Extremely high energy cosmic ray as the probe of new physics

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Abstract

We explore the influence of new physics on extremely high energy cosmic ray (EXCER) particles. In particular, we devote our mind to one example of new physics, unparticle stuff, on one specific process that EXCERs participate in, photopion production of the EXCER nucleon with 2.7K cosmic microwave background radiation (CMBR). Through computing the differential cross section of virtual exchange of unparticle in the $p + \gamma \rightarrow p + \pi^0$ process, we acquire the general consequence of new physics on the EXCER propagation. It is astonishing but reasonable that due to the lowness of interaction energy $\sqrt{s}$, the new physics will play a nearly negligible role in EXCER interaction.

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Since cosmic ray was discovered in 1912 by Hess [1], it became one powerful tool in particle physics in that it had been an important method to discover new particles such as positron, muon and $\pi$ before accelerators were constructed in 1950s. Nowadays owing to its stupendous energy which is greater by about seven orders of magnitude than that the particles in the terrestrial laboratories can obtain, EXCER that generally is termed as the cosmic ray with energy in excess of $10^{19}$ eV, is always deemed as the most hopeful probe to explore various candidates of so-called new physics. In the past decades there are really tremendous efforts [2] on testing new physics with EXCER, especially testing manifestation of VLI induced from various quantum gravity models using the GZK feature of EXCER.

It had been believed that we could obtain the cosmic ray particles with no upper limit of energy and the reason that they hadn’t been detected so far was that their flux was too low to our detectors. However, shortly after the discovery of CMBR in 1966, Greisen [3], Zatsepin and Kuzmin [4] pointed out that the cosmic ray nucleon will interact with the background photon $N + \gamma \rightarrow N + \pi$, and lose about 50% energy, respectively. This process will lead to the GZK feature that the spectrum of cosmic ray will steepen at the GZK predicted energy,
about $5 \times 10^{19}$ eV, for the giant energy loss of cosmic ray particle before it arrives at the atmosphere.

There are three observatories on EXECR, i.e., the Akeno Giant Air Shower Array (AGASA), the High Resolution Fly’s Eye Cosmic Ray Detector (HiRes) and the southern Pierre Auger Observatory (PAO). Nevertheless, there are somewhat controversial on the observations of the EXECR particles among them. The results of AGASA\cite{5} indicate an obvious absence of GZK feature, while HiRes \cite{6} and the southern PAO \cite{7} do observe the GZK cutoff. What’s more, HiRes \cite{8} shows the composition of EXECR transfers from heavy nuclei to protons at about $3 \times 10^{15}$ eV, and PAO \cite{9} favors the results that the composition above $10^{19}$ eV is mostly heavy nuclei. In addition, a correlation of the EXECR events with nearby Active Galactic Nuclei (AGN) was reported \cite{10} according to the early data of PAO, however, HiRes\cite{11} and the recent PAO data \cite{12} reveal no significant correlation of EXECR with any celestial objects.

In general, new physics are classified into two categories. One is motivated by quantizing gravity or unifying the four kinds of fundamental interactions, such as extra dimension, loop quantum gravity, and the recently proposed entropic force \cite{13}. The other is particle physics models extending on the basis of the Standard Model (SM) $SU(3) \otimes SU(2) \otimes U(1)$ of particle physics, for instance, supersymmetry theory, little Higgs models, and recent unparticle physics \cite{14}. The previous pursuits are mainly on applying a very small violation of Lorentz invariance (VLI) related to the former kind of new physics to illustrate the absence of GZK cutoff that AGASA observed. The situation changed crucially after the HiRes and PAO announced their results and confirmed the predicted GZK cutoff, which seemingly does not entail VLI. However, Stecker \cite{15} recently reexcited the interest in VLI on EXECR through proposing another scenario in which VLI will coexist with the HiRes and PAO experimental data.

Nowadays there are a large number of new physics models and theories and a lot of candidates of EXECR particle such as nucleon and heavy nuclei. The extension of SM (that is, the latter kind of new physics) usually predicts new “particles” and couplings that may contribute to the interactions that EXECR particles participate in during their propagation and generate the observable signature in the EXECR spectrum. In this work, we examine the possible effect of the extension of SM on these interactions. For the sake of simplicity and typicality, we take the recent unparticle physics and nucleon as the examples of the new physics and EXECR particle, respectively, and derive some common results for the impact of new physics on the EXECR propagation in the end.

