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# A pot of gold at the end of the cosmic “raynbow”?

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We critically review the common belief that ultrahigh energy cosmic rays are protons or atomic nuclei with masses not exceeding that of iron. We find that heavier nuclei are indeed possible, and discuss possible sources and acceleration mechanisms for such primaries. We also show detailed simulations of extensive air showers produced by “superheavy” nuclei, and discuss prospects for their detection in future experiments.

The unambiguous detection of cosmic rays (CRs) with energies above  $10^{20}$  eV (see [1] for a survey and bibliography on the subject) is a fact of outstanding astrophysical interest. As shown in the pioneering works of Greisen, Zatsepin, and Kuzmin [2], the possible sources and the accelerating mechanisms are constrained by the observed particle spectra due to the interaction with the universal radiation and magnetic fields on the way to the observer. The low flux of particles at the end of the spectrum (the typical rate of CRs above  $10^{20}$  eV is one event/km<sup>2</sup>/century) puts strong demands on the collection power of the experiments, such as can only be achieved by extended air shower detection arrays at ground level. This indirect method of detection bears a number of serious difficulties in determining the energy, mass and/or arrival direction of the primary particles.

Astrophysical mechanisms to accelerate particles to energies of up to  $10^{21-22}$  eV have been identified, but they require exceptional sites [3]. Very recently, we have presented a comprehensive study of a possible nearby superheavy-nucleus-zevatron [4]. We have shown that it is likely that nuclei heavier than iron with energies above a few PeV can escape from the dense core of a nearby

starburst galaxy like M82, and eventually be re-accelerated to superhigh energies ( $E \geq 10^{20}$  eV) at the terminal shocks of galactic superwinds generated by the starburst.<sup>7</sup> This mechanism improves as the charge number  $Z$  of the particle is increased. Furthermore, we have also shown that the nuclei may arrive on Earth. Strictly speaking, the energetic nucleus is seen to lose energy mainly as a result of its photodisintegration. In the universal rest frame (in which the microwave background radiation is at  $3K$ ), the disintegration rate  $R$  of an extremely high energy nucleus with Lorentz factor  $\Gamma$ , propagating through an isotropic soft photon background of density  $n$  is given by [6],

$$R = \frac{1}{2\Gamma^2} \int_0^\infty dE \frac{n(E)}{E^2} \int_0^{2\Gamma E} dE' E' \sigma(E'), \quad (1)$$

where primed quantities refer to the rest frame of the nucleus, and  $\sigma$  stands for the total photon absorption cross section. Above  $10^{20}$  eV, the energy losses are dominated by collisions with the relic photons. The fractional energy loss around this energy is  $R \sim 10^{-15} \text{ s}^{-1}$ . With this in mind, it is straightforward to check that superheavy nuclei may impact on Earth (for details see Fig. 2 of Ref. [4]). In the rest of this report we shall discuss the characteristics of the extensive air showers that these nuclei may produce after interaction with the atmosphere.

<sup>7</sup>It is important to stress that M82 is positioned close to the arrival direction of the highest CR event detected on Earth. This was first pointed out in [5].

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*Golden Shower Simulations:* In order to perform the simulations we shall adopt the superposition model. This model assumes that an average shower produced by a nucleus with energy  $E$  and mass number  $A$  is indistinguishable from a superposition of  $A$  proton showers, each with energy  $E/A$ . We have generated several sets of  $^{197}\text{Au}$  air shower simulations by means of the AIREs Monte Carlo code [7].<sup>8</sup> The sample was distributed in the energy range of  $10^{18}$  up to  $10^{20.5}$  eV. SIBYLL was used to reproduce hadronic collisions above 200 GeV [9]. All shower particles with energies above the following thresholds were tracked: 750 keV for gammas, 900 keV for electrons and positrons, 10 MeV for muons, 60 MeV for mesons and 120 MeV for nucleons and nuclei. The particles were injected vertically at the top of the atmosphere (100 km.a.s.l), and the surface detector array was put at a depth of  $1036 \text{ g/cm}^2$ , i.e., at sea level. Secondary particles of different types and all charged particles in individual showers were sorted according to their distance  $R$  from the shower axis.

In Fig. 1 we show the lateral distributions of different groups of secondary particles (we have considered separately  $\gamma$ ,  $e^+e^-$ , and  $\mu^+\mu^-$ ). One can see that the number of muons from the gold nucleus shower is greater than the number of muons from the proton shower.

