# Testing hadronic models of gamma ray production at the core of Cen A

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The Pierre Auger experiment has observed a few cosmic ray events above 55 EeV from the direction of the core of Cen A. These cosmic rays might have originated from the core of Cen A. High-energy gamma ray emission has been observed by HESS from the radio core and inner kpc jets of Cen A. We are testing whether pure hadronic interactions of protons or heavy nuclei with the matter in the core region or photodisintegration of heavy nuclei can explain the cosmic ray and high-energy gamma ray observations from the core of Cen A. The scenario of $p$-$\gamma$ interactions followed by photopion decay has been tested earlier by Sahu *et al.* and found to be consistent with the observational results. In this paper, we have considered some other possibilities: (i) The primary cosmic rays at the core of Cen A are protons, and the high-energy gamma rays are produced in $p$-$p$ interactions. (ii) The primary cosmic rays are Fe nuclei, and the high-energy gamma rays are produced in Fe-$p$ interactions. (iii) The primary cosmic rays are Fe nuclei, and they are photodisintegrated at the core. The daughter nuclei deexcite, and high-energy gamma rays are produced. The high-energy gamma ray fluxes expected in each of these cases are compared with the flux observed by the HESS experiment to normalize the spectrum of the primary cosmic rays at the core. We have calculated the expected number of cosmic ray nucleon events to be between 55 and 150 EeV in each of these cases to verify the consistencies of the different scenarios with the observations by the Pierre Auger experiment. We find that if the primary cosmic rays are Fe nuclei, then their photodisintegration followed by the deexcitation of daughter nuclei may explain the observed high-energy particle emissions from the core of Cen A. The luminosity of the cosmic ray Fe nuclei required to explain the observational results of HESS and Pierre Auger is higher than the luminosity of the cosmic ray protons in the $p$-$\gamma$ interaction model. The required cosmic ray luminosity depends on the density of the low-energy photons at the source, which photodisintegrate the Fe nuclei, and the size of the emitting region.

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## I. INTRODUCTION

The directional correlation of ultrahigh-energy cosmic rays (UHECRs) and their possible sources has long been studied with the events from the Volcano Ranch [1], SUGAR [2], Fly's Eye [3], HiRes [4], AGASA [5], Yakutsk [6], Haverah Park [7], and AUGER [8] experiments. Compact radio quasars were correlated with UHECRs in Ref. [9]. UHECR events have earlier been correlated with their sources assuming small angular deflections [10–12]. The Galactic magnetic field may play a crucial role in revealing the charge composition of UHECRs [13]. BL Lacertae objects have been correlated with UHECR events by different authors. While Gorbunov *et al.* [14] suggested that gamma ray emission by BL Lacertae objects could be related to their capability of UHECR emission, the study by Torres *et al.* [15] showed that the correlation of UHECRs with BL Lacertae objects is not significant. The correlation of clustered events from the AGASA experiment with BL Lacertae objects and the decay of massive relic particles [16] was examined [17], and a negative result was reported. The correlation of compact radio quasars or 3EG gamma ray blazars and cosmic ray events above 10 EeV was studied with the available data at that time in Ref. [18], and the authors concluded that there is no significant correlation. Virmani *et al.* [19] found an angular correlation of cosmic ray events above 100 EeV with radio-loud compact QSO sources.

The results of correlation studies are highly dependent on the samples of data used from different experiments. This field has remained exciting as different groups have come up with different conclusions. The more interesting aspect is that there may be exotic physical phenomena which may lead to the detection of particles from sources beyond the distance limit due to Greisen-Zatsepin-Kuzmin [20] attenuation. For example, the violation of Lorentz invariance [21,22] and axionlike particles or exotic massive hadrons [23] may lead to the detection of UHECRs from faraway sources. With the successful operation of the Pierre Auger experiment, many UHECR events have been detected which could be successful in shedding light on the correlation of UHECR events above 55 EeV with nearby sources [8,24]. The Pierre Auger experiment has measured the anisotropy of 69 UHECR events above the energy of 55 EeV and correlated them within 3.1° with the positions of Active Galactic Nuclei (AGNs) within a distance of

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75 Mpc from us. The degree of the observed correlation has decreased from earlier study [8,24].

More analysis with future data may establish whether UHECR sources are associated with luminous infrared galaxies [25]. In a recent paper [26], it has been discussed that the correlation of the highest-energy UHECR events from the Pierre Auger experiment with AGNs in the Véron-Cetty-Véron catalogue is stronger than the correlation with the random sets of galaxies selected from large-scale structure. This result implies that the correlation of UHECRs with AGNs is not entirely due to AGNs tracing the distribution of matter in large-scale structure. Chandra observations on some of the AGNs correlated with UHECR events from the Pierre Auger experiment were used to confirm whether their x-ray and optical emissions support strong nuclear activities [27]. Ten galaxies were studied and, none of them showed a significant AGN component. This study reduces the number of correlated AGNs with UHECR events observed by the Pierre Auger experiment. However, more data are needed to confirm the results of this study. Another study on the correlation of local AGNs with UHECR events observed by the Pierre Auger experiments further reveals that the claimed correlation should be considered a result of chance coincidence [28]. UHECRs may come from steady/continuous sources or flares or transients. Advances in radio astronomy have opened the opportunity of observing a large number of transients and exploring the dynamic sky. Radio observations have revealed that mildly relativistic supernovae may accelerate cosmic rays to energies above 60 EeV [29].

