# Mechanism for spectral break in cosmic ray proton spectrum from a supernova remnant surrounded by dense gas

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**Abstract:** Observations of the W44, IC443 and other SNRs by the *Fermi* spacecraft observatory strongly support the idea that the bulk of galactic cosmic rays is accelerated in such remnant shocks by the diffusive mechanism. However many SNR shocks expand into weakly ionized dense gases. In this paper we provide the necessary modifications to the diffusive shock acceleration mechnism and demonstrate that strong ion-neutral collisions in remnant surroundings lead to the steepening of the energy spectrum of accelerated particles by *exactly one power*. The spectral break is caused by Alfven wave evanescence leading to the fractional particle losses. The gamma-ray spectrum generated in collisions of the accelerated protons with the ambient gas is also calculated and successfully fitted to the Fermi Observatory data. The parent proton spectrum of the W44, for example, is best represented by a classical test particle power law $\propto E^{-2}$, steepening to $E^{-3}$ at $E_{br} \approx 7 GeV$ due to deteriorated particle confinement.

**Keywords:** acceleration of particles – cosmic rays – shock waves supernova remnants – turbulence – Radiation mechanisms: non-thermal

**Introduction** Ongoing *direct* observations of a number of galactic supernova remnants (SNRs) in the X- and gamma-ray bands supported by the radio, optical and UV data seem to rapidly close in on the problem of cosmic ray (CR) origin. Overall, the observations favor the diffusive shock acceleration (DSA, operating in SNR shocks) as a mechanism for the production of galactic CRs. However, there are at least two critical questions that observations pose to the theory. First, what exactly is the form of the spectrum that the theory predicts? Second, when do we really see the proton (i.e., the primary CR component) emission and when do we see just a contaminating but radiatively more efficient electron component?

A simple test particle version of the DSA (leading to a power-law $\propto E^{-2}$ particle energy distribution) reproduces (after correcting for the propagation losses) the form of the energy spectrum reasonably well. At the same time, the *direct observations* of emission coming from particles accelerated in SNR shocks often indicate significantly steeper than $E^{-2}$ spectra [2]. Also the recent *Fermi* Large Area Telescope (LAT) observations of the SNRs W44 and IC443 suggest that the spectrum of the gamma ray producing protons is substantially steeper at high energies than the DSA predicts [1]. It should be noted that a similar discrepancy has already been found in the high energy gamma ray spectrum of the SNR RXJ 1713 measured by the CANGAROO [7] and HESS [2] atmospheric Cerenkov telescopes. Motivated by this inconsistency with the DSA theory in par-

ticular, we have previously published a suggestion of the mechanism for the spectral break [10], which can resolve the discrepancies. We believe that a similar phenomenon is also applicable to the recent Fermi-LAT observations, which we discuss below using the W44 as an example. We show that ion-neutral collisions in a molecular cloud, adjacent to the remnant, steepen the energy spectrum of accelerated particles. We calculate the gamma-ray spectrum resulting from the collisions of accelerated protons with the molecular cloud material and fit the result to the Fermi Observatory data.

**Mechanism for the spectral break** The physics of the spectral break is very simple. When a SNR shock approaches a molecular cloud (MC) or a pre-supernova swept-up shell, confinement of accelerated particles generally deteriorates. Due to the particle interaction with magnetic turbulence, confinement requires scales similar to the particle gyroradius Drury [5]. While the waves are in a strongly ionized (closer to the shock) medium, they propagate freely in a broad frequency range at the Alfven speed $V_A = B/\sqrt{4\pi\rho_i}$ with the frequencies $\omega = kV_A$. Here $k$ is the wave number (assumed parallel to the local field **B**) and $\rho_i$ is the ion mass density. As long as the Alfven wave frequency is higher than the ion-neutral collision frequency $\nu_{in}$, the waves are weakly damped. When, on the other hand, the ion-neutral collision frequency is higher (deeper into the cloud), neutrals are entrained by the oscillating

