Radioactivity and electron acceleration in supernova remnants

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We argue that the decays of radioactive nuclei related to ^{44}Ti and ^{56}Ni ejected during supernova explosions can provide a vast pool of mildly relativistic positrons and electrons which are further accelerated to ultrarelativistic energies by reverse and forward shocks. This interesting link between two independent processes—the radioactivity and the particle acceleration—can be a clue for solution of the well known theoretical problem of electron injection in supernova remnants. In the case of the brightest radio source Cas A, we demonstrate that the radioactivity can supply adequate number of energetic electrons and positrons for interpretation of observational data provided that they are stochastically preaccelerated in the upstream regions of the forward and reverse shocks.

I. INTRODUCTION

Supernova remnants (SNRs) are generally believed to be prime candidates for production of both hadronic and electronic components of galactic cosmic rays (CRs) via the diffusive shock acceleration (DSA) mechanism (see e.g. [1] for a review). While the main aspects of the theory are well understood, the key issue related to electrons is the so-called injection problem which despite certain theoretical attempts (see e.g. [2,3]), remains an open question. The injection of electrons is a serious challenge because the electron gyroradius is small compared to the shock thickness which is of the order of the proton gyroradius. In fact this is a more general problem, related not only to DSA but also to other electron acceleration mechanisms, e.g. through different scenarios of stochastic acceleration [4]. In this paper we explore whether the pool of supra-thermal electrons and positrons related to the decay products of radioactive nuclei ^{56}Ni and ^{44}Ti can serve as an effective injector for further acceleration of electrons in SNRs by the forward and reverse shocks.

It is well established that the supernova ejecta contain huge amount of radioactive nuclei. The decays of these unstable nuclei have been proposed as a source of low-energy positrons (see e.g. ref. [5,6]) responsible for the 0.511 MeV annihilation line observed from the direction of the Galactic Center. In the case of the core-collapse supernova Cas A, approximately $0.1 M_\odot$ of ^{56}Ni has been ejected just after the explosion [7]. The nuclei ^{56}Ni decay with a half lifetime $t_{1/2} = 6.1$ days into ^{56}Co. Over the first years after the explosion, the decay products of ^{56}Co ($t_{1/2} = 77$ days) support the supernova optical light emission. At later epochs, less abundant radioactive nuclei with longer lifetimes contribute to the production of low-energy supra-thermal electrons, positrons and gamma-rays. In particular, the detection of characteristic gamma-ray [8] and hard X-ray lines [9] from ^{44}Ti gives a robust estimate of the total mass of radioactive ^{44}Ti ($t_{1/2} = 63$ years) produced in Cas A: $2 \times 10^{-4} M_\odot$. Recently a comparable amount of ^{44}Ti has been found also in the youngest galactic supernova remnant—SNR G1.9 + 0.3 [10].

Cas A, an approximately 300 yr old remnant, shows bright broad-band emission extending from radio to gamma-rays. It consists of both thermal and nonthermal components, indicating the presence of hot thermal plasma, strong magnetic field, relativistic electrons, and likely also protons, accelerated up to multi-TeV energies. All these components constitute a significant fraction of the bulk motion kinetic energy of the shell expanding with a speed of 4000 to 6000 km s^{-1} [11]. Most likely, acceleration of electrons takes place both in forward and reverse shocks.