As the cascade develops in the atmosphere, it grows until a maximum size (number of particles) is reached. The location in the atmosphere where the cascade has developed the maximum size is denoted by  $X_{\text{max}}$ , with units of  $\text{g cm}^{-2}$ . For cascades of a given total energy, heavier nuclei have smaller  $X_{\text{max}}$  than nucleons because the shower is already subdivided into  $A$  nucleons when it enters the atmosphere. At  $10^{20}$  eV, the  $\langle X_{\text{max}} \rangle$  of a proton (gold) shower is  $\approx 879 \text{ g/cm}^2$  ( $\approx 777 \text{ g/cm}^2$ ). A dust-grain has an even larger cross section, so it tends to interact sooner than protons and nuclei [11]. In Fig. 2, we compare the longitudinal profile of showers initiated by a proton, a gold-nucleus and a dust-grain. It is clearly

<sup>8</sup>It should be stressed that for  $A > 140$  the bulk solar-system abundance distribution peaks at  $A = 195$  [8]. To make some estimates, we then refer our calculations to a gold nucleus.

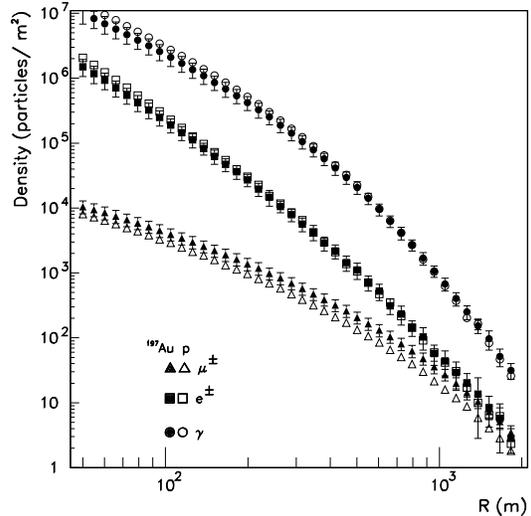


Figure 1. Ground lateral distributions of proton and  $^{197}\text{Au}$  air-showers. The incident energy is  $E = 3 \times 10^{20}$  eV.

seen how the  $X_{\text{max}}$  decreases when increasing the mass. The simulated gold shower is partially consistent with the Fly's Eye data. Furthermore, its longitudinal development better reproduces the data than protons or dust-grains. It should be remarked, however, that extensive air shower simulation depends on the hadronic interaction model [12]. We also point out that for the simulation detector effects were not taken into account.

Even though the superheavy nucleus hypothesis is partially supported by data from the CASAMIA experiment [13], more data is certainly needed to verify this model. In order to significantly increase the statistics at the end of the spectrum, the Southern Auger Observatory is currently under construction [14]. It will consist of a surface array which will record the lateral and temporal distribution of shower particles, and an optical air fluorescence detector, which will observe the air shower development in the atmosphere. These two techniques provide complementary methods of extracting the required information from the shower to test the ideas dis-

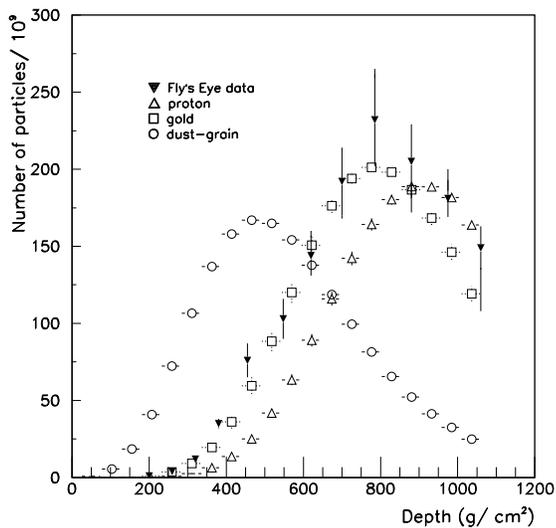


Figure 2. Longitudinal development of  $3 \times 10^{20}$  eV showers induced by a proton, a gold-nucleus and a dust-grain ( $\log \Gamma = 4.5$ ), together with the data of the highest event recorded by Fly's Eye [10].

cussed in this paper.

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