Positron excess in the center of the Milky Way from short-lived $\beta^+$ emitting isotopes

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Observations of the INTEGRAL satellite revealed the presence of yet unexplained excess in the central region of the Galaxy at the energies around 511 keV. These gamma-rays are produced in the process of positron annihilation, the needed rate is around $10^{36}$ s$^{-1}$. In this short paper it is shown that $\beta^+$-emitting isotopes that are formed in interactions of subrelativistic cosmic rays (CRs) with light nuclei (CNONe) can account for a considerable fraction – up to several tens of percent – of $e^+$ production rate in the central region.

**Introduction.** The central region is the most mysterious part of our Galaxy and hosts a lot of different astrophysical phenomena. One of them is an excess in the 511 keV $\gamma$-line that was observed by the SPI/INTEGRAL instrument [1-3]. This excess can be naturally attributed to the positron annihilation in this region. Recent analysis confirmed existence of the central source of the statistical significance $\sim 5\sigma$ and its corresponding steady-state production rate $\dot{N}_e = (0.3 - 1.2) \times 10^{42}$ s$^{-1}$ [3]. Because of limited angular resolution of the instrument there is only an upper limit on the size of this source: $r < 2.7\,\text{arcsec}$, so it could be either point-like, possibly connected with a supermassive black hole Sgr A* in the very center of our Galaxy or it could span larger region up to several hundred pc size. A large number of candidates were proposed in order to explain this excess: $e^+$ could be produced in nucleosynthesis processes related to supernova explosions – decays of radioactive nuclei $^{26}\text{Al}$, $^{44}\text{Ti}$, $^{56}\text{Ni}$ [4, 5], they could be alternatively produced in the immediate vicinity of the Sgr A* [5] or in numerous microquasars [5]. Positron production could be non-stationary, taking place during high-states of the Sgr A* activity or star-bursts [3]. Finally, there are also large number of dark matter models, which could explain the excess, see e.g. [11-14]. A broad spectrum of possible production mechanisms is reviewed in [15].

In this short paper it is shown that $\beta^+$-emitting isotopes that are formed in interactions of subrelativistic cosmic rays (CRs) with CNONe can account for a considerable fraction of $e^+$ production rate in the central region. The idea is simple: the region demonstrates a high uniform degree of ionization that can be caused by CRs permeating it [16, 17]. Alternative viable explanation is heating by turbulent motions [18], or, naturally, both processes could contribute to ionization simultaneously.

High-energy observations at energies larger than 100 MeV by the Fermi LAT instrument constrain these CRs to be mostly sub-relativistic with energy density in the central hundred pc around 50 – 80 eV cm$^{-3}$ [16]. If their spectrum is hard, then flux at $E = 200$ MeV could be as high as $\phi_{CR} = 5 \times 10^3$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, and this value will be used as a benchmark. The central region contains a considerable fraction of the total mass of the galactic gas in the so-called Central Molecular Zone (CMZ) – with a radius 200-300 pc and height $\sim 100$ pc, its mass can reach $7 \times 10^7 M_\odot$ [12, 20]. There are two main components in the CMZ: dense clumps with densities $\sim 10^4$ cm$^{-3}$ and surrounding more tenuous medium ($\sim 10^2$ cm$^{-3}$).

**Method.** Radioactive $\beta^+$ isotopes could be produced in abundance when CRs are interacting with atoms of light elements, such as C, N, O, Ne. These proton-induced reactions have low thresholds around 10-20 MeV and produce positrons with energies 1-2 MeV. Their cross-sections were taken from the JENDL library [21, 22] with the only exception of the $^{21}\text{Ne} + p \rightarrow ^{18}\text{F} + \alpha$ process, which cross-section was estimated using TENDL library [23].

$$^{12}\text{C} + p \rightarrow ^{11}\text{C} + d,$$
$$^{11}\text{C} \rightarrow ^{11}\text{B} + e^+, \quad (1)$$
$$T_{1/2} \sim 1200 \text{ s}, E = 0.97 \text{ MeV}, \quad \sigma_{200 \text{ MeV}} = 40 \text{ mb}$$

$$^{14}N + p \rightarrow ^{14}O + n,$$
$$^{14}O \rightarrow ^{14}N + e^+, \quad (2)$$
$$T_{1/2} \sim 70 \text{ s}, E = 0.78 \text{ MeV}, \quad \sigma_{200 \text{ MeV}} = 7.5 \text{ mb}$$

$$^{14}N + p \rightarrow ^{13}N + d.$$  
$$^{13}N \rightarrow ^{13}C + e^+, \quad (3)$$
$$T_{1/2} \sim 600 \text{ s}, E = 1.19 \text{ MeV}, \quad \sigma_{200 \text{ MeV}} = 9 \text{ mb}$$

