HIGH ENERGY NEUTRINOS PRODUCED IN THE ACCRETION DISKS BY NEUTRONS FROM NUCLEI DISINTEGRATED IN THE AGN JETS

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ABSTRACT

We investigate the consequences of acceleration of nuclei in jets of active galaxies not far from the surface of an accretion disk. The nuclei can be accelerated in the re-connection regions in the jet and/or at the jet boundary, between the relativistic jet and its cocoon. It is shown that the relativistic nuclei can efficiently fragment onto specific nucleons in collisions with the disk radiation. Neutrons, directed toward the accretion disk, take a significant part of energy from the relativistic nuclei. These neutrons develop a cascade in the dense accretion disk. We calculate the neutrino spectra produced in such a hadronic cascade within the accretion disk. We propose that the neutrons produced in such a scenario, from the whole population of super-massive black holes in active galaxies, can explain the extragalactic neutrino background recently measured by the IceCube neutrino detector, provided that a 5% fraction of galaxies have an active galactic nucleus and a few percent of neutrons reach the accretion disk. We predict that the neutrino signals in the present neutrino detectors, produced in terms of such a model, will not be detectable even from the nearby radio galaxies similar to M87.

Key words: galaxies: active – galaxies: jets – radiation mechanisms: non-thermal

1. INTRODUCTION

Hadrons are expected to be accelerated in the vicinity of super-massive black holes (SMHBs) in active galactic nuclei (AGNs) producing GeV–TeV γ-rays and also significantly contributing to the highest energy cosmic rays. The type of particles responsible for this γ-ray emission (leptonic or hadronic) can be only uniquely identified in the case of observations of neutrinos from these objects.

Recently, a few tens of neutrino events have been detected by the IceCube neutrino telescope in the TeV–PeV energy range (Aartsen et al. 2013, 2014). These events form a clear component above the atmospheric neutrino background. Their spectrum can be well described by a power law type extending up to a few PeV (Aartsen et al. 2015a). It has been proposed that these neutrinos are produced within active galaxies at cosmological distances (for review, see Murase 2015 or Becker 2008). Different regions, such as AGN jets, AGN core regions or dense regions around SMHBs, have been suggested as possible emission sites. For example, in one of the first models of this type, Nellen et al. (1993) proposed that protons accelerated in the jet interact with the accretion disk radiation. Neutrons, produced in such collisions, and also some of the protons, escape to the accretion disk producing neutrinos in hadronic collisions. This popular model for neutron production in blazars postulates interaction of the protons with the radiation field via pion production. The radiation comes from the jet and/or the accretion disk, and/or is scattered around the jet in the broad line region (e.g., Stecker et al. 1991; Mannheim 1995; Halzen & Zas 1997; Bednarek & Protheroe 1999; Atayan & Dermer 2001; Mücke & Protheroe 2001; Mücke et al. 2003; Stecker 2005; Murase et al. 2014; Padovani et al. 2015). Most of these models predict neutrino spectra that usually flatten below ~PeV energies, due to the threshold of the pion production in photo-hadronic collisions. Therefore, such models have some difficulty in explaining the observed shape of the neutrino spectrum, which is close to the power law type between ~10 TeV and a few PeV (as measured by the IceCube, see Figure 3 in Murase 2015). The models that involve proton–proton interactions as the dominant mechanism for neutrino production (e.g., Nellen et al. 1993; Beall & Bednarek 1999; Schuster et al. 2002; Becker Tjus et al. 2014; Hooper 2015; Kimura et al. 2015) seem to be more plausible for modeling of the IceCube observations. For example, Becker Tjus et al. (2014) consider two scenarios for the neutrino production; i.e., acceleration of protons, and their interaction with the matter of knots in the inner jets of FR-I galaxies and the lobes of FR-II galaxies. A column density of matter on the order of ~10^{24} cm^{-2} is needed in the first scenario to explain the observed IceCube signal. The authors conclude that the second scenario requires a few orders of magnitude larger column density of the matter than expected in the radio lobes. Therefore, only the first scenario can explain the IceCube results.

In this paper, we consider a more complicated scenario in which produced neutrons might significantly contribute to the flux observed by the IceCube. We note that a significant part of the matter that accretes onto the SMHB in the AGN nucleus has to be composed from nuclei. This matter is likely to be more abundant in heavy nuclei, with respect to primordial matter containing ~25% of helium, due to the efficient star formation occurring in the central parts of the parent galaxies. These nuclei are expected to be accelerated to relativistic energies in the re-connection regions in the jet and/or at the jet boundary layer. The nuclei disintegrate in collisions with the accretion disk radiation, producing relativistic neutrons which, because they are neutral, can easily find their way to the dense accretion disk. Note that the neutrons from the disintegration of the nuclei have energies more than an order of magnitude lower than the neutrons produced in collisions of protons with photons, due to the lower threshold on the first process. Therefore, neutrons from nuclei can easily produce multi-TeV neutrinos consistent with the IceCube observations. We discuss the acceleration process of the nuclei and their interaction with the accretion disk in Sections 2 and 3. The neutrino spectra produced in such a scenario are calculated in...
Section 4. The expected extragalactic neutrino background (ENB), calculated in terms of such a model, from the whole population of the SMBHs in the universe, is compared with the recent observations by the IceCube telescope in Section 5. Finally, we discuss the observability of the neutrino signal from the example nearby active galaxy, M87.

