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The charge composition of primary cosmic rays observed by balloon experiments: detector, data, and interpretation

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Several stratospheric experiments indicate a variety of differences in observation of the same cosmic ray primary flux. Our recent re-examination of candidates of exotic cosmic ray families (in the energy region above 1 PeV) unmasked a heavy primary particle incidence, and revealed specific detector response. Here we show, how instrumental technique and methods applied for the evaluation of the experimental signal, may distort the measurements of the primary cosmic ray flux. We attempt to explain the sources of the differences observed in experiments, and discuss the primary composition near the knee region.

1. Introduction

There have been many investigations on the chemical composition of cosmic rays in the energy region 10^{12}-10^{14}eV/nucleon conducted by balloon experiments with emulsion chambers in the stratosphere [1-6]. One of the key goals of these experiments is to establish directly the chemical composition approaching the knee region (3-5×10^{15}eV/nucleus). The knee region is necessarily important for understanding the basic information on the origin of cosmic ray astrophysics. The knee is considered to be caused either by the astrophysical origin, or by a fundamental change in the nuclear interaction at very high energies, ~ 10^{14}/nucleon. In spite of many years of intensive investigations, the composition, the energy spectra and the flux of primary cosmic rays obtained by various experiments, differ with one another. A summary of experimental data of different authors shows either a change of chemical composition, namely, it becomes heavier with energy [1,2,3,5], or no drastic changes at higher energies [4,6], similarly as observed below the knee.

Generally, the main reasons for the experimental situation are considered to be either statistical, or due to some methodical problems, such as the energy calibration, the detection efficiency calculation, the primary identification, etc. Some of the quoted experiments are still poor in statistics, while others are depending on arguments which are not confirmed experimentally yet. Under these circumstances we have initiated our analysis. We have been motivated by our recent examination of emulsion chamber experimental data [7-9]. First [7,8], the analysis of exotic families from the mountain chamber experiments (10^{14}eV/nucleon) indicated that most of the "unusual phenomena" can be explained within standard hadron interaction physics, once the whole set of specific features of a particular detector was taken into account. Second [9], an explanation for a peculiar cosmic ray event with energy > 10^{15} eV/nucleus detected by the balloon borne emulsion chamber experiment performed in the stratosphere, showed that the observed family is most likely to be a result of a heavy nucleus interaction with an air nucleus.

2. Discussion

The study of cosmic ray experiments by balloons are very interesting, but their inner workings are often not evident, or not brought to our attention. Part of our intent is to examine how the various measurements are consistent in the evaluation of the composition.

The experimental data are routinely presented according to the accumulated statistics. With an increasing number of balloon flights, the statistics increases. Usually authors report their particular selected data, comparing them with data of other experiments in the same energy region. To extract the significant information, authors apply their highly elaborated evaluation procedure, which is relied upon specific methodical condition in any given experiment. Then, the conclusions are drawn.

Under these circumstances, with increasing amount of data, we can expect two outcomes for the old conclusions: 1) they become more solid and confirm previous observations, 2) they change, and the new conclusions are drawn. This is how experiment works, and this situation reflects the nature of the subject. Certainly, there is a preliminary stage, and "the stage of the final conclusions". What is important, if change of conclusions does occur, one has to understand clearly the reason of misinterpretation in either of two (old and new) sets, because it can reflect a signature of the studied physical phenomena, not only involvement of possible subjective factor. From this point of view, we turn our attention to those experiments (see Table 1), which, utilizing the similar type of the detector, using the same elaborated procedure of extraction of the information, based on meticulous simulation, show periodically a change in conclusions. For simplicity hereafter we will call these experiments as A1987/9 and B1995/6. Symbol ΣE_γ stands for the energy released into *γ-ray*s, and MFP for nuclear mean free path. We are going to show that results of these two experiments can be consistently explained with the hypothesis of heavy primary increase with energy.

The experiment A1987 reported observation of many atmospheric secondary *γ-ray*s, which cover the energy region 20-80 TeV. Among ~200 primaries (ΣE_γ > 2 TeV), ~106 were identified as *γ-ray*s, and ~ 62 as protons. It was pointed out [3] that the higher energy part of cosmic ray flux cannot be reproduced by the atmospheric nuclear interaction of the primary protons and He alone. It indicated that for energies above 10^{15}eV/nucleus the contribution of heavier particles becomes significant.

The experiment B1995/6, actually observes the same feature [5]. We found that data of the experiment B1995/6 [5] shows an excess of *γ-ray*s, which can not be explained only by the atmospheric nuclear interaction of the primary protons. The ratio of detected *γ-ray*s to protons, $R_{\gamma-p}$, is similar to the one obtained in the experiment A1987 ($R_{\gamma-p}$~106/62). For B1995 the ratio is ($R_{\gamma-p}$~174/117), and for B1996 ($R_{\gamma-p}$~226/100).