The region around our closest radio galaxy, Centaurus A, shows the largest concentration of events relative to the isotropic expectations. Cen A, being our nearest radio galaxy at a distance of 3.4 Mpc, has been studied extensively as a potential source of UHECRs [30–33]. More investigations in this direction would be helpful to understand the sources of UHECRs.

Cen A's TeV gamma ray emission [34] has been related to the two extremely energetic cosmic ray events observed by Pierre Auger from the direction of the core of Cen A [35] within the hadronic model of $p$-$\gamma$ interactions. In this scenario, the luminosity of the cosmic ray protons has to be close to the Eddington luminosity of the black hole, which is $L_{\rm Edd} \sim 1.3 \times 10^{46}(M/10^8 M_{\rm sun})$ erg/sec. In another paper [31], it has been discussed that a cosmic ray luminosity of $9 \times 10^{39}$ erg/sec is required in the energy interval of 55 to 150 EeV to explain these two events observed by the Pierre Auger experiment within three years. If the lower energy bound is 1 EeV, then the estimated luminosity in the band from 1 to 150 EeV is $5 \times 10^{40}$ erg/sec, which is below the bolometric luminosity of this source, $10^{43}$ erg/sec.

Fraija *et al.* [36] have explained the emission of gamma rays observed by HESS and the UHECR events observed by Pierre Auger with $p$-$p$ interactions, assuming the gamma ray emission is from the lobes of Cen A. They have shown that the scenario of $p$-$\gamma$ interactions in their model is not consistent with the observational results.

The composition of the primary cosmic rays inside their sources is not known; this allows us to assume different compositions. The observed diffuse UHECRs may be a mixture of protons and heavy nuclei [37]. With increasing energy, the difficulty of determining the composition of the observed diffuse UHECRs increases.

The composition of the cosmic ray events observed from the direction of Cen A is not known. They could be protons or neutrons or heavy nuclei. We have assumed that the two cosmic ray events observed from the direction of the core of Cen A are protons or neutrons and that they are emitted from the core of Cen A, as it has been assumed in Ref. [35].

High-energy gamma rays can be produced in interactions of the primary cosmic ray protons with cold matter protons at the core ($p$-$p$), in $p$-$\gamma$ interactions followed by the decay of photopions, in pure hadronic interactions of cosmic ray heavy nuclei with cold matter protons (Fe-$p$), and in the photodisintegration of cosmic ray heavy nuclei followed by the deexcitation of daughter nuclei. In the paper by Sahu *et al.* [35], they have assumed that the primary cosmic rays are only protons and that the gamma rays are produced in $p$-$\gamma$ interactions. They have shown that the scenario they have considered is consistent with the observational results. In this work, we consider some other possibilities. We have studied the following scenarios or possibilities: (i) The primary cosmic rays are only protons, and the high-energy gamma rays are produced in $p$-$p$ interactions. (ii) The primary cosmic rays are only Fe nuclei, and their interactions with the cold matter protons (Fe-$p$) lead to the production of the high-energy gamma rays. (iii) The primary cosmic rays are Fe nuclei; they are photodisintegrated, and the high-energy gamma rays are produced from the deexcitation of the daughter nuclei. We have compared the calculated gamma ray flux in each of these cases with the one observed by the HESS experiment. Thus, the observed high-energy gamma ray flux from Cen A is useful to reveal the hadronic processes inside this source [38,39]. Finally, we check the consistency of each of these scenarios with the observations by the Pierre Auger experiment.

## II. UHECRS AND GAMMA RAYS FROM CEN A

The Fermi Collaboration has observed the gamma ray emission from the core of Cen A [40]. The higher-energy gamma rays observed from Cen A by HESS [34] could be more useful for studying this source as a UHECR accelerator. The HESS experiment has observed gamma ray emission from the radio core and the inner kpc jets [34]. The gamma ray flux above the energy 250 GeV is a single power law with the index $2.73 \pm 0.45_{\rm stat} \pm 0.2_{\rm sys}$, denoted as $\frac{d\phi^o_\gamma(E^o_\gamma)}{dE^o_\gamma dt^o dA}$ in the observer's frame on Earth:

$$\frac{d\phi_\gamma^o(E_\gamma^o)}{dE_\gamma^o dt^o dA} = 2.45\times 10^{-13}\left(\frac{E_\gamma^o}{1\,\mathrm{TeV}}\right)^{-2.73}\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{TeV}^{-1}. \tag{1}$$

The very high-energy gamma ray emission observed by HESS is from the core and inner jets of Cen A.

### A. Pure hadronic interactions

In pure hadronic interactions ($p$-$p$, $A$-$p$, where $A$ is the mass number of the heavy nucleus), neutral and charged pions $\pi^0$, $\pi^+$ and $\pi^-$ are produced with almost equal probabilities. Neutral pions decay to high-energy gamma rays, and the charged pions decay to neutrinos and antineutrinos. In the first case, as mentioned earlier, we have assumed that the primary UHECRs at the core of Cen A are only protons. Their optical depth for pion production in interactions with hydrogen of molecular density $n_H$ cm$^{-3}$ in a blob of size $R = 3\times 10^{15}$ cm in the wind rest frame [40] is $\tau_{pp} = R/l_{pp}$, where the mean free path is $l_{pp} = 3/n_H \times 10^{25}$ cm for the interaction cross section $\sigma_0 = 34.6$ mb. Each pion produced in $p$-$p$ interactions is assumed to carry 20% of the initial proton's energy.