2. ACCELERATION AND DISINTEGRATION OF HEAVY NUCLEI IN THE JET

We consider the processes in the inner part of the active galaxy in which an accretion disk forms around the SMBH. Jets in active galaxies are expected to be launched by a rotating black hole (e.g., Blandford & Znajek 1977) or from the inner part of the accretion disk (e.g., Blandford 1976; Lovelace 1976). In fact, both processes mentioned above can play an important role. Therefore, the jet structure already at its base can be quite complicated. For example, the jet can be composed of a faster-moving core region and a slower moving sheath. The jet can be additionally surrounded by a cocoon. The cocoon can be formed by the matter surrounding the jet, or by the outer layers of the jet expelled from the accretion disk; i.e., the accretion disk wind. We consider two regions as responsible for the acceleration of particles in the jet/cocoon system; i.e., the re-connection regions in the jet and the transition region between the jet and the cocoon. We assume that an essential part of the jet power can be transferred to the relativistic nuclei in the inner part of the jet. The two aforementioned acceleration mechanisms of nuclei are discussed in a more detail, below. As a result of the disintegration of nuclei in collisions with the disk radiation, relativistic neutrons are extracted. In fact, neutrons can take a significant part of the energy of the accelerated nuclei, between \( \sim 8^{-1} \) (in the case of the presence of only primordial helium, assuming the primordial He abundance of \( \sim 0.25 \), e.g., Peimbert et al. 2007) and up to \( \sim 2^{-1} \) (if accelerated hadrons are dominated by heavy nuclei that might appear due to the nuclear burning within the stars forming the central stellar cluster around SMBH). These neutrons irradiate the accretion disk interacting with a large column density of matter. The schematic representation of the processes discussed in this paper are shown in Figure 1.

2.1. Re-connection Regions

We assume that nuclei can be accelerated in re-connection regions, which are oriented in the general direction toward the accretion disk in the SMBH rest frame, to energies allowing them efficient disintegration into individual nucleons. Such situation is expected when the re-connection process is driven by the perpendicular component of the magnetic field in the jet. Acceleration of particles in the re-connection regions has been considered as an important process for energization of particles in different astrophysical scenarios (e.g., see recent reviews by Kagan et al. 2015 and Uzdensky 2016, p. 473). It is expected to be responsible for the acceleration of particles in relativistic jets of blazars (see, e.g., Romanova & Lovelace 1992; Lesch & Birk 1998; Larrabee et al. 2003; Lyutikov 2003; Jaroschek et al. 2004; Giannios et al. 2009; Sironi & Spitkovsky 2014).

For example, following Giannios (2010), we assume that nuclei within the jet can be accelerated in the re-connection regions. We apply a simple model for the acceleration process in the re-connection region. Its length, \( L_{\text{rec}} \), scales with the distance from the base of the jet (e.g., Bednarek et al. 1996). The distance along the jet, \( R \), is given in units of the inner radius of the jet, \( R_{\text{in}} \), according to \( r = R/R_{\text{in}} \). Then, \( L_{\text{rec}} \) is linked to the SMBH mass,

\[
L_{\text{rec}} = \xi R_{\text{in}} r \approx 10^{14} \xi^{-1} M_{\odot} r \text{ cm},
\]

where \( R_{\text{in}} = 3 R_s \approx 9 \times 10^{14} M_{\odot} \text{ cm} \) is the inner radius of the jet, \( R_s \) is the Schwarzschild radius of the black hole, \( M_{\odot} = 10^{6} M_{\odot} \) is the mass of the black hole in the Solar masses, and \( \xi = 0.1 \xi_{-1} \) is the scaling factor of the re-connection region, assumed to be comparable to the perpendicular extend of the jet which is \( \sim 0.1 r \) for the opening angle of the order of \( \sim 0.1 \) rad.

We estimate the mean free path for the disintegration of the Helium nuclei (expected to be the most abundant between the heavy nuclei) in the radiation field of the accretion disk,

\[
\lambda_{\text{des}}^{\text{He}} = (n_{\text{ph}} \alpha_{\text{des}}^{\text{He}})^{-1} \approx 9.4 \times 10^{11} r^{-2}/T_{4.5}^2 \text{ cm},
\]

where \( n_{\text{ph}} \approx 5.3 \times 10^{14} T_{4.5}^{-2}/r^{2} \) ph. cm\(^{-2} \) is the density of the diluted (by the factor \( r \) ) blackbody radiation with the temperature at the inner disk radius \( T_0 = 3 \times 10^{4} T_{4.5} \) K, and \( \alpha_{\text{He}}^{-1} \approx 2 \times 10^{-27} \) cm\(^{2} \) is the cross-section for the disintegration process of He nuclei at its maximum (see Appendix A in Cyburt et al. 2003). As estimated in Section 4, the surface temperature in the inner part of an accretion disk around a massive black hole is expected to be on the order of a few \( 10^{4} \) K. This is consistent with observations of ultraviolet excess in the spectra of some quasars (e.g., \( 2\sim 3 \times 10^{4} \text{ K} \) in the case of 3C 273, Malkan & Sargent 1982).
In order to provide an efficient disintegration of nuclei, $\lambda_{\text{dis}} \text{He}$ should be shorter than the size of the re-connection region. This condition is fulfilled for a distance from the base of the jet (obtained from the comparison of Equations (1) and (2)),

$$r < 100 \xi_{-1} M_0 T_{A5}^{-5}.$$  \hspace{1cm} (3)

Therefore, it is expected that the nuclei can disintegrate inside the inner jet, i.e., within $\sim$pc distance scale.