Thin nonthermal X-ray filaments detected at the periphery of the remnant [12] reveal the presence of a strong ~ 1 mG magnetic field [13] and multi-TeV electrons accelerated at the forward shock of Cas A. Synchrotron X-rays are produced both in the reverse and forward shocks [14]. The time variations of synchrotron X-radiation found for a number of filaments and knots associated with the reverse shock, indicate that magnetic field in these compact structures also is very large, close to 1 mG [15]. Because of large magnetic fields, gamma-rays produced via inverse Compton scattering are strongly suppressed, except for some regions in the reverse shock with relatively small magnetic field. Even so, the total energy in protons, assuming that the detected GeV [16] and TeV gamma-rays [17–19] are of purely hadronic origin, does not significantly exceed 10^{49} erg [16]. On the other hand, the bright synchrotron radio emission of Cas A indicates to the existence of huge amount of relativistic electrons accelerated by forward and reverse shocks with total energy as large as 10^{48} erg [20]. That constitutes approximately 10^{-3} fraction of the explosion (mechanical) energy. A significant fraction of this energy is contained in compact
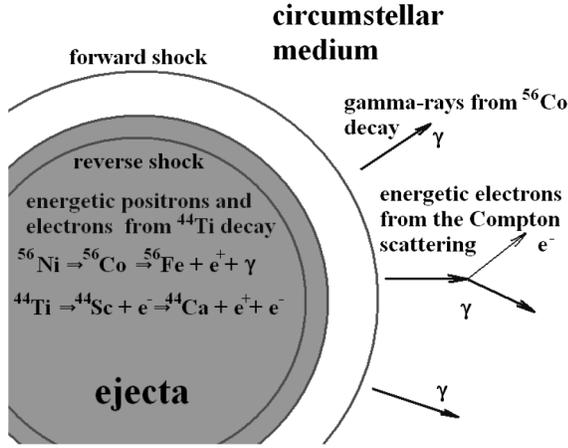
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FIG. 1. Schematic view of a young supernova remnant in the context of the "radioactive origin" of relativistic electrons. The forward shock propagates in the circumstellar medium outward, while the reverse shock propagates into the ejecta (gray color) outward in the laboratory frame and inward in the frame of expanding ejecta. Preexisting energetic electrons are produced in the circumstellar medium via the Compton scattering of gamma-rays from the decay of ^{56}Co. The radioactive decays of ^{44}Ti provide energetic electrons and positrons in the ejecta.

radio-knots of Cas A [21,22] where the pressure of relativistic electrons is comparable to the thermal pressure of the shell.

II. PRODUCTION OF ENERGETIC ELECTRONS AND POSITRONS

Below we assume that the radioactive elements are distributed uniformly throughout the ejecta. Although these elements are synthesized predominantly in the core of the ejecta, during the explosion they can be well mixed in the ejecta.

The ratio of number density of energetic MeV positrons n_+ from β-decay of ^{44}Ti to the baryonic density of the ejecta n_{ej} is given by

$$\frac{n_+}{n_{ej}} = 0.94 \frac{M_{Ti}}{44 M_{ej}} \left[1 - \exp\left(-\frac{t \ln 2}{t_{1/2}}\right) \right]. \quad (1)$$

Here t is the time since supernova explosion, M_{ej} is the mass of ejecta, and M_{Ti} is the total mass of the ejected nuclei ^{44}Ti. Equation (1) takes into account that positrons appear in 94% of the ^{44}Sc decay.

The rate of Coulomb energy losses of electrons and positrons is described as

$$\frac{\dot{E}}{E} = \frac{4 \pi r_e^2 m_e c^4 n_{ej}}{vE} \Lambda \left\langle \frac{Z}{A} \right\rangle = \frac{r_e^2 m_e c^4}{vE} \Lambda \frac{3(k-3) M_{ej}}{2 k m_p V_{ej}^3 t^3}$$

$$\sim \frac{0.025}{t} \frac{m_e c^3}{vE} \frac{\Lambda}{40} \left(\frac{M_{ej}}{M_\odot}\right)^{5/2} \left(\frac{E_{SN}}{10^{51} \text{ erg}}\right)^{-3/2} \left(\frac{t}{63 \text{ yr}}\right)^{-2}. \quad (2)$$

Here r_e is the classical electron radius, m_p and m_e are the proton and electron masses,, respectively, $\Lambda \simeq 40$ is the Coulomb logarithm in fully ionized plasma, E_{SN} is the total energy of explosion, and $V_{ej} = (10(k-5) E_{SN}/ 3(k-3) M_{ej})^{1/2}$ is the characteristic velocity of ejecta with a power-law density distribution characterized by the index $k \sim 10$ [23]. In Eq. (2) the mean ratio of the atomic number to the mass number $\langle \frac{Z}{A} \rangle$ is taken 0.5. Note that, in addition to positrons with energy $E_+ \sim 1$ MeV, one electron of energy $E_- \sim 0.1$ MeV is produced per a ^{44}Ti decay. However, because of difference in energies the positrons have more chances to be accelerated before they are thermalized. Therefore the fraction of the accelerated positrons $n_+/(n_+ + n_-) \gtrsim 1/2$.