plasma and the Alfven waves are also able to propagate, albeit with a factor $\sqrt{\rho_i/\rho_0} < 1$ lower speed, where $\rho_0$ is the neutral density. The propagation speed reduction occurs because every ion is now "loaded" with $\rho_0/\rho_i$ neutrals. In between these two regimes Alfven waves are heavily damped and even disappear altogether for sufficiently small $\rho_i/\rho_0 \ll 0.1$. The evanescence wave number range is then bounded by $k_1 = v_{in}/2V_A$ and $k_2 = 2\sqrt{\rho_i/\rho_0}v_{in}/V_A$. These phenomena have been studied in detail in [8], and specifically in the context of the DSA in [6]. Now we turn to their impact on the particle confinement and emissivity.

In the frame work of a quasilinear wave-particle interaction the wave number $k$ is approximately related to the parallel (to the magnetic field) component of the particle momentum $p_\parallel$ by the cyclotron resonance condition $kp_\parallel/m = \pm\omega_c$ where the (non-relativistic) gyro-frequency $\omega_c = eB/mc$. Therefore, the frequency range where the waves cannot propagate may be conveniently translated into the parallel momentum range

$$p_1 < \left|p_\parallel\right| < p_2 \tag{1}$$

with

$$p_1 = 2V_A m\omega_c/v_{in}, \ \ p_2 = \frac{p_1}{4}\sqrt{\rho_0/\rho_i} > p_1, \tag{2}$$

That a spectral break must form at the photon energy corresponding to the particle momentum $p = p_1 = p_{br}$, can be readily understood from Fig.1. The 'dead zones' $p_1 < \left|p_\parallel\right| < p_2$ imply that particles with $\left|p_\parallel\right| > p_1$ do not turn around (while moving along the magnetic field) and escape from the region of CR-dense gas collisions at a $p_\parallel/p$ fraction of the speed of light. This happens in the region of enhanced gamma radiation. Therefore, an initially isotropic distribution of accelerated particles fills only a slab in momentum space $\left|p_\parallel\right| < p_1$ and becomes highly anisotropic (a 'pancake' distribution). What matters for the integral emission, however, is a locally isotropic component $\overline{f}$ of this new proton distribution. It can be introduced by re-averaging the 'pancake' ($\left|p_\parallel\right| < p_1$) distribution in pitch angle, $\overline{f}(p) \equiv \int_0^1 f(p,\mu)\,d\mu$, and is readily obtained assuming that particles remaining in the dense gas (those with $\left|p_\parallel\right| < p_1$) maintain their isotropic pitch-angle distribution, i.e.

$$\overline{f}(p) = \int_0^{\mu_1} f_0(p)\,d\mu = \begin{cases} (p_1/p)f_0(p), & p \geq p_1 \\ f_0(p), & p < p_1 \end{cases} \tag{3}$$

where $f_0(p)$ is the initial (isotropic) distribution function and $\mu$ is the cosine of the pitch angle (see Fig.1), $\mu_1 = \min\{p_1/p, 1\}$. Thus, the slope of the particle momentum distribution becomes steeper by exactly one power above $p = p_1 \equiv p_{br}$. In particular, any power-law distribution $\propto p^{-q}$, upon entering an MC, turns into $p^{-q-1}$ at $p \geq p_{br}$, and preserves its form at $p < p_{br}$.

By virtue of beinng clumpy, MCs may fill only a small fraction of the precursor. In this case the acceleration process
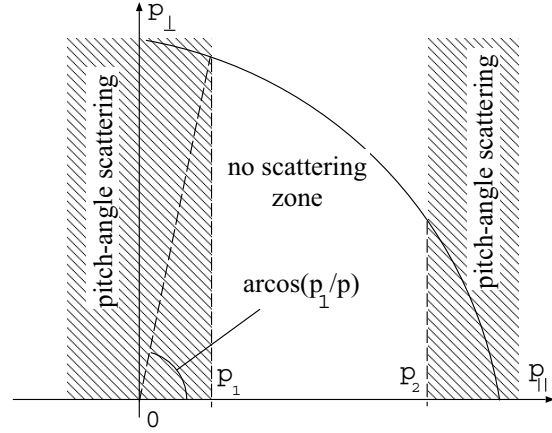