In contrast, helium nuclei have to be accelerated to large enough energies to suffer efficient disintegration. The electric field strength within the re-connection region is parametrized by

$$V_{\text{rec}} = \eta B \approx 3 \times 10^3 \eta_{-1} B_2 r^{-\beta} \text{eV cm}^{-1},$$  \hspace{1cm} (4)

where the magnetic field strength along the jet is described by $B = B_2 r^{-\beta}$ (with $\beta = 1$ for the toroidal component and $\beta = 2$ for the longitudinal component), the magnetic field at the base of the jet is $B_2 = 100 B_2$ G, $\eta = 0.1 \eta_{-1}$ is the efficiency of the re-connection process, and $c$ is the velocity of light. It has been recently shown that, if the re-connection process occurs in the electron-proton plasma, the acceleration efficiency can reach values as large as $\sim 0.2$ (see Sironi et al. 2015). The maximum Lorentz factors of the nuclei can be estimated from

$$E_{\text{He}}^{\text{max}} = V_{\text{rec}} L_{\text{rec}} Z_{\text{He}} \approx 3 \times 10^{17} \eta_{-1} \xi_{-1} M_0 B_2 Z_{\text{He}} r^{-\beta} \text{eV},$$  \hspace{1cm} (5)

where $Z_{\text{He}} = 2e$ is the charge of He nuclei and $e$ is the elementary charge. Note, however, that the inner jet might be already mildly relativistic with the bulk Lorentz factor, $\Gamma_1$, of the order of a few (e.g., Vlahakis & Koenigl 2004). Then, the maximum energies of the nuclei in the disk reference frame are reduced by the value of this Lorentz factor. On the other hand, energies of nuclei can also be larger than estimated in Equation (5), provided that the BH rotates fast, because in such a case the accretion disk should extend closer to the BH, and the magnetic field in the inner jet should be stronger than in the case of the Schwartzschild BH. Therefore, the above formula gives only an order of magnitude estimate of energies to which the nuclei can be accelerated.

The He nuclei are efficiently disintegrated when the soft radiation from the accretion disk reaches energies above $E_{\text{He}} \sim 20$ MeV in their reference frame (e.g., Appendix A in Cyburt et al. 2003). This condition is met for the energies of nuclei on the order of

$$E_{\text{He}}^{\text{min}} = m_{\text{nuc}} c^2 A_{\text{He}} E_{\text{He}}^{\text{min}} = 2.4 \times 10^{15} A_{\text{He}} \frac{E_{\text{rec}}}{T_{A5}} \text{eV},$$  \hspace{1cm} (6)

where $A_{\text{He}} = 4$ is the mass number of He nuclei, $m_{\text{p}} c^2$ is the proton rest energy, $c$ is the velocity of light, and $k_B$ is the Boltzmann constant. Note that neutrons from the disintegration of the nuclei are expected to have Lorentz factors similar to those of the parent nuclei. The obvious condition, i.e., $E_{\text{He}}^{\text{max}} > E_{\text{He}}^{\text{min}}$, is met in the case of $\beta = 2$ in the inner region of the jet; that is, within the distance from the jet base

$$r < 1.2 \times 10^2 \eta_{-1} \xi_{-1} M_0 B_2 T_{A5} Z_{\text{He}} / A_{\text{He}}.$$  \hspace{1cm} (7)

The conditions given by Equations (3) and (7) postulate that the reconnection process has to occur already in the inner part of the jet. In fact, the theory of this process in the AGN jets predicts that the dissipation region is located at the distance $R_{\text{dis}} \approx T_{A5}^2 R_s / \varepsilon \approx 40 \Gamma_1^2 R_s / \varepsilon_{-1}$, where $\Gamma_1 = 2 \varepsilon_2$ is the jet Lorentz factor and $\varepsilon = 0.1 \varepsilon_{-1}$ is the reconnection speed (see Equation (1) in Giannios 2013). Therefore, for mildly relativistic jets the acceleration of nuclei in the reconnection process seems to be present already in the inner jet.

If the structure of the magnetic field in the jet is better described by $\beta = 1$, then the above condition is met everywhere in the jet provided that the magnetic field strength at the base of the jet is

$$B_{\text{in}} \geq 0.8 A_{\text{He}} / (\eta_{-1} \xi_{-1} M_0 T_{A5} Z_{\text{He}}) \text{G}.$$  \hspace{1cm} (8)

Note that the conditions for the disintegration of nuclei in jets of active galaxies can be “easier” fulfilled (i.e., for weaker magnetic fields) for the SMBHs with larger masses.

We assume that a part of neutrons liberated from nuclei impinging onto the accretion disk. Neutrons with Lorentz factors above $\gamma_n > E_{\text{dis}} / (A_{\text{He}} m_p c^2)$ can travel characteristic distances on the order of $X_n \sim c T_{A5} \gamma_n > 8 \times 10^{18}$ cm. This distance scale is clearly larger than that for the efficient extraction of neutrons from the nuclei (given by Equation (7)) for the black holes with masses $< 10^{10} M_\odot$. Therefore, we conclude that, in most cases, the neutrons extracted from the nuclei, moving toward the accretion disk, can reach the disk surface before decaying.

We note that extraction of neutrons from He nuclei is a more important process than the energy losses of the nuclei on the Bethe–Heitler $e^\pm$ pair production in collisions with the disk radiation. Although the cross-section for the disintegration of He nuclei is similar to that for the Bethe–Heitler $e^\pm$ pair production, the inelasticity coefficient for energy extraction by dissolved nucleons from the He nuclei ($-m_{\text{nuc}}/m_{\text{He}}$) is about three orders of magnitude larger than for the $e^\pm$ pair production ($2m_e/m_{\text{He}}$, e.g., Chodorowski et al. 1992), where $m_e$, $m_{\text{nuc}}$, and $m_{\text{He}}$ are the rest masses of the lepton, neutron, and He nuclei, respectively. Therefore, the process of Bethe–Heitler $e^\pm$ pair production can be neglected as the energy loss process with respect to the energy loss process of the disintegrated He nuclei.