For supernova explosions with small ejecta masses, $M_{ej} < 5 M_\odot$, the energy losses of positrons from decays of ^{44}Ti are not significant (see also [6]). For larger ejecta masses, the energetic positrons are thermalized before they are injected into the reverse shock. In any case, these particles cannot travel and approach the forward shock. In this regard, ^{44}Ti cannot provide electrons and positrons for acceleration by the forward shock. Nevertheless, the forward shock can be supplied by supra-thermal electrons, but through a different (indirect) way related to the Compton scattering of MeV gamma-rays—the products of ^{56}Co decays (see Fig. 1).

The number density of energetic electrons of Compton origin produced by MeV gamma-rays from ^{56}Co decays in the circumstellar medium with the number density n is estimated as

$$\frac{n_-}{n} = \xi_\gamma \frac{M_{Ni}}{56 m_p} \frac{\sigma_T}{4 \pi r^2} \sim 1.2 \times 10^{-7} \xi_\gamma \frac{M_{Ni}}{M_\odot} r_{pc}^{-2}. \quad (3)$$

Here σ_T is the Thompson cross-section, r is the distance from the center of the supernova explosion and ξ_γ is the fraction of gamma-rays which escape the expanding ejecta. For photons of energy of $E \sim 0.5$ MeV the cross-section of the Compton scattering is $\sigma_C = 0.4 \sigma_T$. It is taken into account in Eq. (3) that in a single act of decay of ^{56}Co on average 2.5 gamma-ray photons are produced. We should note that a similar idea for the production of energetic electrons in SNRs via the Compton scattering of gamma-rays from the annihilation of ^{56}Co decay positrons has been earlier suggested by Bychkov [24]. This gives additional 0.5 gamma-photons per a decay of ^{56}Co.

In the interstellar medium, the timescale of the Coulomb and ionization losses of energetic electrons is of the order of 10^5 years. During 300 years they cannot diffuse away beyond 3 pc, given that the diffusion coefficient that characterizes their propagation does not exceed the standard value of the diffusion coefficient in the interstellar medium, $D \sim 10^{28}$ cm^2 s^{-1}. Therefore they will be picked up by the arriving SNR shock.

The fraction of gamma-rays that escape the supernova ejecta is determined by the optical depth τ:

$$\tau = \left\langle \frac{Z}{A} \right\rangle \sigma_C \int n_{ej} dr = \frac{3(k-3)M_{ej}\sigma_C}{4\pi(k-1)m_p V_{ej}^2 t^2} \left\langle \frac{Z}{A} \right\rangle$$

$$\sim 0.6 \left(\frac{M_{ej}}{M_\odot} \right)^2 \left(\frac{E_{SN}}{10^{51}\ erg} \right)^{-1} \left(\frac{t}{77\ days} \right)^{-2}. \qquad (4)$$

In order to escape the ejecta without significant loss of energy, the Compton optical depth for gamma-rays τ should not significantly exceed 1. This determines the time t and the corresponding amount of nondecaying ^{56}Co. As it follows from Eq. (4) gamma-rays from decays of ^{56}Co can escape the ejecta only if the mass of latter does not exceed several solar masses. For larger ejecta masses, the contribution of gamma-rays from longer-lived isotopes, e.g. ^{57}Co ($t_{1/2} = 272$ days, mass $\sim 0.003 M_\odot$ [25]), becomes more important.

Note that for any reasonable parameters, the Compton optical depth in the interstellar medium is much smaller than 1 (even in the galactic scales), therefore only a small fraction of energy released at ^{56}Co decays is transferred to energetic electrons in the circumstellar medium. The main fraction of energy goes to the heating of the ejecta.

III. ACCELERATION OF ELECTRONS

At the plane nonmodified shock with compression ratio σ, the far-upstream and downstream momentum distributions of particles, $F_0(p)$ and $F(p)$, respectively, are related as

$$F(p) = \gamma \int_0^p \frac{dp'}{p'} \left(\frac{p'}{p} \right)^\gamma F_0(p'). \qquad (5)$$

Here $\gamma = 3\sigma/(\sigma - 1)$ is the Krymsky's index.

