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The particle number maximum position in air showers as a function of particle energy

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Abstract. The dependence of the particle number maximum position, X_{max}, in air showers as a function of particle energy E is considered in a wide energy range of primary particles $E = 1.5\times10^9$ - 10^{20} eV. It was found that in this energy range the linear dependence between X_{max} and lg E is observed.

1 Introduction

The particle number maximum position, X_{max}, in air showers is an essential characteristic defined by the energy of primary particle, its mass, process of primary particle interaction and shower development in air. The different models describing primary particle interaction and air shower longitudinal development show the dependence of X_{max} from the particle energy and cosmic ray composition (Antonov et al., 1985; Bird et al., 1993; Kalmykov et al., 1995; Gaisser et al., 1997).

Here we give the experimental data on the longitudinal development of air showers and its X_{max} position for primary particles with E = 1.5 - 15 GeV. The data on regular cosmic ray observations in the atmosphere are used (Charakhchyan et al., 1976; Golenkov et al.,1990).

2 Experimental data

In Fig. 1 the altitude dependences of cosmic ray fluxes obtained with Geiger counter telescopes at the several latitudes with the different geomagnetic cutoff rigidities R_c are given (Golenkov et al., 1990). The errors of measurements do not exceed (3 – 7) %.

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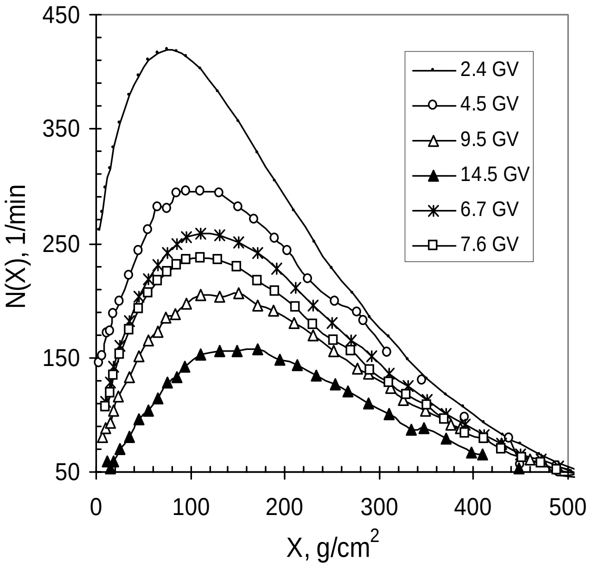

Fig. 1. The count rate of telescope vs. atmospheric pressure, $N(X)$, at the latitudes with the different geomagnetic cutoff rigidities R_c (shown in the insert).

These curves represent the sum of cascades in the atmosphere produced by primaries with $R > R_C$ or $E > E_C$:

$$N(X) = \int_{E_c}^{\infty} I(E) m(E, X) dE \,, \tag{1}$$

where $N(X)$ is the number of particles recoded by our detectors at the atmospheric depth X, $I(E)$ is the differential cosmic ray spectrum, $m(E, X)$ is the probability to detect any secondary particle at X produced by primary with E, E_c is the geomagnetic cutoff energy (Dorman, 1957). At high altitudes when X < 50 g/cm^2 $N(X)$ includes also the reentrant albedo particles. It is seen that the X_{max} values increase with the E_c growth.

From the data given in Fig. 1 we can get the differences between latitude curves with E_{c1} and E_{c2} that is to get the cascade sum produced by primaries with the energy from E_{c1} to E_{c2}. We choose the data obtained at the latitudes with E_{c1}=5.8 GeV and E_{c2} = 6.7 GeV where we have the long-term data set. The average value of particle energy for this energy interval is $E \approx 6.1$ GeV. In Fig. 2 the longitudinal profile of cascade curve produced by these primaries is shown.

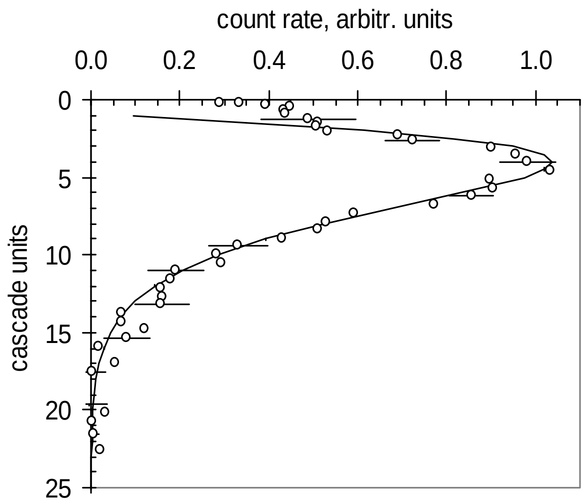

Fig. 2. The longitudinal profile of air shower produced by particle with $E \approx 6.1$ GeV. The vertical axes shows atmospheric depth in cascade units. Open points are experimental data. Horizontal bars show standard deviations. Solid curve was obtained from the expression (2) given below.

This profile can be fitted rather well by the curve calculated from the expression given below (Grigorov, private communication)

$$N(t) = c \cdot (\frac{E}{b})^{0.15} \cdot \exp[\, a(1 - t^{-2})t^{0.5} - 0.72t] + \\ + 0.07 \cdot (\frac{E}{b}) \cdot [\exp(-\frac{t}{3L}) - \exp(-\frac{t}{L})], \tag{2}$$

where t is cascade unit (in air t = 37.1 g/cm^2), c is constant, b is critical energy (in air b = 81 MeV), $a = [0.9 \cdot \ln(\frac{E}{b})]/[1.26 + 0.081 \cdot \ln(\frac{E}{b})]$, L is nuclear interaction length (in air L=90 g/cm^2).

