Propagation of Ultra-High Energy Nuclei with CRPropa

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***Abstract*. Current experimental data indicate that heavy nuclei may contribute to the flux of ultra-high energy cosmic rays. To understand the effects of the propagation of UHE-nuclei on the observed spectrum and anisotropy, the publicly available code CRPropa is presently extended to allow for propagation of nuclei up to iron beyond the already implemented nucleonic propagation. Pion production, photodisintegration and energy losses by pair production of all relevant isotopes in the ambient low energy photon fields are being implemented besides nuclear decay. CRPropa constitutes a good basis for such an effort: it provides a variety of functionalities which can be utilized for the case of nuclei such as deflection in intergalactic magnetic fields and propagation of secondary electromagnetic cascades and neutrinos for a multitude of scenarios for different source distributions and magnetic environments. The status of the implementation of nuclei interactions in the existing CRPropa framework and first validation studies will be presented.**

I. Motivation

The study of the Universe through ultra-high energy cosmic rays (UHECRs) is a complicated problem. Unlike the propagation of optical photons UHECRs are deflected during their voyage and additionally loose energy in reactions with ambient photons. As a consequence, it is currently neither known what are the sources of UHECRs nor is there an agreement on the composition of the primary cosmic rays reaching Earth. Recent measurements by the Auger collaboration indicate that at least some UHECRs are nuclei rather than proton primaries [1]. Additionally, due to their higher charge nuclei can more easily be accelerated to high energies than protons [2]. On the other hand, the Auger collaboration has established a directional correlation at 99% confidence level of UHECR with energies $E > 57$ EeV with the position of active galactic nuclei (AGNs) within 75 Mpc in the Véron-Cetty and Véron catalogue [3]. This is broadly consistent with the observed suppression of the UHECR flux above $\simeq 40\,\text{EeV}$ [4] as expected from the GZK effect, namely pion production by nucleons on the cosmic microwave background (CMB). The angular separation for which the correlation is maximal is $\Psi = 3.2^\circ$ [3]. If the correlating AGNs would indeed be the sources, this would indicate that deflection in extragalactic magnetic fields would be smaller than degree scales and that the chemical composition would have to be light because heavier nuclei would be expected to be deflected by more than a few degrees already in the Galactic magnetic field alone. The experimental situation is, therefore, not clear-cut at the moment and calls for detailed numerical simulations for scenarios with various source distributions, magnetic fields and chemical compositions. To this end, we want to provide to the community a tool that can perform such simulations. For this purpose we are extending the publicly available CRPropa framework - which was designed for the simulation of the propagation of nucleons [6] - to the propagation of heavy nuclei which was extensively discussed in [7] and has been revisited lately [8]. In the following we will shortly discuss the properties of the existing CRPropa framework and describe the planned extensions and the status of their implementation.

II. Introduction to CRPropa

At present the public simulation tool CRPropa can be used to propagate UHE-protons and neutrons. It takes into account pair production by protons and pion production on the CMB and on infrared (IR) and optical (opt) backgrounds, as well as neutron decay. It can be run in one dimensional (1D) mode, appropriate when deflections in magnetic fields are negligible, or in three dimensional (3D) mode in which the Lorentz force on protons is taken into account. In this mode, the user can provide magnetic field distributions in form of three dimensional grids that can either be constructed by CRPropa itself for simple statistical models such as Kolmogorov spectra, or be provided externally, for example, from detailed large scale structure simulations. In both 1D and 3D modes, the production of secondary neutral particles, namely neutrinos and $\gamma-$rays, and electrons and positrons can also be taken into account. In addition, CRPropa contains a module which allows one to follow the electromagnetic cascade that results from photons, electrons and positrons either injected directly as primaries or resulting as secondaries from nucleon interactions, in one-dimensional approximation. All relevant electromagnetic interactions are taken into account in this cascade module, notably pair production by high energy photons with low energy photons and inverse Compton scattering of the low energy photon background by high energy electrons and positrons, but also higher order processes such as double pair production and triplet pair production. Furthermore, synchrotron radiation by electrons and positrons in the magnetic field along the line of sight can also be taken into account.

III. Extension of CRPropa to Nuclei

Nuclei are compound objects and can become disintegrated in reactions with ambient photon fields, namely: pair production, pion production and photodisintegration [7]. While the first two are similar as for proton primaries, the third one - photodisintegration - is characteristic for nuclei. Additionally, during these interactions unstable nuclei may be produced. The decay of these nuclei alters further the evolution of primary cosmic ray composition.