Similar constraints can be also obtained in the case of production of neutrons during collisions of protons with the disk radiation. However, because the cross-section for the photo-pion production process, $p \to \gamma n + \pi^\pm$, is about an order of magnitude lower and the energy threshold for the pion production is about an order of magnitude larger than for efficient disintegration of a He nucleus, the constraints on neutron production by protons are at least an order of magnitude more restrictive. Therefore, the neutron production in $p \to \gamma$ collisions is not expected to be effective process of neutrino production. Moreover, neutrons produced in this last process are expected to have clearly larger energies than required for efficient production of neutrinos, with the simple power law spectra extending between $\sim 10$ TeV and a few PeV.

2.2. Jet Boundaries

The surrounding matter and/or the wind from the accretion disk plays an essential role in the collimation of a jet. Therefore, jets are expected to have regions (boundaries) filled with plasma moving with various velocities. In fact, recent observations of the inner jet structure of nearby radio galaxy Cygnus A show that the transverse width of the jet, already...
very close to the jet base, is significantly larger than the radius of the innermost stable orbit of the SMHB (Boccardi et al. 2016). This suggests that the accretion disk is contributing to the jet launching. The jet likely has a faster inner section, powered by the black hole or the inner disk, and a slower outer section anchored in the more distant parts of the disk. The border between these two parts of the jet has been proposed to provide good conditions for the acceleration of particles. In fact, the acceleration of particles in the plasma at the shear flows has been studied since the works by Berezhko & Krymskii (1981) and Berezhko (1981). The case of the boundary between relativistic jet and its cocoon was discussed by Ostrowski (1990, 1998, 2002) and Bisnovatyi-Kogan & Lovelace (1995). These mechanisms of particle acceleration at the jet boundary are expected to produce relativistic particles with a flat power law spectra (e.g., Ostrowski 1990, 1998, 2000; Rieger & Duffy 2004, 2006). Nuclei accelerated in such mechanism should spend significant time within the cocoon of the jet in which their distribution is close to isotropic. Therefore, they can preferably interact with the nearby accretion disk radiation. As a result, the nuclei can lose nucleons in the photo-disintegration process. We expect that a part of the neutrons released in the disintegration process of the nuclei (as in the example estimated in Section 5) propagate toward the accretion disk and interact with the disk matter. These neutrons will initiate the cascade in the optically thick accretion disk. Neutrinos, produced in hadronic interactions, escape from the disk without absorption. On the other hand, $\gamma$-rays are expected to be absorbed in the disk due to the interactions with the disk matter and radiation field.

The simulation of the particle acceleration process in such conditions by Ostrowski (1990) shows that, in favorable conditions, the considered acceleration process can be very rapid. The acceleration length in the observer’s frame, due to the particle advection along the jet flow, can be $L_{acc} \sim \alpha_0 \lambda_{He}$, where $\lambda_{He} \approx \frac{6 \times 10^6 \gamma_{He} B_G^{-1}}{1.8 \times 10^6 \alpha_0 T_{4.5} r^3 B_G^{-2}}$ cm. (9) should be at least equal to (or shorter than) the mean free path for their disintegration (see Equation (2)), provided that, on this distance scale, the nuclei reach energy above the threshold for disintegration (given by Equation (6)). The condition, $L_{acc} \ll \lambda_{des}$, is fulfilled for the distance from the base of the jet $r \geq 0.02 \alpha_0 T_{4.5} B_G^{-1}$. (10) for the case of the dominant toroidal structure of the magnetic field in the jet, i.e., $\beta = 1$ and $\alpha_0 \sim 10$. If the longitudinal magnetic field component dominates within the jet, i.e., $\beta = 2$, then the condition, $L_{acc} \ll \lambda_{des}$, implies the magnetic field at the base of the jet

$$B_{in} \geq 2 \alpha_0 T_{4.5} G.$$ (11)

The conditions, given by Equations (10) and (11) are consistent with the maximum distance from the base of the jet for which the disintegration process can become efficient (given by Equation (3)).

We estimate the maximum Lorentz factors of nuclei, accelerated at a specific distance, $L$, from the base of the jet, in the jet boundary layer by comparing their characteristic acceleration length, $L_{acc}$, with the distance scale along the jet, $L \approx 10^9 M_{BH}$ cm,

$$\gamma_{max}^\alpha \approx 1.5 \times 10^9 M_{BH} B_G r^{-1/\beta} / \alpha_0.$$ (12)

Assuming $\alpha_0 \sim 10$, this maximum Lorentz factor is $\gamma_{He}^\alpha \approx 1.5 \times 10^9 M_{BH} B_G$ for $\beta = 1$ and $\gamma_{He}^\alpha \approx 1.5 \times 10^9 M_{BH} B_G r$ for $\beta = 2$. These maximum energies of nuclei are clearly above the minimum energies required for their efficient disintegration in the disk radiation field (see Figure 6).

The mechanism of particle acceleration at the jet boundary described above is expected to produce relativistic particles with a flat power law spectrum (e.g., Ostrowski 1990, 1998, 2000; Rieger & Duffy 2006). We conclude that the nuclei, accelerated in the jet not far from the accretion disk, can suffer efficient disintegration process. As a result, relativistic neutrons are injected toward the dense accretion disk. The neutrons reach the disk, producing neutrinos as decay products of charged pions. Our aim is to estimate the contribution of these neutrinos to the high-energy ENB in the universe.

