HE.2.5.04

Realistic nuclear densities and their influence on calculated EAS characteristics

N.N. Kalmykov, S.S. Ostapchenko, and M.K. Alekseeva
Skobeltsyn Institute of Nuclear Physics of Moscow State University, 119899, Moscow, Russia

Abstract

The distribution of nucleons in a nucleus turns out to be quite different for various nuclei when compared to the predictions of the well known Wood-Saxon parametrization. We use realistic nuclear density distributions for individual nuclei and investigate their influence on calculated characteristics of EAS (electron and muon number, depth of shower maximum).

1 Introduction:

The reliability of model predictions at super-high and, especially, ultra-high energies is a point of prime importance in cosmic ray physics. There is quite a number of different models outwardly resembling each other but diverging considerably in their predictions. For example, five options that are available in the well known Monte-Carlo simulation code CORSIKA predict for the average electron number at sea level values varying from $1.11\cdot 10^5$ up to $1.62\cdot 10^5$ for primary proton at 10^{15} eV (Heck, Knapp, & Shatz, 1997). The main reason of existing discrepancies follows immediately from the phenomenological character of models used and the necessity to obtain model predictions outside the domain where a model is warranted. The importance of the reliable model establishing has been recently stressed out in (Erlykin, & Wolfendale, 1998). In this paper we would like to call attention to another source of possible discrepancies and it must be emphasized that this source has nothing to do with the phenomenology of hadronic interactions at super-high energies. Indeed, any calculation of hadron-air and nucleus-air cross sections is based on the assumed configuration of nucleons inside a nucleus and so depends on the nucleon density distribution.

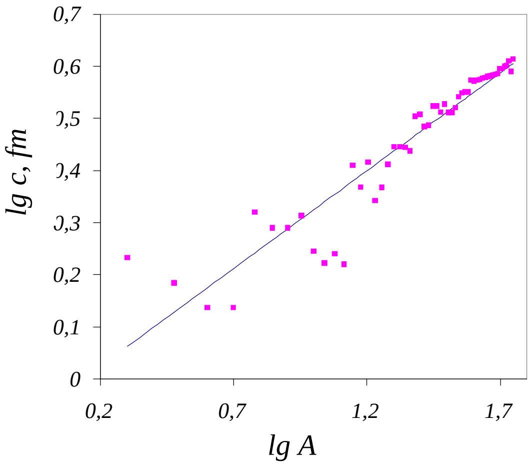

Fig.1. Experimental nuclear half-density radii vs. mass number (taken from [1]) and their approximation by straight line

Usually one adopts a two-parameter Fermi (or Wood-Saxon) distribution for mass number $A \geq 10$

$$\rho(r) = \rho_0 / \left(1 + \exp\left((r-c)/z\right)\right) \qquad (1)$$

where half-density radius c is supposed to be smooth function of A and diffusive parameter $z \approx 0.52 - 0.55$ (Shabelskii, 1991).

But only for experiments performed at relatively low values of momentum transfers q the nuclear data can be described adequately by (1). Generally, it is more proper to introduce an additional parameter (w - a «wine-bottle» parameter) and to use a three-parameter Fermi-distribution (De Vries, De Jager, & De Vries, 1987):

$$\rho(r) = \rho_0 \left(1 + w r^2 / c^2\right) / \left(1 + \exp\left((r-c)/z\right)\right) \qquad (2)$$

(2) enables one to represent correctly the data obtained at high q. Moreover, there is no smooth dependence of c on A and values of z and w are different for different nuclei. These combined effects may influence on predicted extensive air shower (EAS) characteristics.

2 Calculation of cross sections

Values of experimentally obtained half-density radii (De Vries, De Jager, & De Vries, 1987) are shown in Fig.1. In our calculations for $A \geq 10$ we use the distribution (2) with parameters c, z, w taken from (De Vries, De Jager, & De Vries, 1987) and a Gauss distribution for light nuclei. Fig.2 demonstrates the difference between nuclear densities corresponding to distributions (1) and (2). In the framework of the QGSJET model (Kalmykov, Ostapchenko, & Pavlov, 1997) calculations of cross section are based on the Glauber approach (Glauber, 1967), Pomeron description of the nucleon- nucleon (hadron- nucleon) scattering amplitude and Gribov approach to the account of the inelastic screening and diffraction processes (Gribov, 1969). Necessary details may be found in (Kalmykov, & Ostapchenko, 1998). Fig.3 displays the mass number dependence of the inelastic cross section for interactions with air at 200 GeV/nucleon. As is easy to see, deviations from smooth dependence may (in some cases) exceed 10%. The employment of different distributions (that is (1) or (2)) on retention of a mean square radius proves to be essential. The absolute normalized deviation of cross sections obtained with different distributions and averaged over $A = 1, \ldots, 56$ is equal to 3.1% and there are two cases when this deviation is about 12%. It is noteworthy that air as a target may be well represented by ^{14}N (with slight corrections). Indeed, the difference $\delta = \left(\sigma^{in}_{air} - \sigma^{in}_{^{14}N}\right) / \sigma^{in}_{^{14}N}$ varies for nucleons from 2.3% at 10^{12} eV to 1.6% at energy 10^{17} eV, for pions the corresponding values are 2.6% and 1.8% respectively.