We have calculated the high-energy gamma ray flux in the observer's frame on Earth to compare with HESS observations. The Doppler factor $\delta_D$ is $\delta_D = \Gamma^{-1}(1-\beta\cos\theta_{ob})^{-1}$, where $\beta$ is the dimensionless speed of the wind rest frame with respect to the observer on Earth, and $\theta_{ob}$ is the angle between the observed photon and the wind's velocity as measured in the observer's frame. $\Gamma$ is the Lorentz boost factor of the wind rest frame. Cosmic rays can be emitted in any direction in the wind rest frame, as can the gamma rays produced in their interactions. There will be beaming in the observer's frame. The photons traveling along our line of sight are observable. The photons detected on Earth have a Doppler shifted energy which depends on their angle of emission with respect to the direction of the velocity of the wind rest frame and $\Gamma$. The deflection of ultrahigh-energy cosmic ray protons with energy more than 56 EeV is on the average 3° in the Galactic magnetic field. Cen A is 3.4 Mpc away from us. The deflection of the cosmic ray protons of energy more than 56 EeV is negligible in the extragalactic magnetic field in this case [8]. The cosmic ray proton/neutron events detected above 55 EeV with directionality within 3° of the core of Cen A are traveling from the source to the observer with the same Doppler shift in energy as the gamma rays observed by HESS if they all have a common origin. The energies and times in the observer's frame and the wind rest frame are related as $E_\gamma^o = \delta_D E_\gamma$ and $t^{ob} = t/\delta_D$, where we have neglected the redshift correction, as the redshift ($z$) of Cen A is much less than 1. The gamma ray flux expected from decaying energetic pions produced in interactions of UHECR protons [expressed in the number of protons per unit energy per unit time $\frac{dN_p}{dE_p dt}(E_p)$ in the wind rest frame] with matter [41,42] at the core region of Cen A is

$$\frac{d\phi_\gamma^o(E_\gamma^o)}{dE_\gamma^o dt^o dA} = \frac{2Y_\alpha}{\mathbf{4\pi D^2}}\frac{R}{l_{pp}}\int_{E_{\pi^0,\min}}^{E_{\pi^0,\max}}\frac{dN_p(E_{\pi^0})}{dE_{\pi^0}dt}\frac{dE_{\pi^0}}{(E_{\pi^0}^2-m_{\pi^0}^2)^{1/2}}. \tag{2}$$

In the above equation, the number of cosmic ray protons per unit energy at the core of Cen A $\frac{dN_p(E_{\pi^0})}{dE_{\pi^0}dt} = A_p E_{\pi^0}^{-\alpha}$, where $A_p$ is the normalization constant and $\alpha$ is the spectral index. The distance to the source is $D = 3.4$ Mpc. The minimum energy of the pions is $E_{\pi^0,\min} = E_\gamma + m_{\pi^0}^2/(4E_\gamma)$, and the maximum energy is $E_{\pi^0,\max} = 0.2E_n^{\max}$, where $E_n^{\max}$ is the maximum energy of a cosmic ray proton/nucleon, $m_{\pi^0}$ is the pion's rest mass, and $E_\gamma$ is the energy of the gamma rays. The spectrum-weighted moment $Y_\alpha$ has been calculated from Ref. [41]:

$$Y_\alpha = \int_0^1 x^{\alpha-2} f_{\pi^0}(x)dx. \tag{3}$$

The function $f_{\pi^0}(x) \simeq 8.18x^{1/2}(\frac{1-x^{1/2}}{1+1.33x^{1/2}(1-x^{1/2})})^4(\frac{1}{1-x^{1/2}} + \frac{1.33(1-2x^{1/2})}{1+1.33x^{1/2}(1-x^{1/2})})$. For $\alpha = 2.73$, we get $Y_\alpha = 0.03$. With Eqs. (1)–(3), we can find the normalization constant of the UHECR proton spectrum $A_p$. UHECR neutrons produced in $p$-$p$ interactions subsequently decay to protons, electrons and antineutrinos. We have also included the UHECR neutrons decaying to protons in calculating the expected UHECR event rate in the Pierre Auger experiment. The integrated exposure of the Pierre Auger detector is $(9000/\pi)$ km$^2$, and the relative exposure for the declination angle ($\delta = 47°$) is $\omega(\delta) \simeq 0.64$. The number of UHECR events expected in the Pierre Auger detector can be calculated using the UHECR spectrum. The UHECR spectra in observer's frame and wind rest frame are related as

$$\frac{dN_{p,n}^o(E_{p,n}^o)}{dE_{p,n}^o dt^o dA} = \frac{1}{4\pi D^2}\frac{dN_{p,n}(E_{p,n})}{dE_{p,n}dt}, \tag{4}$$

and the number of expected events is

$$N_{p,n}^o = \frac{15}{4}\times\frac{9000}{\pi}(\mathrm{km}^2)\omega(\delta)\int_{E_l^o}^{E_u^o}\frac{dN_{p,n}^o(E_{p,n}^o)}{dE_{p,n}^o dt^o dA}dE_{p,n}^o. \tag{5}$$

We have used $E_{p,n}^o = \delta_D E_{p,n}$, as we have calculated the expected number of events in the Pierre Auger experiment which traveled in the direction $\theta_{ob}$. Also, we have assumed $\delta_D = 1$, which corresponds to $\Gamma = 7$ and $\theta_{ob} = 30°$. In the above equation, the lower and upper limits of the energy bin are $E_l^o = 55$ EeV and $E_u^o = 150$ EeV, respectively. If we assume that the proton spectral index remains 2.73 up to the highest energy and that they are not deflected by the intervening magnetic field, then in 15/4 years, 450 events are expected for $\tau_{pp} = 10^{-6}$, which corresponds to