3. INTERACTION OF NEUTRONS WITH AN ACCRETION DISK

We assume that a part of the neutrons extracted from the relativistic nuclei in the jet region are directed toward the accretion disk. These neutrons have large enough Lorentz factors to reach the accretion disk before decaying. Neutrons have a power law spectrum consistent with the spectrum of the accelerated nuclei. Their Lorentz factors are equal to Lorentz factors of their parent nuclei.

The accretion disks around SMBHs in radio-loud active galaxies are well described by the Shakura & Sunyaev (1973) disk model; i.e., they are optically thick and geometrically thin. This type of disk forms, provided that the accretion rate is not very far from the critical Eddington accretion rate. The surface mass density in the inner part of such a geometrically thin Shakura & Sunyaev (1973) type disk is

$$\Sigma(r) = 4.6 \alpha^{-1/3} r^{-1/2} (1 - r^{-1/2})^{-1} \, \text{g cm}^{-2},$$ (13)

(see Equation (2.9) in Shakura & Sunyaev 1973), where $r$ is the distance from the black hole expressed in units of the inner radius of the accretion disk, $r_{in} = 3 r_S = 6 G M_{BH} / c^2$, $m$ is the accretion rate in units of the Eddington accretion rate, $\alpha$ is the viscosity coefficient, and $G$ is the gravitational constant. The above formula is valid for distances $r < 150 (\alpha m_{BH}^{2/3} h_{10} / \gamma_{10})$, where $m = M_{BH} / M_*$. For reasonable values of the viscosity parameter, $\alpha = 0.1$, the accretion rate $\dot{m} = 0.1$, and the mass of the black hole $m = 10^9$, the formula is valid for $r < 150$. Density of the mass in the inner disk with such parameters is between $4.4 \times 10^3 \, \text{g cm}^{-2}$ for $r = 2$, and $8.5 \times 10^5 \, \text{g cm}^{-2}$ for $r = 150$. On the other hand, the density of mass in the disk is low because the thickness, $z$, of the disk around the supermassive black hole is quite large (see Equation (2.8) in Shakura & Sunyaev 1973),

$$z(r) \approx 3.2 \times 10^6 \dot{m} m_{BH} (1 - r^{-1/2}) \, \text{cm.}$$ (14)

For the parameters $\dot{m} = 0.1$ and $m = 10^9$, the half-thickness of the disk is $z \approx 9.4 \times 10^{13} \, \text{cm}$. The collision length of neutrons
on the hadronic interactions in the inner disk can be estimated from \( \lambda_{\nu p} = (n(r)\sigma_{\nu p})^{-1} \approx 1.5 \times 10^{12} \) cm, where \( n(r) = \Sigma(r)/\mu_A \), \( \Sigma(r) \approx 2.3 \times 10^{13} \) cm\(^{-2}\), and \( \mu_A = 6 \times 10^{23} \) mol\(^{-1}\) is the Avogadro number, \( \mu_A = 16/13 \) g mol\(^{-1}\) is the average molar mass of the matter composed of 75% of hydrogen and 25% of helium, and \( \sigma_{\nu p} = 3 \times 10^{-26} \) cm\(^2\) is the cross-section for hadronic collisions of neutrons with the matter. This interaction length is much shorter than the thickness of the accretion disk.

Density of the matter in the disk is a few orders of magnitude lower than the density of the Earth’s atmosphere. Therefore, pions and muons with considered energies, produced in the interactions of neutrons with the matter, decay onto neutrinos before interacting with the matter. On the other hand, \( \gamma\)-rays are effectively converted into \( e^\pm\) pairs in their interactions with the Coulomb field of the nuclei and the soft radiation within the accretion disk. The optical depths for these processes are much larger than unity for the characteristic disk temperatures of the order of \( 3 \times 10^4 \) K and the column density of the matter and the thickness of the accretion disk estimated above. Note that some neutrons, during such hadronic interactions, convert to protons. These protons are efficiently captured and isotropized by the magnetic field in the disk. Their Larmor radii, \( R_L \approx 3 \times 10^{12} E_{\text{PeV}}/B_G \) cm (where proton energy \( E = 1 E_{\text{PeV}} \) PeV), are expected to be smaller than the depth of the first interaction of neutron in the inner part of the disk, \( d \approx 0.01 \) cm (see above). This condition is fulfilled for protons with energies below \( E \approx 30B_G \) PeV, where \( B_G \) is the magnetic field strength in the disk. We estimate the magnetic field in the disk by assuming that its energy density is comparable to that of the disk radiation field, i.e., \( B \approx 370 T_{\lambda,5} \) G. Then, protons with energies below \( \sim 100 \) PeV are isotropized. Due to the presence of the magnetic field in the disk, neutrinos produced during the cooling process of the primary neutrons are expected to be emitted quasi-isotropically from the inner disk.

