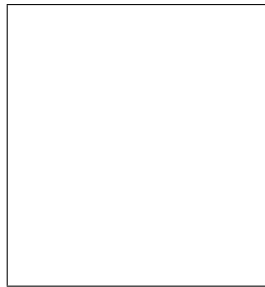# NEUTRINO PRODUCTION IN NUCLEONIC INTERACTIONS IN GAMMA-RAY BURSTERS

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Neutrinos produced in gamma-ray bursters (GRBers) may provide a unique probe for the physics of these extreme astrophysical systems. Here we discuss neutrino production in inelastic neutron-proton collisions within the relativistic outflows associated with GRBers. We consider both the widely used fireball model and a recently proposed magneto-hydrodynamic (MHD) model for the GRB outflow.

1   Introduction

Gamma-ray bursts (GRBs) are short and energetic flashes of gamma rays (~ 100 keV), reaching Earth from apparently random direction at a rate of a few per day (see Ref.[1] for a review). The luminosity of these bursts may be very large, sufficient to temporarily outshine all other gamma-ray sources combined. Following their accidental discovery in 1967, the origin of these remarkable events has puzzled astronomers for three decades. In particular, the question whether gamma-ray bursts were produced by sources within our galaxy or at cosmological distances has remained under debate until the 1990s.

In the last decade there has been tremendous progress in our understanding of GRBs. This is largely due to observations of GRB afterglows – periods of prolonged broad-band electromagnetic emission following the actual burst – that were first discovered in 1997. The cosmological distance scale has been established by redshift measurements of the afterglow, and in some cases afterglow observations have allowed for identification of the host galaxy, providing further clues as to the nature of gamma-ray bursters (GBRers). There is presently compelling evidence that long-duration GRBs (the subclass of GRBs lasting more than 2 sec) are ultimately caused by core-collapse of massive stars[2], although the situation for short-duration GRBs (lasting less than 2 sec) is less clear.

One can easily estimate that the energy released in a stellar core-collapse matches that required to power a GRB, but the mechanism responsible for the energy transfer is far from obvious. The widely accepted framework to describe this is divided into four phases. In the *initial phase*, core-collapse of the massive star results in a black hole-accretion disk system. This launches a jet, a collimated outflow of plasma that contains a small baryonic component. In the *accelerating phase*, this plasma accelerates to a velocity close to that of light (Lorentz factor $\sim$ 300). In this acceleration process, the initial energy of the plasma is transfered to bulk kinetic energy of the baryons that are contained in the plasma. In the *coasting phase*, the outflow moves with a fixed velocity through the pre-burst stellar environment. Here dissipation of the kinetic energy in the flow, most likely as synchrotron emission of shock-accelerated electrons, gives rise to the actual GRB. Finally, the afterglow is attributed to the interaction of the outflow with the external medium during the *afterglow phase*.

Although the framework described above successfully explains the general features of the observations, many questions remain. Arguably one of the most important issues is the nature of the relativistic outflow. Within the widely used fireball model, it is understood that the plasma is initially dominated by thermal energy. Alternatively, the energy may be predominantly in electromagnetic form. Such outflows are expected naturally when a magnetized accretion disk is surrounding the central black hole.[3,4,5] Further questions concern for example the initial collimation of the flow, where magnetic fields may also play an important dynamical role, and the details of the energy dissipation process, which is likely to involve some particle acceleration mechanism such as shock acceleration.

Besides the intrinsic motivation to better understand the physics of GRBers, further motivation is provided by the connection to other fields of physics. Since GRBers are believed to be efficient astrophysical particle accelerators, they are candidate sources of high-energy neutrinos and cosmic rays and provide a laboratory to study the acceleration mechanism. Furthermore, it has been proposed to use GRBs as standard candles to constrain the evolution of the universe.[6] Finally, there are more speculative proposals, e.g. to use the arrival times of low- and high-energy emission to constrain Lorentz violating interactions.[7]