$n_H = 10^4\ \mathrm{cm}^{-3}$. For lower densities, $\tau_{pp}$ will be smaller. In this case, many more protons may escape from the source before interacting with the matter near the core region. The intervening magnetic field may deflect them away from us, and some of them traveling towards us would trigger the detectors at the Pierre Auger observatory. As we are predicting a very large number of UHECR events in this case, the scenario of $p$-$p$ interactions at the core is not favored by the observational data from Pierre Auger. In the $p$-$p$ interaction scenario, the luminosity of UHECRs in the energy bin of 55 to 150 EeV is estimated as $L_{\mathrm{UHECR}} \simeq 3 \times 10^{43}/n_H$ erg/sec, which is much less than the Eddington luminosity for Centaurus A, $L_{\mathrm{Edd}} = 10^{46}$ erg/sec.

In the second case, we have assumed that the primary cosmic rays are only Fe nuclei, and they are interacting with cold matter protons at the core region of Cen A. In this case, the rate for Fe-$p$ interactions is $R_{\mathrm{Fe}\text{-}p} = n_H \sigma_{\mathrm{Fe}} c$, where the cross section for the interaction of nuclei with mass number 56 is $\sigma_{\mathrm{Fe}} = 34.6 \times 56^{3/4}$ mb. If UHECRs are Fe nuclei, then pure hadron interactions may lead to the production of gamma rays. The cross section of interactions is $A^{3/4}$ times higher in comparison to $p$-$p$ interactions, and hence the rate of $A$-$p$ interactions is also higher by the same factor. If we consider there are only iron nuclei near the core region of Cen A, then the gamma ray flux expected on Earth in pure hadron interactions Fe-$p$ is

$$\frac{d\phi_\gamma^o(E_\gamma^o)}{dE_\gamma^o dt^o dA} = \frac{2Y_\alpha}{\mathbf{4\pi D^2}} \frac{R}{l_{\mathrm{Fe}\text{-}p}} \int_{E_{\pi^0,\min}}^{E_{\pi^0,\max}} \frac{dN_{\mathrm{Fe}}(E_{\pi^0})}{dE_{\pi^0} dt} \times \frac{dE_{\pi^0}}{(E_{\pi^0}^2 - m_{\pi^0}^2)^{1/2}}. \tag{6}$$

The number of UHECR Fe nuclei per nucleon energy per unit time at the core region of Cen A is $\frac{dN_{\mathrm{Fe}}(E_p)}{dE_p dt} = 56 \frac{dN_{\mathrm{Fe}}(E_{\mathrm{Fe}})}{dE_{\mathrm{Fe}} dt}$, with $E_{\mathrm{Fe}} = 56 E_p$. We have expressed the number of Fe nuclei per unit energy of neutral pions per unit time as $\frac{dN_{\mathrm{Fe}}(E_{\pi 0})}{dE_{\pi 0} dt}$. The mean free path of Fe-$p$ interactions has been denoted by $l_{\mathrm{Fe}\text{-}p}$, where $l_{\mathrm{Fe}\text{-}p} = 0.048 l_{p\text{-}p}$. Equation (6) can be expressed as

$$\frac{d\phi_\gamma^o(E_\gamma^o)}{dE_\gamma^o dt^o dA} = \frac{2Y_\alpha}{\mathbf{4\pi D^2}} 56^{-\alpha+1} \frac{R}{l_{\mathrm{Fe}\text{-}p}} \int_{E_{\pi^0,\min}}^{E_{\pi^0,\max}} \frac{dN_p(E_{\pi^0})}{dE_{\pi^0} dt} \times \frac{dE_{\pi^0}}{(E_{\pi^0}^2 - m_{\pi^0}^2)^{1/2}}. \tag{7}$$

In pure hadron interactions, protons or neutrons will be produced with neutral or charged pions, respectively. We calculate the flux of nucleons (protons and neutrons) produced in pure hadron interactions:

$$E_{p,n} \frac{dN_{p,n}(E_{p,n})}{dE_{p,n} dt} dE_{p,n} = 0.8 \frac{R}{l_{\mathrm{Fe}\text{-}p}} E_{\mathrm{Fe}} \frac{dN_{\mathrm{Fe}}(E_{\mathrm{Fe}})}{dE_{\mathrm{Fe}} dt} dE_{\mathrm{Fe}}, \tag{8}$$

where $E_{p,n} = 0.8 E_{\mathrm{Fe}}/56$, assuming the secondary nucleon takes away 80% of the primary nucleon's energy. In this case, the secondary nucleon flux produced in $A$-$p$ interactions is very low, and we expect no event in the Pierre Auger detector in 15/4 years. Hence, we conclude that neither the $p$-$p$ nor the Fe-$p$ interaction scenario is consistent with the observational results from the core of Cen A.