Interpretation of B1995/6 made in [6] is based on application of an efficiency calculation to the whole chamber. It shows the difference between the expected number of simulated particles (of particular primary Z) registered by the detector, and the number of actual, experimentally detected particles. According to the procedure of B1995/6, particles, which did not pass the target, and arrived from the side, were also taken into account in simulation, as well as in experiment. The efficiency [6] depends on energy. The numerical values of the efficiencies [6] in the "plateau" region are: in 1995 ~ 0.13, in 1996 ~ 0.18. Since [5] did not mention any irregularities in spectra of *γ-ray*s detected in B1996, we can consider that the spectrum of *γ-ray*s detected in the chamber is nearly parallel to the spectrum of detected protons. So, the excess of *γ-ray*s over protons will stay also at high energies. For instance, taking the ratio of detected *γ-ray*s to protons as $R_{\gamma-p}$~1.5, one would expect at the top of the chamber ($R_{\gamma-p} \times \eta \approx$ 1.5x0.18=0.27), if we use for $R_{\gamma-p}$, for instance, data taken from experiment B1995, mentioned in [5]. In our alternative interpretation of the experiment B1995/6, protons, detected in the chamber, are from two sources: primary protons, and secondary nucleons (from interaction of heavy primaries with air nuclei). In Figure 1 we show estimated altitude variation of $R_{\gamma-p}$ at the chamber top, using different assumptions on primary composition.

3. Conclusion

The objective (of composition measurements near the knee) is to look for apparent changes in the data set which can reveal the origin of the phenomenon. Different experiments can have a systematic shift in measured values, but pattern of ratios between the detected primary components should reflect the same cosmic ray beam. Putting the above knowledge together, one can see the situation with the chemical composition of primary particles. It seems, that the ratio of heavy primary particles to protons starts to increase at around few TeV and becomes dominant in the knee region, similar to the [1]. Our interpretation of B shows this. In addition to an excess of *γ-ray*s, an indication of the actual increase of heavy primary signal (it is likely due to CNO) in experiment B would be also the following features: the intensity of the all-particle spectrum (in interpretation of [6] it is ~30% lower than those [1] in the higher energy region beyond 10^{14}eV/nucleus), and, probably, the intensity of helium, which (in interpretation of [6]) is nearly half of the value obtained by [1]. Based on observation of the cosmic ray family that was most likely initiated by a heavy primary particle in the stratosphere [9], we can make a prediction that there ought to be some similar genuine heavy primary (something like CNO) signature in the form of a family in the expected full data (1995-1999) of experiment B. We agree that "further cross check is quite desirable among observes" [4], and wish to see it in reality.

To refine our conclusions, it will be interesting to see statistically significant results on heavy primaries from ATIC balloon experiment [10], which utilizes an electronic detector.

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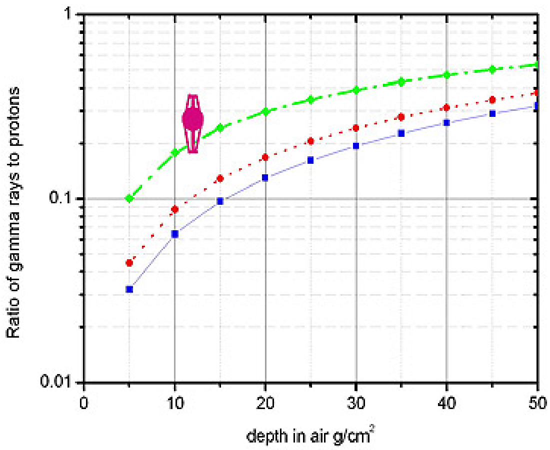

Figure 1. Observation of the ratio of *γ-ray*s to protons at the top of the chamber at different altitudes. Marks are: squares and solid line – for pure proton beam, triangles and dot line – for the proton dominant composition (similar to the average mass number <ln A> predicted by [6]) in the form (p:He:CNO:Fe)= (94.56%, 5.01%, 0.39%, 0.04%), and rhombuses and dash line – for the heavy dominant composition (similar to <lnA> assumed by [1]) (p:He:CNO:Fe) = (80.86%, 16.17%, 2.7%, 0.27%). To derive the composition, we assume the same energy per nucleon. Experimental point is based on B1996/5 experimental data from [5].

Table 1. Measurements of cosmic rays by balloon experiments with emulsion chambers

Index	Experiment	Atm. depth *gcm^{-2}*	Time h	Chamber Area *m^2*	Detector thickness	Preliminary conclusion on Heavy primaries	Note
A	Sanriku 1987 [3]	32.8	~30	0.4	0.42 proton MFP	Contribution becomes significant above 10^{14}eV/nucleus	excess of *γ-rays*
	Sanriku 1989 [4]	11.7	22.2	1.53	15.5 *gcm^{-2}*	Contribution does not show a growing value (>10^{13}eV/nucleus)	Result on silicon and heavier
B	RUNJOB 1995 [5]	~11	297	0.4	0.4 proton MFP	<lnA> increases with energy	use of local inter-action tracks
	RUNJOB 1995 1996 [6]	~11 ~12	297 281.5	0.4 0.4	0.4 0.35 proton MFP	<lnA> is almost constant in the energy range 2×10P^{14}-10^{15} ev/nucleus	use of local inter-action tracks

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