Neutrinos are promising probes of the environment of GRB sources. Neutrino emission is complementary to the electromagnetic emission in two respects. First, neutrinos mostly trace the hadronic component of GRB outflows whereas electromagnetic radiation mostly traces the leptonic component. Second, neutrinos can leave the GRB source when it is still optically thick. Substantial neutrino production may be expected in various phases of a developing GRB. In the initial phase, neutrino emission can constrain the formation of GRB fireballs. Within the fireball model, the dominant neutrino production process in this phase is electron-positron annihilation (providing a counterexample to the mostly hadronic production mechanisms). Under favorable circumstances, this may give rise to copious neutrino production. However, this mechanism is not sufficiently efficient to carry away the bulk of the fireball energy or to qualitatively modify the dynamical behavior of the fireball.[8] In both the coasting and afterglow phases of a developing GRB, it is believed that kinetic energy is dissipated through shock acceleration of electrons. These shocks will likely also accelerate any protons contained in the fireball. Interactions of these high-energy protons with target nucleons or photons give rise to a flux of high-energy neutrinos that offers good detection prospects with the upcoming km^3 neutrino detectors such as IceCube.[9,10] These neutrinos provide information on the nature of the flow, in particular the strength of the hadronic component, and on the energy dissipation process.

Here we report on a different mechanism to create neutrinos in GRBers, namely inelastic neutron-proton (np) collisions that occur during the accelerating phase. We compare the typical neutrino emission through this mechanism for two competing models: the fireball model and the recently proposed 'AC' model[5,11], which assumes that the energy in the outflow is predominantly electromagnetic. The motivation of this work is to estimate the detection prospects of this

neutrino emission and to investigate whether it can be used to differentiate between the fireball model and the AC model. The np mechanism has been considered within the fireball model before.[12,13] Our estimates are more pessimistic than existing ones, which can be traced to the more accurate modeling of the inelastic np cross section adopted in our work. For the AC model, the mechanism was first considered in Ref.[14], which forms the basis of the present discussion.

In the following section we discuss the dynamics of GRB outflows containing neutrons and protons, both within the fireball model and within the AC model. We then discuss neutrino production through np interactions, and finally we present our conclusions.

2 Dynamics

2.1 Acceleration in the fireball model and the AC model

A striking feature of GRB models is the bulk relativistic motion. This ingredient is motivated by an observational paradox: the short timescales and large energies suggest a huge energy density and thus an optically thick source. This then implies that the photon spectrum should be quasi-thermal, while observations show that it is not. Relativistic motion solves this problem by increasing the physical timescale compared to that inferred from observations, and by decreasing the photon energy in the source compared to the observed energy. The mechanism to accelerate the flow to relativistic velocities differs between models. In the fireball model, acceleration results from the pressure that photons exert on the optically thick fireball. In this case the dynamics of the flow may be approximated with[15]

$$\Gamma \propto r \,, \tag{1}$$

where Γ is the Lorentz factor of the flow, and r the radius of the flow (i.e., the distance from the central black hole). In the AC model, the energy to accelerate the outflow is provided by magnetic reconnection, a mechanism that converts electromagnetic energy into heat and bulk motion. When the magnetic field lines predominantly change polarity in the flow direction, as we will assume, the dynamics of the flow may be approximated with[16]

$$\Gamma \propto r^{1/3} \,. \tag{2}$$

Comparison with eq. (1) shows that the acceleration of the flow is much more gradual in the AC model than in the fireball model. As we will see, this directly affects the neutrino flux from np collisions.

In both the fireball model and the AC model, acceleration of the flow stops when there is no more energy available to further accelerate the baryons. In the fireball model, the acceleration of the flow can also be terminated when the flow, whose energy density decreases with increasing radius, becomes optically thin.

2.2 Neutron-richness

Since the baryons that are contained in the flow are to be accelerated to high Lorentz factors, the initial baryon density cannot be too large. This requirement is generally stated in terms of a dimensionless *baryon loading parameter*

$$\eta \equiv L/\dot{M}c^2 \sim 10^3 \,, \tag{3}$$

where L denotes the total luminosity of the flow and $\dot{M}$ the mass flux. Near the central black hole, the typical energy density is larger than nuclear binding energies so that the baryonic component will consist predominantly of free protons and neutrons. The ratio of neutrons to

protons at the base of the outflow is determined by the competition of electron capture on protons and positron capture on neutrons. Recent studies[17] favor a neutron-rich environment, so that we expect that the outflow associated with a developing GRB is initially also neutron-rich. The neutron-to-proton ratio is parameterized with

$$\xi \equiv \dot{M}_n/\dot{M}_p \sim 1 \,, \tag{4}$$

where $\dot{M}_{n(p)}$ denotes the neutron (proton) mass flux. At larger radii, where the energy densities are smaller, nucleosynthesizing reactions reduce the number of free neutrons. However, a significant amount of neutrons is expected in the flow up to the radius where neutron decay becomes important. This radius is much larger than the radii relevant to np collisions and thus neutron decay is not important for the mechanism considered in this work.