In CRPropa, we use the high energy limit $\beta \approx 1$. For photodisintegration reactions the energy per nucleon is kept fixed in calculating the energy of the reaction products. Furthermore, the propagation direction of the outgoing reaction products is taken equal to the direction of the initial nucleus since the angular distribution in the center of mass system (CMS) will be strongly boosted into the forward direction if seen from the observer's frame. These approximations correspond to neglecting the momentum of the final states in the CMS. As long as one is not far over the threshold of the reaction, the momentum transfer will be of the order of the binding energy of the nucleon. Therefore, the momenta of the final products are much smaller than the masses of these reaction products and the longitudinal momentum of the incoming nucleus. Note, that we use natural units throughout this paper.

A. Photodisintegration

If in a photonuclear reaction of a UHE-nucleus ${}^{A}_{Z}X$ with mass number A and charge number Z the CMS energy of the photon is of the order of typical nuclear binding energies the nucleus can become disintegrated into a residual nucleus ${}^{A'}_{Z'}Y$ and m lighter particles. This is due to the giant dipole resonance (GDR) with a photodisintegration cross section of up to ~ 100 mb. Here, we will focus on combinations (n, p, d, t, h, a) of n neutrons, p protons, d deuteron, t tritium, h helium-3 or a α-particles with a combined mass of $\Delta A = A - A'$ and charge $\Delta Z = Z - Z'$. A collection of cross sections for all nuclear transitions ${}^{A}_{Z}X \rightarrow {}^{A'}_{Z'}Y$ for given ΔA and ΔZ can be obtained using the nuclear reaction framework TALYS for energies $\epsilon' \in [10^{-3}, 250]$ MeV and mass numbers $12 < A \leq 56$ [9], [10]. An approach similar to the one in [11] can be used for smaller mass numbers. For a given cross section σ one can calculate the mean free path λ using

$$\lambda^{-1} = \frac{1}{2\gamma_{\rm CR}} \int_0^\infty \frac{d\epsilon}{\epsilon^2} \frac{dn_{\rm a}(\epsilon, z)}{d\epsilon} \int_0^{2\gamma_{\rm CR}\epsilon} d\epsilon' \epsilon' \sigma(\epsilon') \quad (1)$$

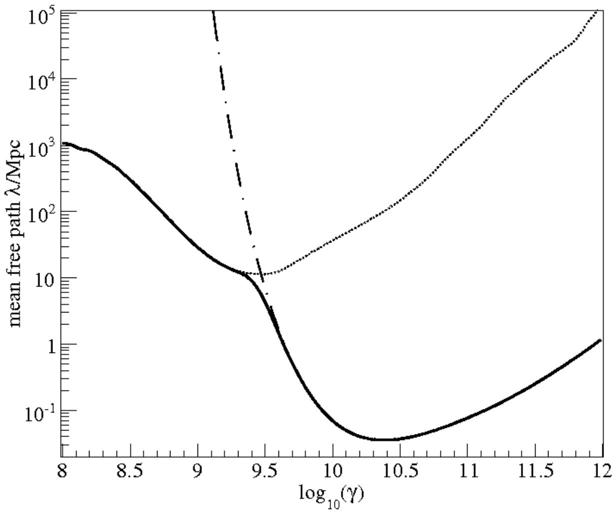

Fig. 1.
Mean free path λ for photodisintegration of iron in the CMB (dashed), infrared (dotted) and both photon backgrounds (solid) at redshift $z = 0$ as a function of the iron Lorentz factor.

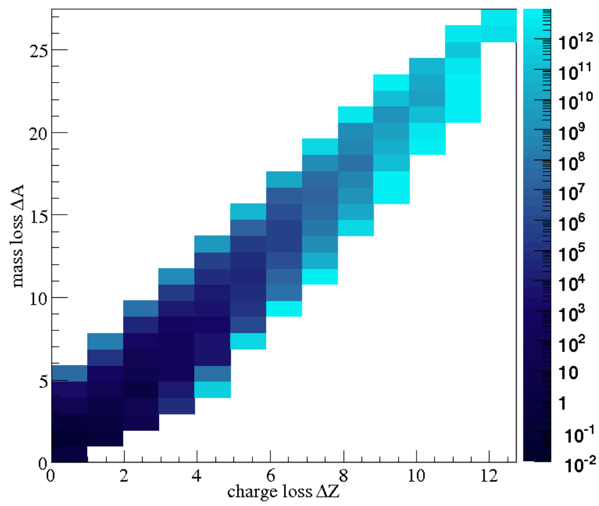

Fig. 2.
Loss of mass ΔA and charge ΔZ for iron in photodisintegration on the CMB at redshift $z = 0$. The mean free path λ/Mpc is color coded for a primary iron energy of $E \sim 1.2 \times 10^{21}$ eV.

where $\gamma_{\rm CR}$ is the Lorentz-factor of the nucleus, $dn_{\rm a}(\epsilon, z)/d\epsilon$ is the ambient photon density per photon energy ϵ at redshift z - both in the cosmological frame - and ϵ' is the ambient photon energy in the UHECR rest frame [12].