4. SPECTRA OF NEUTRINOS

We calculate the all-flavor neutrino spectra produced in the above-discussed scenario for the SMBHs with different masses. As an example, we assume that nuclei are accelerated with the power law spectrum and an exponential cut-off. Neutrinos are extracted from these nuclei with a similar spectrum. It is of the form

\[
dN_\nu/dE_\nu \propto E_\nu^{-\delta} \exp(-E_\nu/E_\nu^{\text{max}}).
\]

The power taken by neutrons (i.e., the normalization factor in this spectrum) can be obtained by relating it to the accretion luminosity of the SMBH. This accretion luminosity can be again related to the Eddington luminosity of the SMBH, assuming the cosmological redshift averaged accretion efficiency

\[
L_{\text{acc}} = \chi L_{\text{Edd}} = 1.3 \times 10^{46} \chi^{-1} M_9 \text{ erg s}^{-1},
\]

where \( L_{\text{Edd}} \) is the Eddington luminosity, and the efficiency of the accretion process is \( \chi = 0.1 \chi^{-1} \). In the case of the radio-loud AGN, this value has been estimated to be in the range \( \sim(0.01-0.1) \) (e.g., Wu & Liu 2004). It is assumed that approximately half of the energy released by accretion is irradiated from the accretion disk surface, \( L_D = 0.5L_{\text{acc}} \), and half of the accretion energy is transferred to the jet, \( L_j = 0.5L_{\text{acc}} \). Assuming the Shakura & Sunyaev (1973) disk model, we estimate the characteristic temperature of the radiation emitted from the inner disk on

\[
T_D = \left( \frac{L_D}{4\pi r_D^2\sigma_{SB}} \right)^{1/4} \approx 5.5 \times 10^4 \chi_{-1}^{1/4} M_9^{1/2} \text{ K}.
\]

The inner disk temperature determines the minimum energy of He nuclei for which their disintegration in the disk radiation becomes efficient. In order to estimate the characteristic maximum energies of neutrons, \( E_{\nu}^{\text{max}} \), as a function of the SMBH mass, we set the upper limit on the magnetic field strength at the base of the jet by assuming that the jet power is mainly carried out in the form of the Poynting flux,

\[
L_j \approx \pi r_D^2 c (B_0^2/8\pi)^2.
\]

This relation allows to estimate the magnetic field

\[
B_0 \approx 1.3 \times 10^{3} (\chi_{-1} M_9^{1/2}) \text{ G}.
\]

Introducing this value of the magnetic field strength to the formula for the maximum energy, which nucleons can be accelerated in the jet (see Equations (5) and (12)) and applying the assumed scaling values for other parameters, we estimate the characteristic maximum energies of neutrons as

\[
E_{\nu}^{\text{max}} = 2 \times 10^{9} (\chi_{-1} M_9^{1/2}) \text{ GeV}.
\]

For simplicity, in Equations (5) and (12), we fixed the parameter describing the distribution of the magnetic field in the jet on \( \beta = 1 \). Then, the maximum energies of the nuclei are independent of the distance from the SMBH. On the other hand, the minimum energies of neutrinos are obtained from the combination of Equations (6) and (17),

\[
E_{\nu}^{\text{min}} = 1.4 \times 10^{8} M_9^{1/2}/\chi_{-1}^{1/4} \text{ GeV}.
\]

They depend on the mass of the SMBH and on the accretion efficiency of the SMBHs through dependence on the temperature of the inner part of the accretion disk.

Some of the neutrons, extracted from the nuclei, move toward the accretion disk and interact with the matter-producing neutrinos in hadronic collisions. As an example, we show the dependence of the neutrino spectra on the SMBH mass (see Figure 2 on the left), on the spectral index of the spectrum of nuclei (see Figure 2 in the middle), and different efficiency of the accretion process (see Figure 2 on the right). Note that the spectra of particles with indexes as low as \( \delta = 1 \) are expected in the case of the re-connection process (e.g., Larrabee et al. 2003). The spectra shown in the first two figures on Figure 2 are calculated for the SMBH, accreting matter at a rate of \( \chi = 10\% \) of the Eddington accretion rate. It is assumed that half of this accretion energy is taken by the jet. The nuclei take 10% of the jet power.

The power in the neutrino spectrum, as well as its high-energy cut-off, depends in a simple way on the mass of SMBH and the acceleration efficiency. In the considered range of SMBH masses, the neutrino spectra clearly extend up to the PeV energies, for an efficiency of acceleration close to \( \chi = 0.1 \). Such SMBHs might be responsible for the PeV neutrino events recently detected by the IceCube telescope (see Aartsen et al. 2013). However, the spectral index of accelerated nuclei has to be close to 2, in order to transfer significant
energy into the PeV neutrinos. If the accretion efficiency is closer to ∼0.01, as obtained by Wu & Liu (2004) for closer radio-loud AGNs, the spectral indexes of accelerated nuclei should be flatter than 2 in order to efficiently produce ∼PeV neutrinos.

In the next section, we estimate the ENB produced by the population of accreting SMBHs in the universe. The neutrino spectra expected in our model are compared to the recent observations of the neutrino events by the IceCube telescope.

5. EXTRAGALACTIC NEUTRINO BACKGROUND

We wonder whether neutrinos produced in the scenario described above can explain the observations of the very high-energy ENB reported recently by the IceCube Collaboration. In order to determine the contribution of the neutrinos produced in the accretion disks around SMBHs to the ENB, we integrate the neutrino spectra over the luminosity function of the spheroids around SMBHs in active galaxies. This luminosity function is related to the masses of SMBHs. We integrate this formula over the part of the universe up to the redshift \( z = 2 \).