Figure 1: **Momentum space of accelerated protons.** Particle scattering zones on the $\left(p_\parallel, p_\perp\right)$- plane of momentum space. Particles in the stripes $p_1 < \left|p_\parallel\right| < p_2$ are not scattered by waves (see text). Therefore, particles from the domains $\left|p_\parallel\right| > p_2$ maintain their propagation direction and promptly escape from the dense gas region.

continues almost unimpeded, the accelerated protons illuminate the 'cloudlets' and make them visible in $\gamma$-rays due to the high density target material.

**Break momentum**    According to eq.(2), $p_{br}$ ($\equiv p_1$) depends on the magnetic field strength, on ion density and on the frequency of ion-neutral collisions, $v_{in} = n_0\langle\sigma V\rangle$. Here $\langle\sigma V\rangle$ is the product of the collision cross-section and collision velocity averaged over the thermal distribution. Using an approximation of [4, 6] for $\langle\sigma V\rangle$, $p_{br}$ can be estimated as

$$p_{br}/mc \simeq 10B_\mu^2 T_4^{-0.4} n_0^{-1} n_i^{-1/2}. \tag{4}$$

Here the gas temperature $T_4$ is measured in the units of $10^4 K$, magnetic field $B_\mu$ -in microgauss, $n_0$ and $n_i$ (number densities corresponding to the neutral/ion mass densities $\rho_0$ and $\rho_i$) -in $cm^{-3}$. The quantities in the last formula are known too poorly to make an accurate independent prediction of the position of the break in the gamma ray emission regions. Those are the regions near the blast wave where complicated physical processes unfold. They include particle acceleration, strong MHD turbulence (driven by particles and their interaction with ambient gas inhomogeneities), gas ionization by shock generated UV photons, turbulent plasma heating and even evaporation of magnetic cloudlets [4]. Also important may be the ionization by the low energy CRs accelerated at the blast wave. However, as their diffusion length is shorter than that of the particles with $p \gtrsim p_{br}$, we may assume that they do not reach the MC.

**Particle spectra**    To calculate the particle spectra, we need to determine the degree of nonlinear modification of

the shock structure. In principle, it can be calculated consistently, given the shock parameters and the particle maximum momentum, $p_{max}$. In the case of a broken spectrum, $p_{br}$ plays the role of $p_{max}$, since this is the momentum where the dominant contribution to the pressure of accelerated particles comes from, thus setting the scale of the modified shock precursor. Note that in the conventional nonlinear (NL) acceleration theory, the cut-off momentum $p_{max}$ plays this role, because the nonlinear spectra are sufficiently flat to make the pressure diverge with momentum.

The break in the photon spectrum is observed at about 2 GeV, which places the break on the proton distribution at about $p_{br} \simeq 7 GeV/c$ [1]. For the strength of the break $\Delta q = 1$, the spectrum above it is clearly pressure converging. Using this break momentum we applied an analytic approach for a stationary nonlinear acceleration problem [11].

Apart from $p_{br}$, the nonlinear solution depends on a number of other parameters, such as the injection rate of thermal particles into acceleration, Mach number, the precursor heating rate and the shock velocity $V_s$. Of these parameters only the latter is known accurately, $V_s \approx 300 km/s$, the other parameters are still difficult to ascertain. Fortunately, in sufficiently strong shocks the solution generally tends to either stay close to the test particle (TP) solution (leaving the shock structure only weakly modified) or else it transitions to a strongly modified NL-solution regime. The TP regime typically establishes in cases of moderate Mach numbers, low injection rates and low $p_{max}$ (now $p_{br}$), while the NL regime is unavoidable in the opposite part of the parameter space.