Let us assume now that the supra-thermal electrons with a mean energy E_{inj} are injected into the plane shock. For a nonmodified strong shock with compression ratio $\sigma = 4$ we have the following expression for the pressure of accelerated electrons:

$$P_- = \frac{4}{3} n_- E_{inj} \ln\frac{E_{max}}{E_{inj}}. \qquad (6)$$

Here E_{max} is the maximum energy of electrons accelerated at the shock. In young SNRs E_{max} is of the order of 10–100 TeV. Using the number density given by Eq. (1), we can estimate the ratio of the pressure of positrons P_+ to the ram pressure of the reverse shock, ρu_r^2, propagating at $t \gg t_{1/2}$ into the ejecta with a speed u_r:

$$\frac{P_+}{\rho u_r^2} = \frac{4}{3} \frac{0.94 M_{Ti}}{44 M_{ej}} \frac{E_{inj}}{m_p u_r^2} \ln\frac{E_{max}}{E_{inj}}$$

$$\sim 2.7 \frac{M_{Ti}}{M_{ej}} E_{inj}^{MeV} \left(\frac{u_r}{10^3\ km\ s^{-1}} \right)^{-2} \ln\frac{E_{max}}{E_{inj}}. \qquad (7)$$

A similar estimate for the ratio of the electron pressure to the ram pressure ρu_f^2 of the forward shock propagating in the circumstellar medium with a speed u_f, gives

$$\frac{P_-}{\rho u_f^2} = \frac{4}{3} \xi_\gamma \frac{M_{Ni}}{56 m_p} \frac{\sigma_T}{4\pi r^2} \frac{E_{inj}}{m_p u_f^2} \ln\frac{E_{max}}{E_{inj}}$$

$$\sim 1.5 \times 10^{-5} \xi_\gamma \frac{M_{Ni}}{M_\odot} E_{inj}^{MeV} r_{pc}^{-2} \left(\frac{u_f}{10^3\ km\ s^{-1}} \right)^{-2} \ln\frac{E_{max}}{E_{inj}}. \qquad (8)$$

From these equations follows that the ratio of the electron pressure to the ram pressure can vary, depending on the several principal model parameters, within a broad range, from 10^{-7} to 10^{-3}. We assume that electrons are injected with their original energy ~ 1 MeV. However their energy can be significantly larger if particles are preaccelerated in the upstream regions of the shocks.

IV. PRE-ACCELERATION OF ELECTRONS

High-energy particles accelerated at strong shocks excite plasma waves and produce small-scale shocks and turbulence in the upstream region. The turbulence may amplify magnetic fields at the shocks of young SNRs [26]. Also, the dissipation of the turbulence results in substantial gas heating upstream of the shock. The latter limits the total compression ratio of the shock modified by CR pressure. This is an important feature of modern nonlinear shock acceleration models (see for a review ref. [1]). At these conditions, some preacceleration of energetic electrons via the stochastic (second order Fermi) mechanism which also energizes thermal electrons and ions in this region seems rather plausible. Note that in principle the stochastic acceleration can be realized also via ensemble of random shocks. Also we should emphasize that there is an essential difference between the preexisting energetic (supra-thermal) electrons and those, which in principle could be injected at the shock front from the thermal pool. While the preexisting energetic electrons pass through the whole extended turbulent region upstream of the shock, the particles injected in the shock front occupy a narrow region at the shock. That is why preacceleration of these electrons is not significant. The reacceleration of sub-keV electrons from the thermal pool of upstream plasma is problematic also because of strong Coulomb losses (see Eq. (2)).

The energy E_{inj} is determined by the efficiency of stochastic acceleration upstream of the shock. The rate of stochastic (second order) acceleration is $\tau_{st}^{-1} \sim u_t^2/D$ while the rate of DSA is $\tau_D^{-1} \sim u^2/D$, where u_t is the the velocity of turbulence (plasma waves) and D is the diffusion coefficient. The maximum energy of protons is of the order of 100 TeV in young SNRs. Then for $u_t/u \sim 0.1$, the maximum energy of particles accelerated through the stochastic mechanism is expected to be $E_{inj} \sim 1$ TeV. However, this should be considered as an optimistic upper limit, given that the diffusion coefficient for the low-energy particles in the turbulent region upstream of the shock can be significantly larger than the Bohm diffusion coefficient.