$$^{14}N + p \rightarrow ^{11}C + \alpha,$$ 
$$T_{1/2} \sim 1200 \text{ s}, E = 0.97 \text{ MeV}, \quad \sigma_{200 \text{ MeV}} = 24 \text{ mb}$$

$$^{16}O + p \rightarrow ^{15}O + d,$$  
$$^{15}O \rightarrow ^{15}N + e^+, \quad (5)$$
$$T_{1/2} \sim 122 \text{ s}, E = 1.7 \text{ MeV}, \quad \sigma_{200 \text{ MeV}} = 40 \text{ mb}$$

$$^{16}O + p \rightarrow ^{11}C + n + p + \alpha,$$ 
$$T_{1/2} \sim 1200 \text{ s}, E = 0.97 \text{ MeV}, \quad \sigma_{200 \text{ MeV}} = 10 \text{ mb}$$

$$^{16}O + p \rightarrow ^{13}N + \alpha,$$ 
$$T_{1/2} \sim 600 \text{ s}, E = 1.19 \text{ MeV}, \quad \sigma_{200 \text{ MeV}} = 7.5 \text{ mb}$$

$$^{21}\text{Ne} + p \rightarrow ^{18}\text{F} + \alpha,$$  
$$^{18}\text{F} \rightarrow ^{18}O + e^+ \quad (8)$$

$$T_{1/2} \sim 6600 \text{ s}, E = 0.64 \text{ MeV}, \quad \sigma_{200 \text{ MeV}} = 6 \text{ mb}$$

Relevant cross-sections can be written out for each nuclei species:

$$\sigma_C(200 \text{ MeV}) = 40 \text{ mb} \quad (9)$$
$$\sigma_N(200 \text{ MeV}) = 40 \text{ mb}$$
$$\sigma_O(200 \text{ MeV}) = 60 \text{ mb}$$
$$\sigma_{Ne}(200 \text{ MeV}) = 6 \text{ mb}$$
Production rate can be estimated as follows:

$$\mathcal{R} = 4\pi \int \phi_{CR} \sum_i n_i \sigma_i dV = 4\pi \phi_{CR} \sum N_i \sigma_i, \quad (10)$$

where $\phi_{CR}$ is a CR flux, which level is adopted to be constant across the central region [24], $n_i$, $\sigma_i$, $N_i$ are number density, cross-section (see Eq. (10)), and total number of $i$-th species atoms in the region, correspondingly. Total number of atoms $N_i$ can be linked with number of H atoms in the CMZ and, eventually, with its mass:

$$N_i = K \eta 10^{X_i - 12.0} M_H / m_p, \quad (11)$$

where a coefficient $K = 2 - 5$ describes enhancement of metallicity in the center [23, 26], $X_{i,\odot}$ is the solar system abundance of $i$-th species [27], $M_H$ is the total mass of the hydrogen in the CMZ, $M_H = 0.75 M_{CMZ}$, $m_p$ is the proton mass, and $\eta \leq 1$ describes the suppression effect that arises due to an inability of low-energy CRs to penetrate inside dense clouds [16]. On the other hand, this impediment could lead to enhanced rate of interactions in the boundary/envelope regions of dense clouds. The morphological properties of these clouds are highly uncertain and all the complexity of effects involved is encoded in a single coefficient $\eta$. In order to get an upper limit on possible positron production, values $K = 3$, $\eta = 1$, $M_H = 5 \times 10^7 M_\odot$ were adopted in the subsequent calculations.

Number of nuclei can be readily estimated using solar abundances $X_{H,\odot} = 8.39$, $X_{N,\odot} = 7.86$, $X_{O,\odot} = 8.73$, $X_{Ne,\odot} = 8.05$ [27]:

$$N_C = 1.5 \times 10^{61} K$$

$$N_N = 4.5 \times 10^{60} K$$

$$N_O = 3.4 \times 10^{61} K$$

$$N_{Ne} = 7.0 \times 10^{60} K$$

Combining (10) with (12) we obtain the final expression:

$$\mathcal{R} = 5.4 \times 10^{40} \eta \left( K/3 \right) \left( \phi_{CR} / 5 \times 10^2 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \right) \times$$

$$\times \left( \frac{M_{200 \text{ pc}}}{7 \times 10^7 M_\odot} \right) \text{ s}^{-1}, \quad (13)$$

where $M_{200 \text{ pc}}$ is the total gas mass in $r = 200 \text{ pc}$ radius. There also could be some considerable contribution from reverse spallation process, i.e. when CNOe CRs hit $p-$ or $He-$ targets. The rate calculated above can significantly contribute to the total production rate $(3 - 12) \times 10^{41} \text{ s}^{-1}$ that was estimated from the observations [4].