In the TP regime the spectrum is close to a power-law with the spectral index 2 throughout the supra-thermal energy range. In the NL regime, however, the spectrum develops a concave form, starting from a softer spectrum at the injection energy, with the index $q \simeq (r_s + 2)/(r_s - 1) > 2$, where $r_s < 4$ is the sub-shock compression ratio. Then it hardens, primarily in the region $p \sim mc$, where both the partial pressure and diffusivity of protons change their momentum scaling. The slope reaches its minimum at the cut-off (break) energy, which, depending on the degree of nonlinearity, can be as low as 1.5 or even somewhat lower if the cut-off is abrupt. Generally, in cases of low maximum (or, equivalently, low spectral break $p_{br} \lesssim 10$) momentum, the shock modification is weak, so the spectrum is more likely to be in only slightly nonlinear, almost TP regime. On the other hand, there is a putative indication from the electron radio emission that their spectrum may be close to $q_e \approx 1.75$, which could be the signature of a moderately nonlinear acceleration process. It should be remembered, however, that this is a global index across the W44 remnant. There are resolved bright filaments where a canonical $\alpha = -0.5$ spectrum, corresponding precisely to the TP parent electron spectrum with $q_e = 2$ is observed [3]. Moreover, there are regions with the positive indices $\alpha \lesssim 0.4$ which cannot be indicative of a DSA process without corrections for subsequent spectral transformations such as an
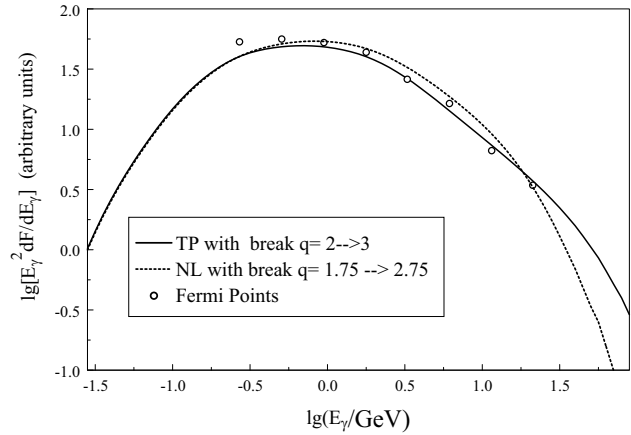


Figure 2: **Gamma radiation spectra.** Photon spectra resulting from $\pi^0$ decay and calculated for two different parent proton spectra compared against the Fermi data (open circles). Solid line: a test particle acceleration regime with the spectral index $q = 2$ below the break and $q = 3$ above the break at $p_{br} = 7 GeV/c$. Dashed line: a moderately nonlinear acceleration regime corresponding to a NL spectrum (with $q \simeq 1.75$ and $q \simeq 2.75$ below and above the break, respectively). Cut-offs are placed at 300 GeV for TP- and 100 GeV, for NL-spectrum.

absorption by thermal electrons [3]. These regions can very well contribute to the overall spectral hardening discussed above, mimicking the acceleration nonlinearity.

In using the electron radio spectrum as a probe for the level of acceleration nonlinearity, the following two relations are useful. First, there is a relation between the electron energy and the radio frequency $v_{MHz} = 4.6 \cdot B_\mu E_{GeV}^2$. The second relation, $q_e = 1 - 2\alpha$, links the spectral index of radio emission $\alpha$ (assuming the radio flux $\propto v^\alpha$) and the spectral index of the parent electrons $q_e$ (assuming their energy spectrum $\propto E^{-q_e}$). Once the global radio spectral index of W44, $\alpha \simeq -0.37$ [3] is generated by freshly accelerated electrons in the frequency range $74 < v < 10700$ MHz, the electrons should maintain their modified spectrum over the energy range spanning more than one order of magnitude. For example, assuming $B_\mu \simeq 70$ [1], one sees that electrons must maintain an index $q_e \approx 1.75$ between $0.46 < E < 5.8$ GeV. While the upper bound is acceptable given the spectral break proton energy inferred from the super GeV emission measured by the Fermi LAT, the lower end is rather uncomfortable, since the nonlinear modification of both protons and electrons with the Bohm (or other similar for protons and electrons turbulent diffusivities) starts (slowly) only at the proton rest energy. The calculated nonlinear spectra can be found in Fig.2 of ref.[11]. At and below 1GeV, the electron spectrum is very close to the test particle solution, $q_e \approx 2$, even though the proton spectrum may be somewhat steeper there, as we mentioned above.