### B. Photodisintegration of heavy nuclei

The photodisintegration process of gamma ray emission has been discussed in many earlier papers [41,43]. If the primary cosmic rays are only Fe nuclei at the core of Cen A, then they may be photodisintegrated by the low-energy photons in that region. The multiwavelength observations have revealed the broadband spectral energy distribution (SED) at the core of Cen A as shown in our Fig. 2 [40]. After the photodisintegration of the primary nuclei, daughter nuclei and secondary nucleons (protons/neutrons) are produced. The daughter nuclei deexcite by emitting gamma rays. If the observed high-energy gamma ray emission from Cen A is due to this process, then we can calculate the expected nucleon (proton/neutron) flux from Cen A using the observed gamma ray flux [41]. The rate of the photodisintegration process is calculated with Eq. (6) of Ref. [41]:

$$R_{\text{phot-dis}} = \frac{c\pi\sigma_0\epsilon_0'\Delta}{4\gamma_p^2} \int_{\epsilon_0'/2\gamma_p}^{\infty} \frac{dn(x)}{dx} \frac{dx}{x^2}. \tag{9}$$

The value of the cross-section normalization constant is $\sigma_0 = 1.45A$ mb, the central value of the giant dipole resonance is $\epsilon_0' = 42.65A^{-0.21}$ MeV for $A > 4$, and the width of the giant dipole resonance is $\Delta = 8$ MeV. The Lorentz factor of each nucleon is $\gamma_p = E_{\mathrm{Fe}}/(56 m_p)$. We have used the photon spectral energy distribution observed on Earth, $\epsilon_\gamma^{o2} \frac{dN_\gamma^o(\epsilon_\gamma^o)}{d\epsilon_\gamma^o dt^o dA}$ (MeV cm$^{-2}$ sec$^{-1}$) from the fit given in Ref. [40], also shown with the solid curve in our Fig. 2. The photon density per unit energy in the core region $\frac{dn(x)}{dx}$ is

$$4\pi R^2 c \frac{dn(x)}{dx} = 4\pi D^2 \delta_D^{-p} \frac{dN_\gamma^o(\epsilon_\gamma^o)}{d\epsilon_\gamma^o dt^o dA}, \tag{10}$$

where $p = n + \alpha + 2$ and $n = 2, 3$ for continuous and discrete jets, respectively [44]. We have denoted the energy of the low-energy photons in the observer's frame by $\epsilon_\gamma^o$, and $\epsilon_\gamma^o = \delta_D x$. The value $\alpha$ is the spectral index of the SED given in Fig. 2, $\epsilon_\gamma^{o2} \frac{dN_\gamma^o(\epsilon_\gamma^o)}{d\epsilon_\gamma^o dt^o dA} \propto \epsilon_\gamma^{o-\alpha}$; $\alpha$ takes different values in different energy regimes, as shown in Fig. 2.

From the above equation, it is noted that the photon density at the source depends on $\delta_D$. In Abdo *et al.* [40], they have taken various values of $\Gamma$ and $\delta_D$; the SED fit of the SSC model to Fermi data is given for $\Gamma = 7$ and $\delta_D = 1$, which corresponds to $\theta_{ob} = 30°$. For smaller values of $\delta_D$, the photon density at the source would be much higher. The distance of the source $D = 3.4$ Mpc, and the radius of the core region $R = 3 \times 10^{15}$ cm. In the photodisintegration process, protons and neutrons can be produced with equal probabilities. TeV gamma rays may be produced in this process from PeV UHECRs. Similar to Eq. (28) given in Ref. [41], we can relate the neutron, proton and gamma ray fluxes from the photodisintegration of nuclei of mass $A$:

$$\frac{dN^o_{n,p}(E^o_{n,p})}{dE^o_{n,p}dt^o dA} = \frac{\bar{E}'_{\gamma A}}{m_n \bar{n}_A} \frac{d\phi^o_\gamma(E^o_\gamma)}{dE^o_\gamma dt^o dA}, \tag{11}$$

where in the wind rest frame $E_\gamma = E_n \bar{E}'_{\gamma A}/m_n$. We are interested in calculating the number of proton or neutron events in the Pierre Auger experiment above 55 EeV which maintain their directionality while traveling from the core of Cen A to the observer. They have the same Doppler shift in energy as the gamma rays observed by HESS, as they are produced in the same wind frame and traveling in the same direction from the source to the observer. If the gamma ray emission is monochromatic in the rest frame of the nucleus, then its average has been denoted by $\bar{E}'_{\gamma A}$. The value $\bar{n}_A$ is the average multiplicity of gamma rays, and $m_n$ is the rest mass of each nucleon. For Fe nuclei, $\bar{E}'_{\gamma 56} =$ 2–4 MeV, and gamma ray multiplicity is $\bar{n}_{56} = 1$–3. Assuming the same spectral index of the neutron and proton spectrum from TeV to the highest energy, we calculate the expected number of events in the Pierre Auger detector in 15/4 years in the energy bin of 55 to 150 EeV. We get two events for the spectral index 2.45 with $\bar{E}'_{\gamma,56} = 4$ MeV and $\bar{n}_{56} = 2$, which agrees with the detection by the Pierre Auger experiment from the direction of the core of Cen A. The power law spectrum which fits HESS data has the spectral index $2.73 \pm 0.45_{\rm stat} \pm 0.2_{\rm sys}$ [34]. The spectral index 2.45 used in our calculations is within the range of error in the spectral index obtained by the HESS group.