The diffuse neutrino flux is then given by,

\[
\Phi_\nu = \frac{c}{4\pi H_0} \int_{z=0}^{z_{\text{max}}} \frac{dz}{[(1+z)^3\Omega_m + \Omega_\Lambda]^{1/2}} \times \int dL \frac{dN(L,z)}{dLdV} \frac{dN_e(E, (1+z))}{dE_d dt},
\]

where \( dN(L,z)/dLdz = (dN(L,z)/dLdV)(dV/dz) \) is the spheroid luminosity, \( L \) function \( z \) is the redshift, and \( V \) is the volume. The spheroid luminosity is related to the SMBH mass through the formula

\[
\log \frac{M_{\text{BH}}}{M_\odot} = 1.13 \log \frac{L}{L_\odot} - 4.11 - 0.316z + 1.4 \log (1+z),
\]

taken from Li et al. (2011). The luminosity function is expressed as a Schechter (1976) function,

\[
\frac{dN(L,z)}{dLdV} = \Phi_0(z) \left( \frac{L}{L_*} \right)^{-1.07} \exp \left( -\frac{L}{L_*} \right),
\]

where the function, \( \Phi_0(z) = 3.5 \times 10^{-3} \exp[-(z/1.7)^{1.4}] \) Mpc\(^{-3}\) is given by Equation (12) in Li et al. (2011) and \( L_\odot(z) = 1.4 \times 10^{11} \Omega_\Lambda^{0.4}(z/1.7)^{0.47} \) L\(_\odot\) is given by Equation (A6) in Li et al. (2011). Note that the parameters describing the above relations have typical errors on the order of ∼10%.

We expect that their effect on the final spectra of neutrinos are much smaller than that of the unknown parameters describing the accretion and acceleration process of nuclei. Therefore, we do not consider such subtle effects during comparisons of the calculated neutrino spectra with the measured neutrino spectra, because they have uncertainties on the order of ∼2 (see spectral points in Figure 3). In our calculations, we apply \( \Omega_m = 0.3 \), \( \Omega_\Lambda = 0.7 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). For the specific luminosity of spheroid galaxy, we derive the mass of the SMBH (from Equation (23)) and determine the accretion luminosity. The ENB is calculated after integrating over the population of the SMBHs within the active galaxies, and over different distances to the observer (up to \( z_{\text{max}} = 2 \)). The results are compared in Figure 3, with the all-flavor ENB reported by the IceCube (Aartsen et al. 2015a), assuming different spectral indexes of the accelerated nuclei (on the left) and different values of the accretion efficiency onto the SMBHs (Figure 3 on the right). The best description of the ENB is obtained for the spectral index equal to \( \delta = 2.2 \) and rather large accretion efficiency \( \chi = 0.1 \). The level of calculated ENB is consistent with the observations, provided that the normalization factor of the spectrum of nuclei is equal to \( A_N \approx 2 \times 10^{-6} \). The factor \( A_N \) is the product of a few coefficients, i.e., the accretion power of the SMBH (in units of the Eddington luminosity) expressed by \( \chi \), a factor describing the part of energy of nuclei taken by neutrons (in the range \( \sim 8^{-1} \) to \( \sim 2^{-1} \)), the part of the accretion
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**Figure 3.** Extragalactic (all flavor) Neutrino Background (ENB) produced by neutrons in collisions with the matter of the optically thick accretion disks around black holes in the universe up to the redshift of \( z_{\text{max}} = 2 \). The ENB, calculated for the power law spectrum of neutrons with the exponential cut-off at \( E_{\text{min}}^n \) and spectral index equal to \( \delta = 2.2 \) (thick dashed curve), \( 2 \), and \( 2.4 \) (thin dashed curves), is shown on the left figure. The normalization factor of the spectra (see the main text for precise definition) is equal to \( A_N \approx 2 \times 10^{-6} \), \( 3 \times 10^{-7} \), and \( 2 \times 10^{-7} \), respectively, for the spectral indexes mentioned above. The spectrum of neutrons extends above \( E_{\text{min}}^n \) (given by Equation (21)) and \( \gamma_\nu^n \) is given by Equation (20). The efficiency of the accretion process onto the SMBHs is fixed on \( \chi = 0.1 \). The population of the SMBHs in the universe is modeled as described in Section 5. The dependence of the ENB on the efficiency of the accretion process, for \( \chi = 0.1 \) and \( \delta = 2.2 \) (dashed curve), 0.03 and \( \delta = 2 \) (dotted-dashed, \( A_N \approx 10^{-6} \), 0.03 and \( \delta = 2.2 \) (dotted-dashed, \( A_N \approx 6 \times 10^{-6} \), is shown on the right-hand figure. The reported spectrum of the (all flavor) neutrino background is shown by the solid error bars, and its power law model by the thick solid line (Aartsen et al. 2015a).

power transferred to the jet (assumed \( 2^{-1} \)), the efficiency of acceleration of nuclei (usually assumed 10%), the parameter describing a part of all SMBHs that are active within galaxies, and the parameter describing a part of neutrons that reach the accretion disk. The last two factors are the most uncertain. For the values of the other coefficients mentioned above, the product of these two last parameters should be on the order of \((0.8-3.2) \times 10^{-3}\). Therefore, the model can explain the observations of the ENB provided that, e.g., 1.6%–6.4% of the neutrons reach the accretion disk surface and 5% of SMBHs are in the active phase. In fact, the AGN fraction of field galaxies has been estimated as 5%, based on visual observations (Dressler et al. 1985). Using the X-ray data for galaxy clusters with luminosity \( \geq 10^{44} \) erg s\(^{-1}\) s, Martini et al. (2006) found the AGN fraction equal to \((5 \pm 1.5)\%\), for galaxies magnitude brighter than \( M_R < -20 \) (see also, Arnold et al. 2009). Moreover, the AGN fraction increases significantly for high-redshift clusters (e.g., Eastman et al. 2007). We conclude that nuclei, accelerated and disintegrated in jets of SMBHs, can inject neutrons toward the accretion disks. They are able to produce a very high-energy neutrino background in the universe recently observed by the IceCube.