In CRPropa, the second integral in eq. (1) was tabulated to calculate λ which can then be converted to a reaction probability $P(x) = 1 - \exp(-x/\lambda)$ after a distance x. Thus, $P(x)$ is needed to determine the interaction point in the Monte Carlo procedure.

As an example Fig. 1 shows the mean free path λ for photodisintegration of an iron nucleus as function of its Lorentz factor $\gamma_{\rm CR}$. Fig. 2 illustrates λ individually for the photonuclear transition channels ${}^{56}_{26}Fe \rightarrow {}^{56-\Delta A}_{26-\Delta Z}Y$ - indexed by $(\Delta A = 56 - A', \Delta Z = 26 - Z')$ - which have

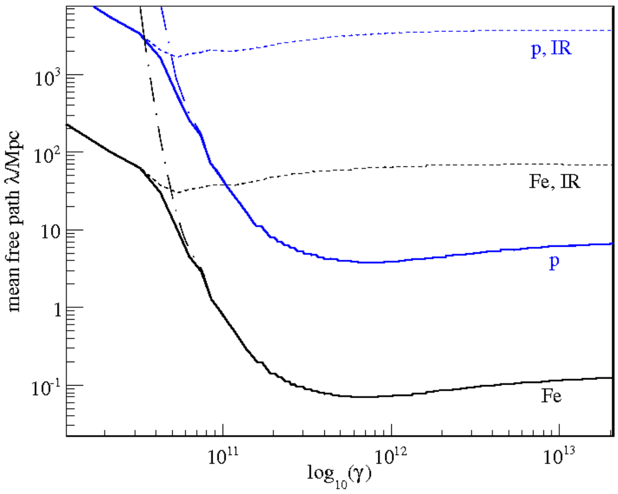

Fig. 3.
Mean free path λ for photopion production for protons and iron on the CMB (dashed), the IR (dotted) and the combined photon background (solid), as a function of the nucleus Lorentz factor.

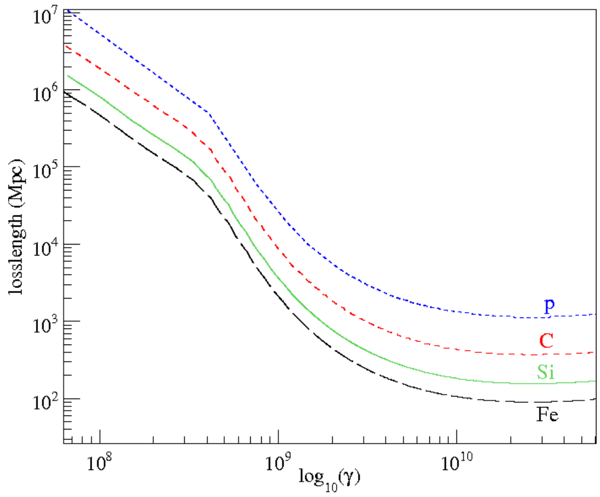

Fig. 4.
Losslength $E \times \partial t/\partial E$ of protons and various nuclei due to pair production in CMB and IR background.

been included in the calculation of λ. For that purpose we have fixed the energy of the iron nucleus to be $E \sim 1.2 \times 10^{21}$ eV, close to the minimum for λ in Fig. 1. Clearly, not all of the considered channels will be of importance for the simulation due to their large mean free path, or small branching ratio. Therefore, we will only account for reaction channels with a mean free path $\lambda < \lambda'$ in the energy range of interest within CRPropa where λ' is adjustable by the user.

B. Photopion Production

The baryonic resonances are dominated by the process ${}^A_Z X + \gamma \rightarrow {}^{A'}_{Z'}Y + \pi^{\pm,0}$. Since photo pion production dominates over photodisintegration only beyond $\gamma \sim 10^{11}$ (cf. Fig. 3 and Fig. 1), we use a simple superposition model to describe photopion production of nuclei with charge Z and mass number A. This model treats a nucleus as a collection of free nucleons (Z protons, $A-Z$ neutrons) which leads to the combined cross section

$$\sigma_{A,Z} = Z\sigma_p + (A-Z)\,\sigma_n\,. \tag{2}$$

Here, σ_p and σ_n are the cross sections for a single proton or neutron, respectively. This cross section gives good agreement for the mean free path with more sophisticated approaches such as [11]. Presently, we assume that the participant nucleon will be removed from the nucleus after pion production [11].