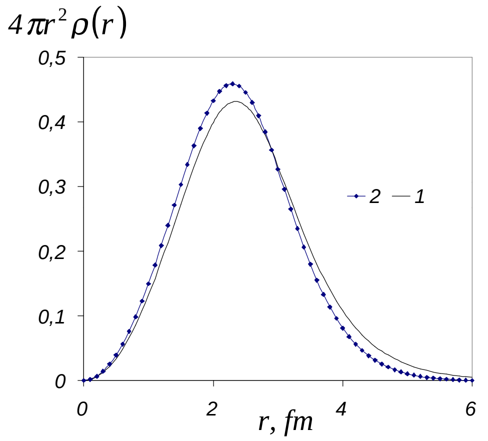

Fig.2. Nuclear densities in ^{14}N for two-parameter (1) and three-parameter (2) Fermi distribution

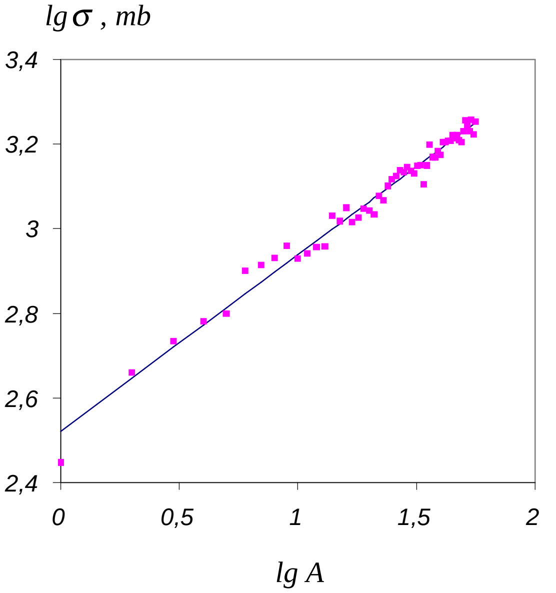

Fig.3. Inelastic cross section in air vs. mass number and their approximation by straight line

3 Influence on EAS characteristics

It follows from Fig.1 and 2 that new cross sections on ^{14}N and ^{16}O exceeds those obtained from the average dependence. If we compare the "old" cross sections used in the QGSJET model (Kalmykov, Ostapchenko, & Pavlov, 1997) with the new ones then

$$\left(\sigma^{p(\pi)air}_{new} - \sigma^{p(\pi)air}_{old}\right) / \sigma^{p(\pi)air}_{new} \cong 0{,}05$$

with sufficient accuracy over a wide range of energies. Some 80% of this difference is due to an increase in the size of target nuclei and the remaining part comes from the modified distribution.

In this paper we consider electron and muon (>1 GeV) numbers at sea level and an average shower maximum depth. The calculation of the shower characteristics variations is not so simple as it requires a rather high accuracy. If normalized inclusive spectra of secondary particles were not dependent on cross sections then, at least for electron and muon numbers, one should use the results of the sensitivity theory (Lagutin, Litvinov, & Uchaikin, 1995). But this is not the case. So we employ traditional methods but artificially magnify (when necessary) deviations to the size which ensures correct results in a reasonable time.

The calculated variations of the disscussed shower characteristics are shown in Fig.4 for showers initiated by primary protons.

Excluding the electron number variation at 10^{15} eV, predicted variations are well below presently attained experimental accuracies of EAS parameter measurements. But they must not be ruled out as with better precision of experimental data and model calculations corrections due to the cross section refinement may become essential.

