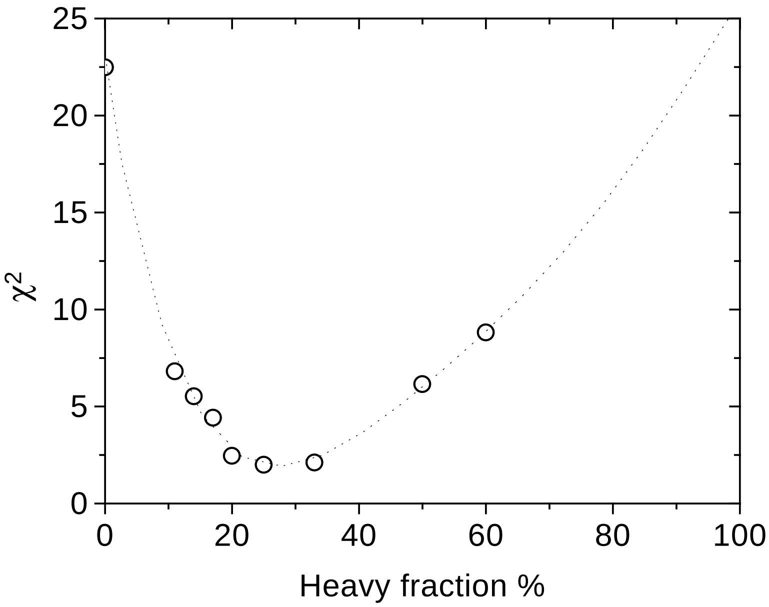

Fig. 2. Correlation plot on χ^2 versus fraction of heavy nuclei induced families of $\Sigma E_{vis} > 1000$ TeV in $E_cR_c > 500$ TeV mm region.

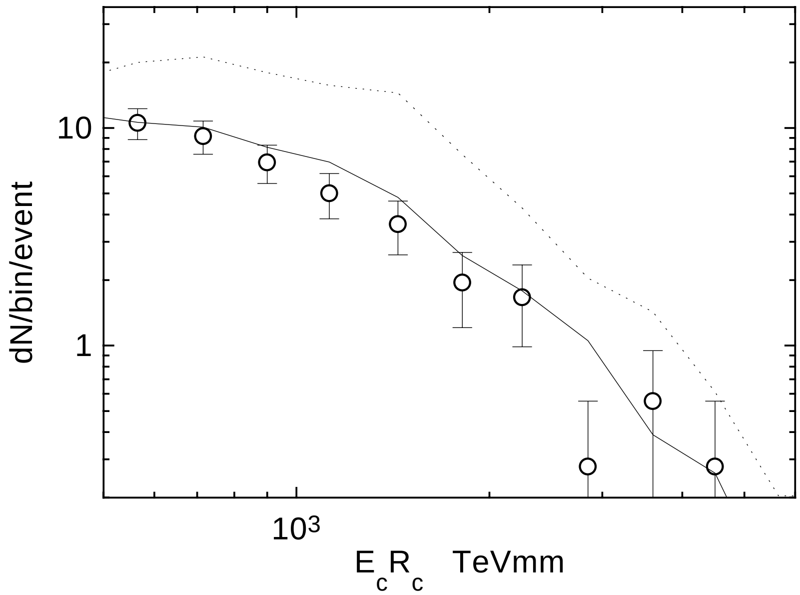

Fig. 3. The same as Fig.2 for families of visible energy above 100 TeV and below 700 TeV.

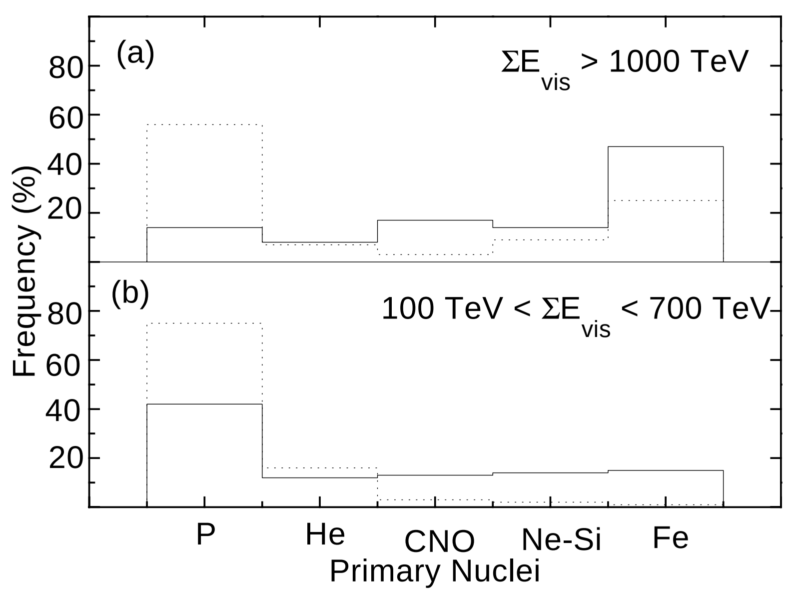

Fig. 4. Distribution of the chemical primary cosmic ray composition in the simulation at Pamir level inducing the families with $\Sigma E_{vis} \geq 1000$ TeV (a) and $100TeV \leq \Sigma E_{vis} \leq 700TeV$ (b). Marks are: solid line - input and dash line - output.