**Photon spectra** The above considerations somewhat weaken the radio data as a probe for the slope of the electron and (more importantly) for the proton spectrum. Therefore, the exact degree of nonlinearity of the acceleration remains unknown and we consider both the TP and weakly NL regimes in our calculations of the photon spectra, generated in $p - p$ collisions. The results are shown in Fig.2. The best fit to the Fermi data is provided by a TP energy distribution ($\propto E^{-2}$) below $p_{br} \simeq 7$GeV/c with the spectrum steepening by exactly one power above it. The spectrum steepening is perfectly consistent with the proton partial escape described above (with no parameters involved) and shown in Fig.1. For comparison, a weakly NL spectrum [11] is also used for these calculations (dashed line in Fig.2), but its fit would require a stronger break ($\Delta q > 1$) or a low momentum cut-off, Fig.2, i.e. at least one additional free parameter.

**Discussion** To summarize the results, the previously suggested mechanism for a break on the spectrum of shock accelerated protons [10] is found consistent with the recent [1] Fermi LAT observations of the SNR W44. The observed gamma ray spectrum most likely results from the decay of $\pi^0$-mesons which are born in $p - p$ collisions of shock accelerated protons with an ambient dense gas. The parent proton spectrum is best represented by a classical test particle power law $\propto E^{-2}$, steepening to $E^{-3}$ at $E_{br} \approx 7GeV$ due to deteriorated particle confinement caused by the ion-neutral collisions and the resultant Alfven wave evanescence. The position of the break momentum in the particle spectrum may be estimated using eq.(4), or conversely, the combination of parameters involved in this estimate can be inferred from the measured break momentum. The cut-off momentum is not constrained in this scenario.

An alternative explanation, based on a different mechanism of the break, associated with the change of the particle transport in the CR shock precursor [9] is also possible but is less definitive in the spectrum slope variation $\Delta q$ across the break. Besides, it would imply a considerable nonlinearity, i.e. a stronger CR shock precursor than it seems appropriate for the observed low break momentum. Still alternatively, assuming our "environmental" break mechanism is at work, i.e. $\Delta q = 1$, but the shock structure appreciably modified, we arrive at the $E^{-1.75}$ spectrum below the break (as the radio observations suggest for the electrons), and $E^{-2.75}$ above the break. A fit to the data is marginally possible, but it would require a relatively low cut-off momentum at about 100 GeV/c. This possibility may be supported or ruled out once the data (upper limit) around this energy become available.

The most robust and attractive aspect of the suggested mechanism for the spectral break is the exact $\Delta q = 1$ variation of the spectral index. Indeed, this change in the spectral slope is due to truncation of the particle momentum phase space and does not depend on any parameters. In a combination with the test particle regime operating be-

low the break, which is consistent with the low value of the break momentum, it provides a very good fit to the *Fermi* LAT data. Of three physically different types of spectral breaks suggested earlier (see [9] and references therein), namely the current, "environmental" mechanism appears to be plausible in situations where dense target gas is present, as required for efficient $\pi^0$ production. In a more general context, a spectral break is a natural resolution of the well known but puzzling trend of the *nonlinear* (i.e. supposedly improved) DSA theory to develop spectra which are even harder than the simple test particle spectra. Such a spectrum – i.e., diverging in energy– exhausts the shock energy available for the acceleration as the cut-off momentum grows. Note, that the spectrum of the RX J1713.7-3946 [2] is also consistent with the same break mechanism but with $p_{br} \sim 10^3 GeV/c$ and with naturally stronger acceleration nonlinearity [10]. However, it is difficult to make the case for hadronic origin of the gamma-ray emission of the RX J1713.7-3946. The fundamental role of the W44 for the problem of CR origin is that this particular remnant seems to rule out contaminating electron emission due to Bremsstrahlung and the inverse Compton scattering [1] thus favoring the hadronic origin of the gamma emission.

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