A more realistic estimate is given below. We shall consider the reacceleration of particles by multiple small-scale shocks in the upstream region of the SNR shock. A particle is picked up by the small-scale shock, accelerated and advected downstream where it loses energy adiabatically. Then the particle is picked up by the next small-scale shock, *etc.*

The energy density of relativistic electrons just downstream of the small-scale shock can be found after integration of Eq. (5). Because of the adiabatic expansion in the downstream region, this value drops by a factor of $\sigma_s^{4/3}$, where σ_s is the compression ratio of the small-scale shock. So the energy density ϵ_- after one acceleration cycle is

$$\frac{\epsilon_-}{\epsilon_0} = \frac{\gamma_s}{\gamma_s - 4}\sigma_s^{-4/3} = \frac{3\sigma_s}{4 - \sigma_s}\sigma_s^{-4/3}. \quad (9)$$

Here ϵ_0 is the electron energy density at the beginning of the cycle.

It is interesting to compare the relative change of the electron energy density to the relative change of the gas pressure P. Using the Rankine-Hugoniot conditions we find

$$\frac{P}{P_0} = \frac{4\sigma_s - 1}{4 - \sigma_s}\sigma_s^{-5/3}. \quad (10)$$

Here P_0 is the gas pressure in the beginning of the cycle.

One can see that the relative changes of the electron energy density and of the gas pressure are similar. For example, for $\sigma_s = 3$ we have $\epsilon_-/\epsilon_0 = 2.08$ and $P/P_0 = 1.76$. For weaker shocks, the change of the electron energy density is higher than the change of the gas pressure. This means that after many cycles, the relative change of the gas pressure is comparable or smaller than the change of the electron energy density. In other words, the gas heating in the upstream region of the SNR shock is accompanied by a similar or stronger electron reacceleration.

Although the gas heating can not directly estimated from observations of SNRs, one can constrain it (a lower bound) assuming non-negligible amplification of the magnetic field. Numerical studies of the Bell's instability show that the energy density of the heated gas is comparable or higher than the energy of the amplified magnetic field [26–28]. Namely, within the synchrotron-loss interpretation of thin X-ray filaments in young SNRs (see e.g. ref. [13]), the field in the upstream region can be amplified by a factor of 5 to 10. Therefore the gas pressure should be increases by a factor as large as 100. The similar level of the gas heating is needed to limit the strong shock modification and to avoid the appearance of the concave CR spectra (see e.g. ref. [1]). It is sufficient to have 8 cycles to provide a 100-fold increase of the gas pressure at the shocks with $\sigma_s = 3$. The corresponding increase of $E_{inj} = \epsilon_-/n_-$ equals several hundreds.

The modeling of the Bell's instability with DSA [27] shows that the upstream region of a young SNR of width $L \sim 10^{18}$ cm is filled with a supersonic MHD turbulence with Mach number 3–4, while the distance between small-scale shocks is $l \sim 10^{16}$ cm. For these parameters and for turbulent motions $u_t/u \sim 0.1$ the expected number of cycles is $Lu_t/lu \sim 10$.

One should note that the preaccelerated electrons may have an impact on the upstream turbulence and thus regulate their own acceleration efficiency. In particular, the higher number density of preexisting electrons would make lower the energy E_{inj}. Under these conditions, the energy density of preaccelerated electrons may be of the order of the energy density of the upstream turbulence. The latter is believed to be several percent of the ram pressure ρu^2 at CR modified shocks. So the upper limit for the number density of preaccelerated electrons is $n_- E_{inj} \sim 10^{-2}\rho u^2$ in Eq. (6).

Even for a modest energy $E_{inj} = 100$ MeV, one can obtain, according to Eq. (7), quite high ratio $P_+/\rho u_r^2 \sim 0.1$. The shock may be slightly modified by the pressure of accelerated electrons and positrons!

V. APPLICATIONS TO SNRS

The above discussed picture of preacceleration of electrons and positrons from the products of decays of radioactive short-lived elements can be relevant to the reverse shock of Cas A. This can explain why the pressure of energetic positrons (electrons) in the shocked ejecta is comparable to the gas pressure in the supernova shell. The same could be true also for the radio-knots if they are fast moving clumps of the shocked ejecta. At the present epoch, the pressure of energetic electrons at the forward shock of Cas A is not very high, as it follows from Eq. (8). However, most likely it was much higher in the past when the radius of the remnant was smaller than 0.1 pc. Since the forward shock of Cas A propagates in a dense stellar wind of the supernova progenitor with a density profile $\sim r^{-2}$, the accelerated electrons have been produced mainly in the past when the synchrotron cooling in the amplified field was significant. Now these electrons are located inside the forward shock. This can explain the rather steep radio-spectrum of Cas A.