The shape of the CR spectrum is very important – all previous considerations used a very simplistic approach of a mono-energetic spectrum, which in fact is a good approximation for a very hard spectrum – $dN/dE \propto E^{-0.5}$ [10]. If instead much softer spectrum, like $dN/dE \propto E^{-2.5}$ [17] was used, then things get more complicated: it is necessary to convolve the spectrum with individual energy-dependent cross-sections [21] down to the thresholds of corresponding reactions of Eq. (10). We use the spectrum from the [17] paper: $dN/dE = A_0 (E/E_0)^{-2.5}$, $A_0 = 1.4 \times 10^{-11} \text{ MeV}^{-1} \text{ cm}^{-3}$ is the normalization coefficient at the energy scale $E_0 = 1 \text{ MeV}$. ‘Effective’ cross-sections can substitute for cross-sections given in Eq. (10):

$$\sigma_{eff} = \frac{\int_{E_{min}}^{E_{max}} \sigma(E) dN/dE(E) v(E) dE}{4\pi \phi_{CR}} \quad (14)$$

$$\sigma_{effC} = 10 \text{ mb}, \quad (15)$$

$$\sigma_{effN} = 90 \text{ mb}, \quad \sigma_{effO} = 18 \text{ mb}, \quad \sigma_{effNe} = 36 \text{ mb},$$

and the corresponding luminosity:

$$\mathcal{R}_{soft} = 2.7 \times 10^{40} \eta \left( K/3 \right) \left( \phi_{CR} / 5 \times 10^2 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \right) \times$$

$$\times \left( \frac{M_{200 \text{ pc}}}{7 \times 10^7 M_\odot} \right) \text{ s}^{-1}, \quad (16)$$

which is only two times smaller than value from Eq. (10) despite large difference between the respective spectra. Obviously, if the spectrum demonstrated a break around 10 MeV, the luminosity can be even higher than estimated in Eq. (13).

**Related phenomena.** Collisions of subrelativistic cosmic rays with CNO can also result in an emergence of nuclear gamma-ray lines: excited nuclei during transition to their lower energy levels radiate photons with characteristic energies around several MeV [28]. E.g., one of the most promising target is the 4.44 MeV line from the deexcitation of $^{12}C^*$ nuclei, which in turn can be produced in inelastic collisions with protons and also in processes of proton-induced spallation of N and O nuclei. The resulting flux at the Earth can be calculated using cross-sections from [29]. In case of very hard spectrum ($dN/dE \propto E^{-0.5}$, $E_{max} = 200 \text{ MeV}$) the flux is equal to:

$$F_{4.44 \text{ MeV}} \sim 10^{-6} (K/3) \text{ ph cm}^{-2} \text{ s}^{-1}, \quad (17)$$

and it increases sixfold up to $6 \times 10^{-6} (K/3) \text{ ph cm}^{-2} \text{ s}^{-1}$ in case of soft spectrum ($dN/dE \propto E^{-2.5}$). Unfortunately, in both cases it is below the sensitivity threshold of the SPI/INTEGRAL instrument. However, future missions such as proposed GRIPS [30] can be sensitive
enough to detect these elusive lines that come from p-CNO interactions.

The $^{11}$C isotope forms in several reactions and afterwards quickly decays into stable $^{11}$B with the production rate $R_B$ that is equal to almost 40% of total rate $R$. In 10 Gya it would lead to local enrichment which could be roughly estimated neglecting advection and changes in CMZ composition and CR flux levels throughout galactic history: $X_B = 5.0$. This value is much higher than $X_B = 2.8$. Unfortunately, boron searches require UV-observations that can hardly be performed for the very central region of the Galaxy. This boron overabundance can also manifest itself in alteration of the observed local B/C ratio if boron nuclei, especially produced in the vicinity of the GC [31] can be used for testing the model – they can demonstrate unusually high levels of $^{11}$B, though this characteristic can also be erased during star’s evolution [32].

Conclusions. Short-lived $\beta^+$-emitting isotopes can be produced in interactions of subrelativistic cosmic rays (CRs) with light nuclei in the CMZ. In case of very hard spectrum of the CRs, $dN/dE \propto E^{-0.5}$, the positron production rate can be as high as $5.4 \times 10^{10}$ s$^{-1}$, while the production is somewhat suppressed for softer spectra, $R = 2.7 \times 10^{10}$ s$^{-1}$ for $dN/dE \propto E^{-2.5}$. It can account for up to 20% of total positron production rate in the central region. The corresponding gamma-ray emission from nuclear de-excitation lines is too weak to be observed with current instruments but can be detected with future MeV-detectors.

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