2 Dependence of X_{max} position from primary particle energy E

In Fig. 3 the X_{max} position vs. primary particle energy E is depicted. The data on X_{max} of extensive air showers were taken from the published papers (Antonov et al., 1985; Bird et al., 1993; Kalmykov et al., 1995; Kalmykov and Khristiansen, 1995; Gaisser et al., 1997). The lowest point was taken from Fig. 2.

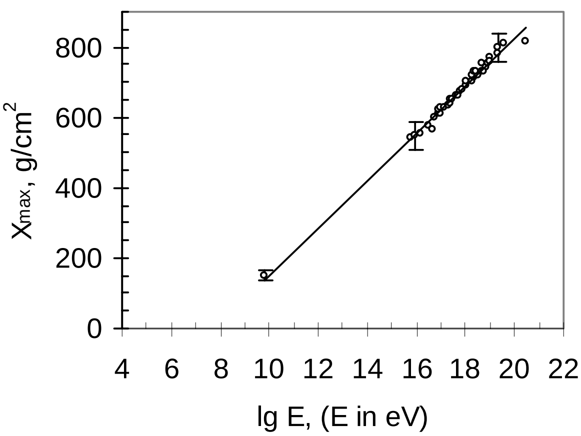

Fig. 3. The X_{max} position vs. primary particle energy E. The errors are shown by the vertical bars. The solid line was obtained from the extensive air shower data on X_{max} by the least - square method (the point at $E = 3\times10^{20}$ eV was excluded).

The fit of the data given in Fig. 3 can be expressed as

$$X_{\max}(E) = 70.149 \cdot \lg E - 555.5\,, \tag{3}$$

where X_{max} is in g/cm^2 and E is in eV. This expression describes rather well the dependence of X_{max} from primary particle energy E in a wide energy interval of primaries from $E \approx 10^9$ to 10^{20} eV. From this expression it is easily to get the $X_{max}(>E_c)$ position for cascade curve sum produced by particles with $E > E_c$. In our case E_c is defined by the geomagnetic field.

$$X_{\max}(>E_C) = \frac{\int_{E_C}^{\infty} X_{\max}(E) I(E) dE}{\int_{E_C}^{\infty} I(E) dE}\,, \tag{4}$$

where $I(E)$ is the differential cosmic ray spectrum, which we take in the form of $I(E) \sim E^{-2.7}$. The experimental data on $X_{max}(>E_c)$ for cascade curve sum produced by particles with $E > E_c$ in the atmosphere were taken from the latitudinal cosmic ray measurements (Golenkov et al., 1990; Stozhkov et al., 2001; see, also, Fig. 1).

The $X_{max}(>E_c)$ values are given in Fig. 4. The vertical bars show the standard deviations of the experimental points. The solid and dashed curves were calculated from the expression (4) with the values of elongation rate $ER = dX_{max}/d(lgE)$ equal ER = 70.15 g/(cm^2 eV) and 68.13 g/(cm^2 eV) correspondingly. For the second case (dashed curve) the ER value was found from the all data given in Fig. 3 including the point at $E = 3\times10^{20}$ eV. Rather good agreement is observed between experimental data and calculated solid curve.

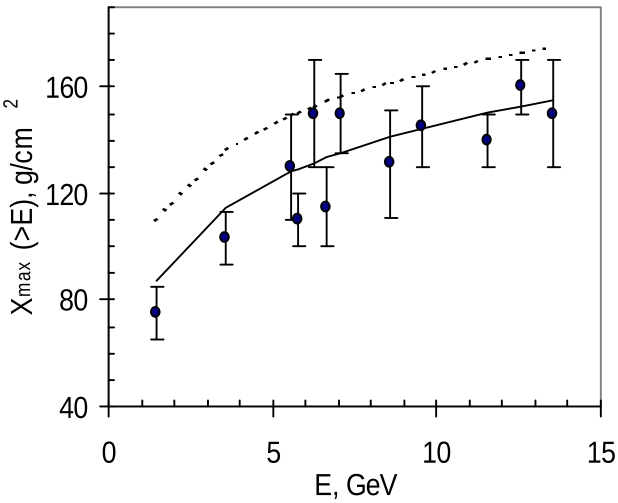

Fig. 4. The experimental data on $X_{max}(> E)$ obtained from the latitudinal measurements of cosmic ray absorption curves in the atmosphere. Vertical bars show standard errors. The solid and dashed curves were calculated from the expression (4). For the dashed curve the point with $E = 3\times10^{20}$ was included.

4 Conclusion

In the wide energy range of primaries ($E = 10^9$ -10^{20} eV) the $X_{max}(E)$ position vs. primary cosmic ray particle E is described by the liner expression $X_{max}(E) = 70.15\cdot\lg E$-555.5 where $X_{\max}$ is in g/cm^2 and E is in eV. The air shower development models have to take into account this experimental fact.

The value of the elongation rate $ER \approx 70$ g/cm^2 agrees with the averaged value of $ER = 70\pm8$ g/cm^2 obtained earlier from the different experimental data analysis (Glushkov et al., 1985)

The obtained result led to the conclusion that a) – the value of $X_{max}(E)$ is not sensitive (or sensitive weakly) to the cosmic ray chemical composition changes, or b) – in the considered energy interval the cosmic ray chemical composition is gradually transformed with the increase of E without any abrupt changes.

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