In this scenario, variability of the source (increasing the emission) may yield more UHECR events from the direction of Cen A. Due to the low gamma ray flux from Cen A, it was not possible for the HESS experiment to detect variabilities in time scales shorter than days or with increments below a factor of 15 to 20 [34]. If the size of the emission region is $R = 3 \times 10^{15}$ cm [40], and the rate of the photodisintegration process is $R_{\rm phot\text{-}dis}$, then the high-energy gamma ray emission can be related to the number of UHECR Fe nuclei per nucleon energy per unit time at the core of Cen A $\frac{dN_{\rm Fe}}{dE_N dt}(E_N)$ as follows:

$$\frac{d\phi^o_\gamma(E^o_\gamma)}{dE^o_\gamma dt^o dA} = \frac{1}{\mathbf{4\pi D^2}} \frac{R}{\beta c} \frac{\bar{n}_{56} m_N}{2\bar{E}'_{\gamma,56}} \times \int_{\frac{m_N E_\gamma}{2\bar{E}'_{\gamma,56}}} \frac{dN_{\rm Fe}(E_N)}{dE_N dt} R_{\rm phot\text{-}dis} \frac{dE_N}{E_N}, \tag{12}$$

where $\beta = v/c \sim 1$ for UHECR nuclei.

We calculate the normalization constant of the UHECR Fe nuclei flux from Eq. (12). The HESS spectrum is measured above $E^o_\gamma = 250$ GeV. Gamma rays of energy 250 GeV are produced by Fe nuclei with per-nucleon energy $E_N = E_\gamma m_N/(2\bar{E}'_{\gamma,56}) = 29$ TeV.

In our Fig. 1, we have plotted the rate of photodisintegration of Fe nuclei with the energy per nucleon in the wind rest frame along the $x$ axis. Between 1 and 100 TeV nucleon energy in the wind rest frame, the rate is almost constant at $2 \times 10^{-8}\ {\rm sec}^{-1}$ for $\Gamma = 7$ and $\delta_D = 1$. At higher energy, the rate increases but the cosmic ray nuclei flux decreases more rapidly, as it follows a power law with spectral index $-2.45$.

In this case, the luminosity of the UHECR Fe nuclei flux in the energy bin of $55 \times 56$ EeV and $150 \times 56$ EeV is $\sim 10^{42}$ erg/ sec , which is much below the Eddington luminosity. The 170 KeV photons at the second peak of SED in Fig. 2 photodisintegrate Fe nuclei of energy $E_{\rm Fe} =$ 2.8 TeV. This result is obtained using the threshold energy condition $\epsilon'_0/2\gamma_p = 170$ KeV, where $\gamma_p$ is the Lorentz factor of each nucleon in the wind rest frame, and we have used $\delta_D = 1$ for the Doppler shift of the low-energy photons. The gamma ray energy produced from the photodisintegration of 2.8 TeV Fe nuclei is calculated using the

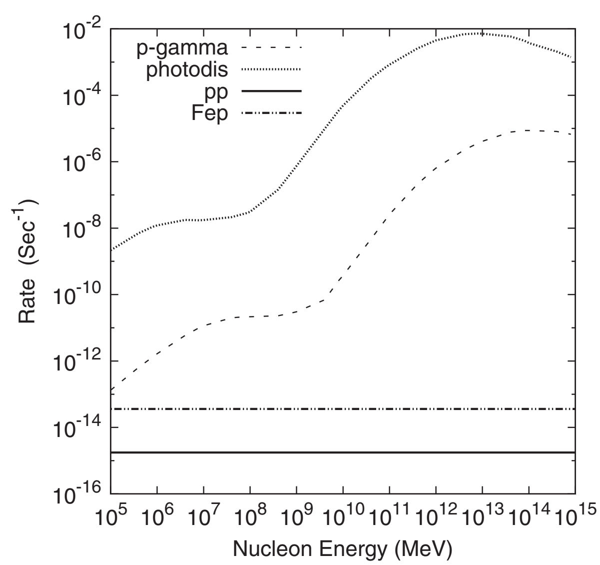


FIG. 1. The $p$-$p$ (solid line), Fe-$p$ (dash-dotted line) for $n_H = 1.7\ {\rm cm}^{-3}$ [39], $p$-$\gamma$ (dashed line), and photodisintegration rates of Fe nuclei (dotted line) calculated with the fit of the SED [40] also given in our Fig. 2. The $x$ axis represents energy per nucleon in the wind rest frame.

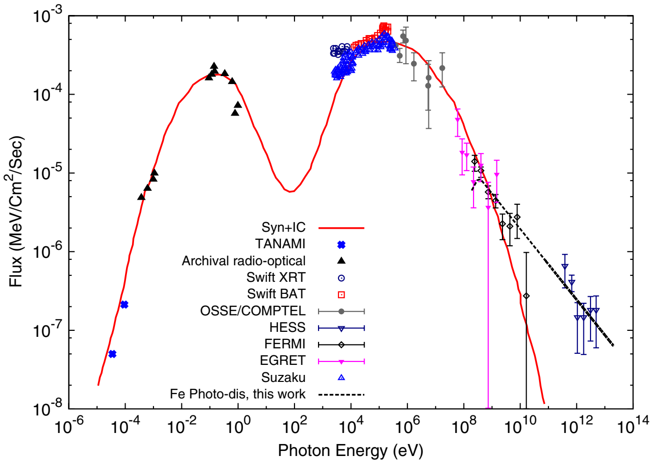


FIG. 2 (color online). Spectral energy distribution (SED) $\epsilon_\gamma^{o2} \frac{dN_\gamma^o(\epsilon_\gamma^o)}{d\epsilon_\gamma^o}$ (MeV cm$^{-2}$ sec$^{-1}$) from the Cen A core. The solid red curve is the fit with the synchrotron and SSC from Ref. [40], and the high-energy gamma ray spectrum from the photodisintegration of Fe nuclei is shown with the black dashed line.