In 2007, Georgi \cite{14} proposed the existence of unparticle which is a scale invariant sector with a non-trivial infrared fixed-point. In the following years, a number of papers appear and cover a lot applications of unparticle physics, such as collider physics \cite{16}, $CP$ violation \cite{17}, Higgs physics \cite{18}, cosmology \cite{19}, and supersymmetry \cite{20}, etc., and also focus on many fundamental issues in unparticle physics \cite{21}.

It is evident that the unparticle can only play a role in the neutral pion $\pi^0$ photoproduction $p + \gamma \rightarrow p + \pi^0$ but not in the similar charged pion $\pi^\pm$ photoproduction $p + \gamma \rightarrow n + \pi^\pm$. 
and $n + \gamma \rightarrow p + \pi^-$ on the premise that the unparticle stuff does not possess the quantum number of gauge group, such as the electric charge $Q$. The process can only occur through the $t$-channel for axial vector unparticle operator $O_U^{\mu}$, and the effective couplings among $\gamma$, $\pi^0$, and vector unparticle operator $O_U^{\mu}$ is

\begin{equation}
L_{\gamma\pi U} = \frac{ie\lambda_1}{4\Lambda_U^d} \epsilon_{\mu\nu\rho\sigma} F^{\mu\nu} O_U^{\rho\sigma} \Pi,
\end{equation}

where $\Pi$ is the pion field, $\Lambda_U$ is the energy scale at which scale invariance emerges, $\epsilon_{\mu\nu\rho\sigma}$ is the totally antisymmetric tensor, $F^{\mu\nu} = \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu}$ is the electromagnetic field strength, and $O_U^{\mu\nu} := \partial^{\mu} O_U^{\nu} - \partial^{\nu} O_U^{\mu}$. Combined (1) and the effective couplings among two protons and vector unparticle operator $O_U^{\mu}$, we can acquire the spin-averaged amplitudes squared is deduced as

\begin{equation}
|\mathcal{M}|^2 = \frac{8m^6 - 2(4s + t + 4u)m^4 + 2(s + u)(2m^2 + m_{\pi}^2)m^2 - t(s^2 + u^2)}{|t|^3} \left( \frac{|t|}{\Lambda_U^d} \right)^{2d_U - 1}
\times \frac{e^2 \lambda_1^2 \lambda_{2d_U}^2 Z_{d_U}^2}{4}, \quad Z_{d_U} = \frac{8\pi^{5/2}}{\sin(d_U\pi)(2\pi)^{2d_U}} \frac{\Gamma(d_U + 1/2)}{\Gamma(d_U - 1)\Gamma(2d_U)},
\end{equation}

where $m$ is the mass of proton, $m_{\pi}$ is the mass of $\pi^0$, $\lambda_2$ is the coupling constant among two protons and unparticle operator $O_U^{\mu}$, and $d_U$ is the scale dimension of the unparticle operator $O_U$. The differential cross section in the center of mass (cm) frame is derived as follows

\begin{equation}
\frac{d\sigma}{d\Omega} = \frac{p_1}{64\pi^2 E_k(E + k)} |\mathcal{M}|^2,
\end{equation}

where $k$ is the energy of incident photon, $E$ is the energy of the incident proton, and $p_1$ is the magnitude of momentum vector of the outgoing proton.

Now we will come to the details but key points. The energy spectrum of cosmic ray particles can extend to the highest $10^{21}$eV and the typical energy $\epsilon$ of CMBR photons is about $10^{-3}$eV. Thus in the earth frame the 4-momentum of EXECR proton can be taken as $p_p = (E_1, 0, 0, p_1)$ and that of CMBR photon will be $p_\gamma = (E_\gamma, 0, 0, -E_\gamma)$. The Mandelstam variable $s$ that is the square of cm energy of the interaction between an EXECR proton and a CMBR photon is $s = (p_p + p_\gamma)^2 = m_p^2 + 2(E_1 + p_1)E_\gamma \sim \text{GeV}^2$ owing to the tininess of the typical energy of CMBR photon. The total center-of-mass energy is only in the GeV order, which can be achieved in the terrestrial laboratories and new physics will not appear at this energy scale much below TeV!