C. Pair Production

For pair production, ${}^A_Z X + \gamma \rightarrow {}^A_Z X + e^+e^-$, the description given by Blumenthal [13] is followed. This is, we model pair production as a continuous energy loss mechanism. Compared to pair production by protons with energy E_p the energy loss scales like

$$\frac{\partial E_{(A,Z)}}{\partial t}\left(\frac{\partial E_p}{\partial t}\right)^{-1} = Z^2 f\left(\frac{m_{(A,Z)}}{E_{(A,Z)}}\right) f\left(\frac{m_p}{E_p}\right)^{-1}, \tag{3}$$

where $E_{(A,Z)}$ is the energy of an UHE-nucleus with mass number A and charge Z, and $f(x)$ is a parameterization given by Blumenthal which only depends on the Lorentz factor of the UHECR. The energy loss length by pair production is shown in Fig. 4 for some nuclei. Unlike the other interactions of UHE-nuclei, pair production is not altering the nuclear species of a UHECR.

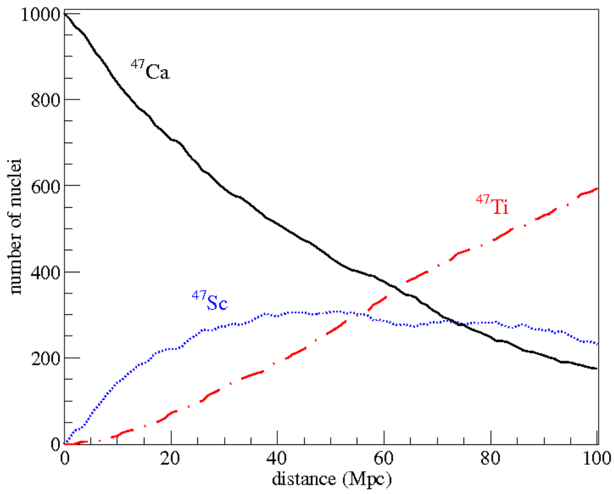

Fig. 5.
Decay of initially 1000 ^{47}Ca nuclei with an energy of 450 EeV (compare text).

D. Nuclear decay

Unstable nuclei produced by photodisintegration or pion production can decay during their voyage through the universe. The corresponding decay length $\lambda_\mathrm{d} = \gamma\tau$

can be as short as some hundreds of meters even for Lorentz factors of $\gamma \sim 10^{10}$. This is much shorter than the typical step size T which is used in CRPropa. Moreover, only at runtime it is possible to know which kind of unstable nuclei is produced in photodisintegration and pion production. Therefore, we use an algorithm which automatically handles the decay chains at runtime. The decay times t_i are determined from a random number $p_i \in [0, 1]$ as

$$t_i = -\gamma\tau \ln(p_i) \tag{4}$$

where the life time of the nuclei is obtained from [14]. Note, that this is just the inverse of the familiar exponential decay law $N(t + \delta t)/N(t) = \exp(-\delta t/\tau)$.

If the calculated t_i for a given nucleus is larger than the time-step T as used in CRPropa, the nucleus is kept unchanged and is tested against possible interactions (e.g. photodisintegration, pion production) and its deflection is calculated (in the 3D version). In the opposite case, the nucleus decays into a daughter nucleus. This procedure is repeated i times for the resulting daughter nuclei until the sum of all decay times is larger than the simulated time step $\sum_i t_i > T$. In this way one can handle very short decay times t_i and corresponding decay chains of nuclei without decreasing the overall step size T within CRPropa. A decreasing T would needlessly slow down the entire simulation procedure. As an example, one can find an illustration of the nuclear decay chain starting with $^{47}\mathrm{Ca}$ in Fig. 5. In this case $^{47}\mathrm{Ca}$ was injected with an initial energy of 450 EeV, corresponding to a decay length $\lambda_{Ca} \approx 56$ Mpc. It then decays sequentially via $^{47}\mathrm{Sc}$ to the stable $^{47}\mathrm{Ti}$ with a decaylength of $\lambda_{Sc} \approx 41$ Mpc.

IV. Summary and Status

The currently existing public version of the CRPropa framework is presently been extended to allow for the propagation of UHE-nuclei. The resulting framework will be of use to study composition, anisotropy and the spectrum of UHE-nuclei taking into account all relevant effects of propagation, namely interactions with the CMB, infrared and optical photon backgrounds, deflection in large scale magnetic field structures and different source distributions and injection spectra.

Our goal is to provide a public simulation tool for the propagation of high energy extragalactic cosmic rays, $\gamma-$rays and neutrinos that allows one to study scenarios as general as possible. Given the current experimental situation and the prospects for a large increase of data, not only due to existing instruments, but also due to future observatories such as Auger North [15] and, possibly, a space-based detector such as JEM-EUSO [16], it will be important to perform more and more sophisticated simulations of UHECR propagation in a highly structured Universe. We hope to develop with the CRPropa extensions a suitable simulation tool that can be useful for the cosmic ray community.

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