In Cas A, the energy of preaccelerated electrons E_{inj} can not exceed 100–200 MeV, otherwise this would be in conflict with the observed synchrotron radio-spectrum. The spectral flattening seen at 20 MHz [29] can be attributed, for the magnetic field at the reverse shock of the order of 100–200 μG, to the lower energy cut-off in the electron spectrum at 100 MeV. The magnetic field at the forward shock of Cas A is larger. However since radio-emitting electrons have been accelerated in this region in the past, because of adiabatic losses their low-energy cut-off is now located below 100 MeV.

We conclude that the high radio brightness of Cas A is caused by the dense stellar wind where the forward shock propagates, and by a relatively high amount of radioactive

[44]Ti the decay of which provides supra-thermal electrons and positrons for the further acceleration by the reverse shock. This is in contrast to other historical young SNRs like Tycho, Kepler and SN1006. They are results of Ia supernova explosions in uniform medium. Therefore, in these objects the electrons accelerated by forward shocks, are produced predominantly at later epochs. In addition, the ejecta of Cas A, because of the dense stellar wind has been shocked very early, likely just after the explosion. The radiative instabilities operated in the shocked ejecta could result in the formation of ejecta clumps [30,31], which presently are observed as radio-knots.

Since the reverse shock of Cas A contains about 1% of the explosion energy, the energy fraction of electrons and positrons is close to 10^{-3}. The electrons accelerated at the forward shock have a similar energetics. So we expect that in Cas A approximately 10^{-3} fraction of supernova energy is transferred to the accelerated electrons and positrons. This conclusion is in agreement with estimates based on radio observations [20].

The fraction of energy 10^{-3} found for positrons in the reverse shock of Cas A is expected to be the same for all young core-collapse supernova. However GeV positrons leave the remnant only at late stages when its radius becomes a factor of 10 larger than the radius at the transition to the Sedov phase when the positrons have been accelerated. Since the energy of particles adiabatically drops (inverse proportional to the remnant's radius), the energy fraction of positrons will be reduced down to 10^{-4}. The luminosity in galactic CR positrons at multi-GeV energies based on the recent measurements of the Pamela collaboration [32] is close to 10^{38} erg s^{-1}. Given the overall mechanical power of the galactic core-collapse supernova 10^{42} erg s^{-1}, our model can explain the flux of the primary CR positrons by reverse shocks of young SNRs without invoking other source populations (for a review on different potential sources of galactic CR positrons see [33]).

It is important to note that our model applied to Cas A predicts the positron-to-electron ratio close to 1. The reason is that (i) the estimated energetics of leptons in forward and reverse shocks in Cas A based on radio observations are comparable, and (ii) our model implies that while electrons are accelerated in the forward shock, in the reverse shock the content of positrons is equal or larger than the content of electrons. If so, Cas A, as well as other young SNRs alone cannot provide the total flux of galactic CR electrons. In fact this is a model-independent statement based on the estimates of numbers of electrons in young SNRs. For old SNRs the situation is different. While the reverse shocks disappear in these objects, the forward shock continue to accelerate electrons (although to modest energies, $E \leq 1$ TeV). In our model, the electrons produced via the Compton scattering of gamma-rays from [56]Co are accelerated by forward shocks in old Ia SNRs

expanding in the uniform medium. According to the observed light curves, the ejecta of Ia supernova contains $\sim 0.6 M_\odot$ of [56]Ni just after the supernova explosion. The energetics of galactic Ia supernova is of the order of 3×10^{41} erg s^{-1}, implying approximately one supernova per century. On the other hand, the production rate of galactic CR electrons is close to 10^{39} erg s^{-1} [34]. So a fraction of 0.3% of energy of Ia supernova must be transferred to CR electrons. The similar ratio of CR electron pressure to the ram pressure is estimated for an old remnant with the radius 30 pc and the shock speed 300 km s^{-1} if $E_{\text{inj}} = 3$ GeV (see Eq. (9)). The required higher value of E_{inj} can be explained by a lower number density of the circumstellar medium where the Ia supernova explosions occur.