Let’s continue to calculate the cross section and compare it with that derived in the Standard Model without new physics to present some quantitative and straightforward results. The unknown quantities on the right-hand of Eq. (3) can be derived from the earth frame to the cm frame via the Lorentz invariance of Mandelstam variable $s$, $t$ and $u$. What’s more, the energy scale of the interaction can be determined by the energy $k$ of incident photon in the cm frame due to the following fact: the 4-momentum of the incident proton and photon
are separately $p_p^{cm} = (E, 0, 0, k)$ and $p_\gamma^{cm} = (k, 0, 0, -k)$, which leads to the energy scale of the interaction is

$$\sqrt{s} = \sqrt{(p_p^{cm} + p_\gamma^{cm})^2} = E + k = \sqrt{m_p^2 + k^2 + k} .$$  \hspace{1cm} (4)

As a consequence, $k$ will also at the GeV scale in the case $\sqrt{s} \sim$ GeV.

In order to show the influence of new physics on the differential cross section clearly, it is necessary to present some curves of $d\sigma/d\Omega$ versus the pion cm angle with different $d_U$ for several $k$ in the case $\Lambda_U$ and $\lambda_1 = \lambda_2$ are in the reasonable range. For the convenience to compare with the experimental data [22], the energy of incident photon in the cm frame are taken as $k = 0.26$ GeV (corresponding to $\sqrt{s} = 1.233$ GeV) and $k = 0.32$ GeV (corresponding to $\sqrt{s} = 1.311$ GeV) in Fig.1 and Fig.2, respectively, which are same as those in [22]. The other parameters are taken as $\Lambda_U = 1$ TeV and $\lambda_1 = \lambda_2 = 1.0$.

$k = 0.26$ GeV

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{The differential cross section $d\sigma/d\Omega$ in units of $\mu$b vs the pion cm angle $\theta$ in the case $k = 0.26$ GeV for $d_U = 1.1, 1.3, 1.5, 1.8$. The dashes get longer as $d_U$ increases.}
\end{figure}
In terms of Fig.1 and Fig.2, it is astonishing but reasonable that the contribution from the unparticle stuff can really be overlooked compared to the data of differential cross section of pion photoproduction with magnitude of order of tens of $\mu b$ [22] provided that $\Lambda_U$ is in the proper range, no matter the way $d_U$ changes. The key point to comprehend this conclusion is as follows. Although EXECR is seemed as the most hopeful window to probe the new physics, but, it is not stressed so far that the interaction energy $\sqrt{s}$ of the pion meson photoproduction is about 1 GeV at which scale nearly all new physics do not manifest themselves.

In addition, the lowness of $\sqrt{s}$ is not only limited to the pion photoproduction but a general feature of all processes that propagating EXECR particles participate in (such as the photodisintegration of EXECR nuclei with CMBR and IR background photons [23], the pair-production of UHE photons off the background photons: $\gamma\gamma_B \rightarrow e^+e^-$, and inverse Compton scattering (ICS) of the electrons (positrons) on the background photons, etc.) owing to the lowness of the typical energies of various background radiations. Consequently, it is general and justified that new physics will have minute effect on the propagating EXECRs’ interactions except the possible alteration of their spectra from VLI motivated from the new physical model or theory based on the previous illustration and combined with our previous results [24].

In the final let us close with some comments

1. For the non-conventional candidates of EXECR particle, such as neutrino and exotic particles, similar effects can also be discussed. However, the PAO presents the upper limit on detected photon flux [25], which disfavors most exotic candidates, and the
observed profile of extensive air shower is somewhat contradictory with that neutrino produces. Hence our subject just involves the conventional EXECR particles namely nucleon, nuclei and \(e^\pm, \gamma\) [24].

2. It is obvious that our investigation is different from the work motivated from the VLI and our results are distinct reasonably. Moreover, there is another important distinction between our and others’ researches. There are no special frame in our derivation due to the Lorentz invariance of the Mandelstam variables hence our analysis are frame-independent. In contrast, the extent of VLI is frame-dependent and the conclusions from VLI are also frame-dependent which are often drawn in the Earth frame.

In conclusion, the two categories of new physics have distinct significance on the interactions of EXECR with various background radiations: Some of the former that predict the VLI will affect the observed spectrum of EXECR to some extent [15], and the latter almost only play a negligible role in the same interactions.

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