expression $E_\gamma = 2\bar{E}'_{\gamma,56}E_N/m_N$, where $\bar{E}'_{\gamma,56} = 4$ MeV, and the energy of each nucleon $E_N = 50$ GeV. We find the peak energy in the gamma ray spectrum from the photodisintegration of Fe nuclei by 170 KeV photons at 400 MeV. The spectrum of cosmic ray Fe nuclei has a break at 2.8 TeV due to the second peak in the SED at 170 KeV. Above 2.8 TeV, the spectral index $-2.45$ gives a good fit to the observational results. The total luminosity of the Fe cosmic rays has to be of the order of $10^{47}$ erg/ sec , which is higher than the Eddington luminosity of Cen A. We note that the luminosity required to accelerate cosmic rays to above $10^{20}$ eV in Cen A is higher than $10^{46}$ erg/ sec [40,45]. Dermer *et al.* [45] have shown that the apparent isotropic luminosity can easily exceed $10^{46}$ erg/ sec in Cen A during high flaring states for small beaming cones.

The SED we have used is the fit to the SSC model obtained by Abdo *et al.* [40]. There are error bars on the observed photon flux, and there are also no observational data points between the two peaks as shown in our Fig. 1. The lower-energy photons photodisintegrate the higher-energy Fe nuclei. The rate of photodisintegration is directly proportional to the density of low-energy photons at the source. A higher density of low-energy photons would lead to a higher rate for the photodisintegration process. If the rate of photodisintegration is higher, then a lower luminosity of cosmic rays would be required to explain the observational results.

Along the direction of the x-ray jet of Cen A, the x-ray photon density is higher. This would lead to more efficient production of high-energy gamma rays and would require lower UHECR luminosity.

We have shown the high-energy gamma ray spectrum from the photodisintegration of Fe nuclei in Fig. 2 with a black dashed line.

## III. *p*-*γ* INTERACTIONS

The $p$-$\gamma$ interaction rate is calculated using the photon SED from Ref. [40] and the formalism discussed in Ref. [46]:

$$R_{p\gamma} = \frac{c}{\gamma_p^2}\int_{\epsilon_o}^{\infty} \sigma(\epsilon)\xi\epsilon d\epsilon \int_{\epsilon/(2\gamma_p)}^{\infty} \frac{dn(x)}{dx}\frac{dx}{x^2}, \qquad (13)$$

where $\sigma(\epsilon_{\rm peak}) = 0.5$ mb is the cross section of interaction at the resonance energy $\epsilon_{\rm peak} = 0.3$ GeV in the proton rest frame, and the full width of the resonance at half maxima is 0.2 GeV. The fractional energy going to a pion from a proton is $\xi = 0.2$. The threshold energy of pion production in the proton rest frame is $\epsilon_o = 0.15$ GeV. The $p$-$\gamma$ process has been discussed in detail in Ref. [35]. There the authors have shown that it can explain the observational results. In this model, the luminosity of the cosmic ray protons at 13 TeV has to be $4 \times 10^{45}$ erg/ sec for the production of 190 GeV gamma rays. The optical depth for $p$-$\gamma$ interactions for 13 TeV protons with 170 KeV photons is estimated to be $10^{-6}$ in Ref. [35]. We get a similar optical depth for $p$-$\gamma$ interactions at 13 TeV proton energy using our calculated rate of $p$-$\gamma$ interactions given in Fig. 1.

## IV. DISCUSSIONS AND CONCLUSIONS

Our calculated rates of the various processes of high-energy gamma ray production are shown in Fig. 1 with a hydrogen density of $n_H = 1.7$ cm$^{-3}$ and the photon spectral energy distribution (SED) from Ref. [40]. The rate of photodisintegration of Fe nuclei is the highest among all processes of high-energy gamma ray production. The increase in the rates of photodisintegration and $p$-$\gamma$ interactions near $10^{19}$ eV shown in Fig. 1 is due to the first peak or the synchrotron peak in the photon SED, as shown in our Fig. 2 from Ref. [40]. The high-energy gamma ray flux from the photodisintegration of Fe nuclei is shown with a black dashed line in Fig. 2. The photodisintegration of Fe nuclei followed by the deexcitation of daughter nuclei is found to be consistent with the UHECR proton/neutron event rate observed by Pierre Auger between 55 and 150 EeV, and the high-energy gamma ray flux measured by HESS. We compare our results with the high-energy gamma ray flux estimated in other papers. The $p$-$\gamma$ interaction scenario discussed in Ref. [35] predicts a peak in the high-energy gamma ray spectrum at 190 GeV due to the $p$-$\gamma$ interactions of the 170 KeV photons with 13 TeV protons. Due to the photodisintegration of Fe nuclei by 170 KeV photons, we expect a peak in the high-energy gamma ray spectrum at 400 MeV. In Ref. [36], the authors have used the low-energy photon spectrum from Ref. [40] for calculating the high-energy gamma ray flux from the lobes of Cen A, but the low-energy photon spectrum given in Ref. [40] is observed from the core of Cen A.