We have also investigated the effect of a much lower accretion efficiency of matter onto the SMBHs by showing the neutrino spectra for \( \chi = 0.03 \) and different spectral indexes of the neutrons (Figure 3 on the right). It is clear that the lower accretion efficiency might be also consistent with the observations, provided that the spectral index of accelerated nuclei is clearly flatter than the previously considered value 2.2 (taking into account large error bars of the neutrino spectral points). We have also checked that the contribution to the ENB from SMBHs at larger red-shifts than \( z = 2 \) can be safely neglected.

The neutrinos produced in terms of such a model are expected to be only mildly beamed in the direction perpendicular to the accretion disk. Therefore, different types of observed active galaxies; i.e., blazars, radio galaxies, or even Seyfert galaxies with evidences of jets, could contribute to the ENB. Due to this feature of unbeamed neutrino emission, only the closest AGNs might be expected to produce observable neutrino event rates in the IceCube telescope. In order to check this, we calculate expected neutrino event rates from the nearby active galaxy, M87, under the hypothesis that it is a typical contributor to the ENB; i.e., assuming the average normalization factor \( A_N = 2 \times 10^{-6} \) derived from the modeling of the ENB. For the active galaxy M87, which is at the distance of 16.4 Mpc (Bird et al. 2010) and harbors an SMBH with mass \( \sim 5 \times 10^9 M_{\odot} \) (Walsh et al. 2013), the expected neutrino event rate in the IceCube telescope is estimated as \( \sim 0.7 \nu yr^{-1} \). We used the effective area of the IceCube neutrino detector reported in Aartsen et al. (2015b). In these calculations, we assumed the spectral index of nuclei to be equal to 2; i.e., marginally consistent with the modeling of the ENB (see Figure 3). Note, however, that M87 is an under-luminous active galaxy with the estimated accretion rate \( \dot{m} \approx 1.6 \times 10^{-3} \) (di Matteo et al. 2003). The accretion process in M87 may not be correctly described by the considered in this paper Shakura-Sunyaev disk model. Therefore, this neutrino event rate should be considered as the upper limit. We conclude that the perspectives for the identification of the neutrino events with these specific active galaxies are not very promising, in terms of the considered model.

6. CONCLUSION

We propose that nuclei accelerated in jets produced by the supermassive black holes in AGN can be efficiently disintegrated in their interaction with soft radiation from the inner part of the accretion disk. Neutrons, from their fragmentation, can reach dense regions of the accretion disk producing neutrinos in collisions with the disk matter. For a typical temperature in the inner disk, the Lorentz factors of neutrons extracted from nuclei are clearly lower than those produced in pure proton–photon collisions (by one to two orders of magnitude). Therefore, the neutrino spectra extend down to the TeV energy range, in contrast with the case of neutrons produced in the proton–photon collisions (\( p - \gamma \rightarrow n + \ldots \)), in which case the neutrino spectrum is expected to flatten below PeV energies, due to the higher threshold for neutron
production. The process of neutron production we consider is also more efficient than the proton–photon process, due to the larger value of its cross-section for the disintegration of nuclei. Therefore, the process of extraction of neutrons from nuclei, discussed here, seems to provide a more suitable explanation of the observed cosmic neutrino events that show the power law spectrum clearly extending below a few PeVs down to \( \sim 10 \) TeV.

We propose that nuclei can be accelerated in the magnetic field reconnection regions within the jet and/or at the boundary between a fast jet and its slowly moving cocoon. Then, the basic parameters describing the model can be linked to the mass of the central SMBH, the accretion rate onto this black hole, and the magnetic field strength at the base of the jet. Most muons, produced in collisions of neutrons with the matter of the accretion disk, can decay before interacting because the density of matter in the disk is low. Therefore, the neutrino spectra can clearly extend from low energies up to PeV energies.

We calculate the spectra expected from a specific SMBH within an active galaxy as a function of SMBH mass. SMBHs with larger masses are expected to produce neutrinos with larger fluxes extending to higher energies, provided that the accretion rate is a constant (independent of the black hole mass) fraction of Eddington accretion rate. However, in order to produce significant fluxes of neutrinos at \( \sim \)PeV energies, the spectral index of primary nuclei should be close to 2.

We aim to explain the recent measurements of the very high energy ENB by the IceCube telescope (Aartsen et al. 2015a) in terms of our model. We determine the parameters of the population of the SMBHs in the universe, based on the observed link between masses of the SMBHs within the galaxies and their spheroid luminosity function. A good description of the ENB is obtained provided that the free parameter describing the neutrino flux produced in terms of our model is on the order of \( 2 \times 10^{-6} \). The parameter is the function of the fraction of active (accelerating nuclei) SMBHs, the accretion rate onto black hole, the acceleration efficiency of nuclei, and the fraction of neutrons that reach the accretion disk. This factor seems to be reasonable. For example, it could be obtained provided that the AGN fraction of galaxies is \( \sim 5\% \), the accretion rate is equal to 10% of the Eddington rate, the nuclei are accelerated with \( \sim 10\% \) efficiency, and provided that \( \sim 2\% - 6\% \) of neutrinos reach the accretion disk. Moreover, the spectrum of accelerated nuclei should be on the power law type with the spectral index close to 2.2.

Because neutrinos produced in such a model are not strongly beamed along the jet axis, different types of active galaxies are expected to contribute to the observed ENB. In order to check whether such active galaxies might be directly observable by the IceCube neutrino telescope, we estimate the neutrino event rate expected from the nearby radio galaxy, M 87. It is assumed that M 87 is a typical contributor to the ENB, i.e., the normalization of its emission is described by the factor obtained above from the fitting of the ENB. However, the predicted neutrino event rate in the case of M87, \( \sim 0.7 \) neutrino events per year, should be considered as the upper limit because the accretion rate onto the SMBH in M87 is expected to be low.

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