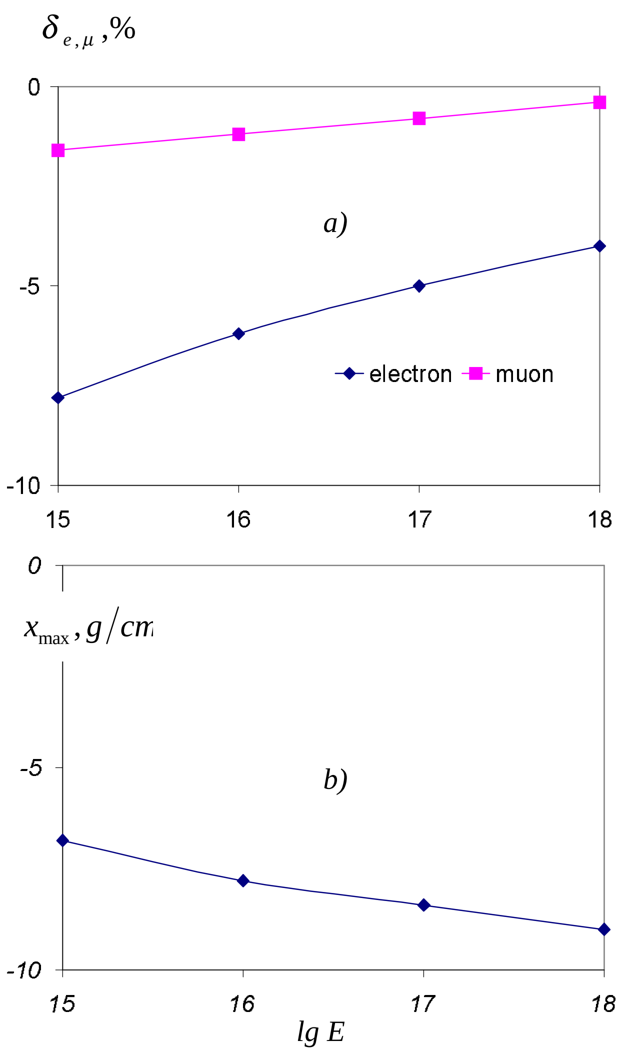

Fig.4. Variation of EAS characteristics vs. primary energy. a) for electron and muon number, b) for EAS maximum depth

Assuming the simplest ansatz that primary nuclei totally desintegrate after the first interaction one may evaluate variations of shower characteristics which are due to variations of nucleus-air cross sections. Table 1 contains results of calculations corresponding to 10% variation of $\sigma_{inel}^{(air)}(A)$ for different primary nuclei at 10^{16} eV.

Table 1

A	4	16	56
δ_e,%	-1.7	-1.0	-0.6
$\delta x_m\left(g/cm^2\right)$	-3.0	-1.8	-1.2

It follows from results presented that the influence under investigation is not very substantial. The more complicated problem of EAS fluctuations will be considered later on.

5 Conclusion

The use of realistic nuclear densities results in a marked difference in predicted hadron-air and nucleus-air cross sections. Moreover, this difference may even be greater as we cannot be too sure in assumptions adopted. The corresponding variations of EAS characteristics are also noticeable but they are below presently attained experimental accuracy. Though these variations must be taken into account if the precision of cosmic ray experiments (as well as model calculations) will be improved.

Acknowledgement

Authors recognize the financial support of the RFBR (grants 96-15-96783 and 99-02-16250).

References

De Vries, H., De Jager, C.W., & De Vries, C. 1987, Atomic Data and Nuclear Data Tables v. 36, 495

Erlykin, A.D., & Wolfendale, A.W. 1998, Proc. 16^{th} European CR Symposium, Alcala de Henares, p. 269

Glauber, R.J. 1967, High Energy Physics and Nuclear Structure, Elsevier Science B.V., Amsterdam

Gribov, V.N. 1969, ZHETF, v.59, p. 892 (in Russian)

Heck, D., Knapp, J., & Shatz, G. 1997, Nucl. Phys. B (Proc. Suppl.) 52 B, 139

Kalmykov, N.N., & Ostapchenko, S.S. 1998, Preprint 98-36/537, Skobeltsyn Institute of Nuclear Physics, Moscow

Kalmykov, N.N., Ostapchenko, S.S., & Pavlov, A.I. 1997, Nucl. Phys. B (Proc. Suppl.) 52 B, 17

Lagutin, A.A., Litvinov, V.A., & Uchaikin, V.V. 1995, The sensitivity theory in cosmic ray physics, Barnaul (in Russian)

Shabelskii, Yu.M. 1991, Izv. Akad. Nauk SSSR, Ser. Fiz., v.55, 638