In summary, we have found that the scenario of $p$-$p$ interactions gives excess UHECR events from the core region of Cen A in the energy bin between 55 and 150 EeV. If we consider that there are only Fe nuclei as primary cosmic rays, then in the case of pure hadronic interactions Fe-$p$, the estimated UHECR event rate is very low. Sahu *et al.* [35] have considered the production of 190 GeV gamma rays in the interaction of 13 TeV protons with 170 KeV photons in the second peak of the SED. In their model, the luminosity of the 13 TeV protons has to be $4 \times 10^{45}$ erg/sec. In our case, a 29 TeV per-nucleon energy of the Fe nuclei is required to produce gamma rays of energy 250 GeV in the photodisintegration of Fe nuclei. In our model of the photodisintegration of Fe nuclei, the total cosmic ray power has to be of the order of $10^{47}$ erg/sec. The required luminosity of the Fe cosmic ray nuclei is higher than the Eddington luminosity of Cen A. However, we note that the requirement of luminosity depends on the photon density inside the source and the size of the emitting region. The cosmic ray luminosity required in the photodisintegration model will be lower if the density of the low-energy photons is higher at the source or the size of the emitting region is smaller. Moreover, it has been discussed earlier that the isotropic luminosity in Cen A can easily exceed its Eddington luminosity of $10^{46}$ erg/sec during flaring states [45].

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## APPENDIX

The spectral energy distribution from Ref. [40], shown by a red solid curve in our Fig. 2, has been fitted in 14 energy intervals with an average error less than 10%. The parametrizations used in our calculations are given below:

$$f(x) = -6.15 \times 10^{-9} + 2.21 \times 10^{3}x + 2.01 \times 10^{13}x^2; \qquad 1.00 \times 10^{-5} \le \frac{x}{\mathrm{eV}} \le 7.7 \times 10^{-5}. \tag{A1}$$

$$f(x) = 1 \times 10^{-6} - 2.06 \times 10^{4}x + 1.502 \times 10^{14}x^2; \qquad 7.7 \times 10^{-5} \le \frac{x}{\mathrm{eV}} \le 1.17 \times 10^{-4}. \tag{A2}$$

$$f(x) = -1.49 \times 10^{-7} + 5.23 \times 10^{3}x + 1.49 \times 10^{13}x^2; \qquad 1.17 \times 10^{-4} \le \frac{x}{\mathrm{eV}} \le 4.32 \times 10^{-4}. \tag{A3}$$

$$f(x) = -1.55 \times 10^{-6} + 1.34 \times 10^{4}x - 4.63 \times 10^{11}x^2; \qquad 4.32 \times 10^{-4} \le \frac{x}{\mathrm{eV}} \le 1.36 \times 10^{-2}. \tag{A4}$$

$$f(x) = 5.17 \times 10^{-5} + 3.77 \times 10^{3}x - 3.99 \times 10^{10}x^2 + 1.39 \times 10^{17}x^3; \qquad 1.36 \times 10^{-2} \le \frac{x}{\mathrm{eV}} \le 1.34 \times 10^{-1}. \tag{A5}$$

$$f(x) = 1.96 \times 10^{-4} - 1.07 \times 10^{2}x + 2.63 \times 10^{7}x^2 - 2.33 \times 10^{12}x^3; \qquad 1.34 \times 10^{-1} \le \frac{x}{\mathrm{eV}} \le 4.54. \tag{A6}$$

$$f(x) = 5.30 \times 10^{-5} - 5.77x + 2.65 \times 10^{5}x^2 - 4.14 \times 10^{9}x^3; \qquad 4.54 \le \frac{x}{\mathrm{eV}} \le 28.3. \tag{A7}$$

$$f(x) = 3.57 \times 10^{-6} + 2.21 \times 10^{-2}x + 2.18x^2; \qquad 2.83 \times 10^{-2} \le \frac{x}{\mathrm{keV}} \le 3.48. \tag{A8}$$

$$f(x) = 1.99 \times 10^{-5} + 2.62 \times 10^{-2}x - 5.74 \times 10^{-1}x^2; \qquad 3.48 \le \frac{x}{\mathrm{keV}} \le 17.8. \tag{A9}$$

$$f(x) = 2.14 \times 10^{-4} + 6.44 \times 10^{-3}x - 5.75 \times 10^{-2}x^2 + 1.64 \times 10^{-1}x^3; \qquad 17.8 \le \frac{x}{\mathrm{keV}} \le 185. \tag{A10}$$

$$f(x) = 4.77 \times 10^{-4} - 6.54 \times 10^{-5}x + 4.21 \times 10^{-6}x^2; \qquad 0.185 \le \frac{x}{\mathrm{MeV}} \le 7.16. \tag{A11}$$

$$f(x) = 3.33 \times 10^{-4} - 1.95 \times 10^{-5}x + 5.55 \times 10^{-7}x^2 - 5.31 \times 10^{-9}x^3; \qquad 7.16 \le \frac{x}{\mathrm{MeV}} \le 49. \tag{A12}$$

$$f(x) = 1.26 \times 10^{-4} - 1.16 \times 10^{-6}x + 4.35 \times 10^{-9}x^2 - 5.49 \times 10^{-12}x^3; \qquad 49 \le \frac{x}{\mathrm{MeV}} \le 352. \tag{A13}$$

$$f(x) = 2.54 \times 10^{-5} - 3.3 \times 10^{-8}x + 1.29 \times 10^{-11}x^2; \qquad 0.352 \le \frac{x}{\mathrm{GeV}} \le 1.44. \tag{A14}$$

$$f(x) = 2.73 \times 10^{-6} - 2.39 \times 10^{-10}x + 5.25 \times 10^{-15}x^2 - 3.26 \times 10^{-20}x^3; \qquad 1.44 \le \frac{x}{\mathrm{GeV}} \le 90.94. \tag{A15}$$


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