We should note that another source of the supra-thermal electrons at supernova shocks has been recently suggested by Morlino [35]. Partially ionized multi-GeV ions accelerated at the shock can produce multi-MeV electrons via photo-ionization by optical Galactic emission. The fraction $\eta = n_-/n$ of the corresponding electrons is estimated as $\eta \sim 0.1 x_{\text{He}} \gamma^{-1} u^2/c^2$ at CR modified shocks. Here $x_{\text{He}} \sim 0.1$ is the fraction of Helium in the interstellar medium, $\gamma \sim I_{\text{He}}/\epsilon_{\text{ph}}$ is the gamma-factor of He$^+$ ion ionized by Galactic optical photons with energy ϵ_{ph}, and $I_{\text{He}} = 54$ eV is the ionization potential of Helium. This results in $\eta \sim 10^{-4} u^2/c^2$ in young SNRs where $\gamma \sim 100$ and ions are photo-ionized by eV optical photons, and $\eta \sim 10^{-3} u^2/c^2$ in the old remnants where $\gamma \sim 10$ and ions are photo-ionized by ultraviolet photons. These numbers are comparable or higher than numbers given by Eq. (3). Even without any preacceleration by MHD turbulence this mechanism results in the electron to proton ratio $K_{\text{ep}} \sim x_{\text{He}} m_{\text{e}}/m_{\text{p}} \sim 10^{-4}$. Although the preacceleration of these electrons is more problematic because they are produced closer to the shock by 10–100 GeV ions, it is not excluded. Then the corresponding injection energy necessary for explanation of galactic CR electrons can be below 1 GeV closer to $E_{\text{inj}} = 100$ MeV as argued above for reverse shock of Cas A.

Finally, in the context of the proposed model, one can expect harder CR positron spectrum. The positrons of higher energies leave the remnant earlier and are subject to lower adiabatic losses in comparison with the positrons of lower energies. This effect does not have an impact on the spectra of electrons accelerated predominantly by forward shocks in old SNRs. The harder source spectrum of positrons is in agreement with the recent Pamela measurements [32].

According to the scenario proposed in this paper, only forward shocks of young SNRs produced by supernova explosions with a small ejecta masses $M_{\text{ej}} < 2M_\odot$, can contain large amount of accelerated electrons. The relevant SNRs belong to the Ia/b/c and, probably, IIb (like Cas A) type supernovae. Note that the brightest in TeV gamma-rays

young SNR RX J1713.7-3946 most likely belongs to Ib/c type SNR with a small ejecta mass [36]. In the case of IIP supernova with large ejecta masses gamma-rays from ^{56}Co decay cannot effectively escape the ejecta and ''feed'' the forward shock by supra-thermal electrons for further acceleration. If so, we should expect forward shocks of IIP SNRs to be dim in radio and nonthermal X-rays. On the other hand, large amount of electrons and positrons from decays of ^{44}Ti can be accelerated at reverse shocks of young SNRs of all types including the most frequent IIP supernovae. In this regard, the youngest galactic SNR G1.9 + 0.3 is of a special interest. It shows both large content of ^{44}Ti and ongoing acceleration of electrons by reverse shock [10]—two key components required in our model.

VI. SUMMARY

The ''radioactive'' origin of electron injection, related to both the forward and reverse shocks, seems to be a natural scenario in SNRs with the following key components:

(1) the energetic positrons (and possibly also electrons) from ^{44}Ti decay are accelerated at reverse shocks of young SNRs;

(2) the energetic electrons from the Compton scattering of ^{56}Co-decay gamma-rays are accelerated at forward shocks of both old and young SNRs of type Ia/b/c and IIb;

(3) a modest preacceleration (presumably of stochastic origin) to energies $E_{inj} \sim 0.1$ GeV in the upstream regions of the forward and reverse shocks is a necessary condition in Cas A for explanation of the energetics in relativistic electrons;

(4) the proposed scenario can explain not only the overall flux of galactic CR electrons by SNRs, but also the recently reported tendency of gradual increase of the positron-to-electron ratio with energy.

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