2.3 Neutron decoupling and pion production

Eqs. (1) and (2) are idealized approximations that are only valid when the baryons contained in the plasma play no dynamical role. Detailed numerical studies[14,18] indicate that a reasonably strong baryonic component affects the dynamics. However, eqs. (1) and (2) provide a reasonable approximation to the full dynamical behavior that captures the properties which are essential to the particle production problem discussed here. We will thus neglect the dynamical importance of nucleons in this section.

Regardless of the mechanism that accelerates the flow, protons are strongly coupled to the other plasma components by electromagnetic interactions and follow the dynamics of the flow. The neutrons, on the other hand, are only coupled to the plasma through inelastic np collisions. The nucleon number densities are initially very large so that the np interaction timescale is much shorter than the dynamical timescale. In this regime, the neutrons and protons essentially behave as a single fluid. As the outflow expands, the number densities decrease and the scattering timescale increases. When the np scattering timescale becomes smaller than the dynamical timescale, the neutrons effectively decouple from the plasma and coast with a certain terminal velocity.

When the flow is still in the accelerating phase at np decoupling, the protons are accelerated further and consequently a bulk velocity difference develops between protons and neutrons. If this velocity becomes sufficiently large, pions can be created in inelastic np collisions. The threshold condition to produce pions may be expressed as $\chi \equiv \Gamma_p/\Gamma_n > \chi_\pi \equiv 2.15$, where $\Gamma_{p(n)}$ denotes the proton (neutron) Lorentz factor. Approximating the dynamics of the outflow with $\Gamma \propto r^p$ (where $p = 1$ corresponds to the fireball model and $p = 1/3$ to the AC model), we observe that the radius where pion production occurs r_π and the decoupling radius r_{np} are related through $r_\pi \simeq r_{np}\chi_\pi^{1/p}$. Hence, in the fireball model the pion production radius is roughly twice the decoupling radius, while in the AC model it is an order of magnitude larger.

If the outflow contains many baryons, the available amount of energy per baryon is relatively small. In this case the acceleration of the flow may saturate before np decoupling, thus preventing inelastic collisions. Hence a sufficiently 'pure' flow ($\eta \gtrsim 500$ for the fireball model, or $\eta \gtrsim 200$ for the AC model) is required for particle production in inelastic np collisions.

3 Particle production in neutron-proton collisions

3.1 Interaction probability

The probability $d\tau$ for a neutron moving with dimensionless velocity β_n to interact with a proton population moving with dimensionless velocity β_p, within an infinitesimal radius $r \ldots r + dr$ is[14]

$$d\tau = \sigma \Gamma_p n_p' \left(\frac{\beta_p - \beta_n}{\beta_n} \right) dr \simeq \frac{\sigma n_p'}{2\Gamma_n} \left(\chi - \frac{1}{\chi} \right) dr \,, \tag{5}$$

where n'_p denotes the comoving proton density, σ is the inelastic np cross section[a], and we have assumed that $\beta_n \simeq 1$ and $\beta_p \simeq 1$ in the second equality. For outflows that follow an acceleration profile $\Gamma \propto r^p$ up to infinity, integrating eq. (5) gives the probability τ for an inelastic np collision to occur somewhere between the pion production radius and infinity. The result is independent of any model parameters except the index p. Performing this integral, we find that $\tau \simeq 0.2$ for the fireball model ($p = 1$) and $\tau \simeq 0.008$ for the AC model ($p = 1/3$). A comparison of these estimates with numerical results[14] shows that the estimate on τ is fairly accurate for the AC model over a large range of parameters. For the fireball model, however, this procedure tends to overestimate the optical depth. The reason for this is that, for a large range of model parameters, the flow becomes optically thin shortly after pion production becomes possible. This prevents further acceleration of the flow. Hence the acceleration profile $\Gamma \propto r$ does not hold up to large radii and the above estimate is not very accurate. Numerical results indicate that a typical value for the fireball model is $\tau^{\mathrm{FB}} \simeq 0.05$, while for the AC model $\tau^{\mathrm{AC}} \simeq 0.01$. Qualitatively, this difference can directly be understood from the dynamics: in the AC model, pion production is only possible at radii an order of magnitude larger than the np decoupling radius. This implies that the number density of target protons has decreased significantly since decoupling, leading to a small interaction probability. For the fireball model, pion production occurs closer to the decoupling radius, where the dilution of target protons is not so strong.

3.2 Neutrino emission

The neutrino fluence from a single GRB source at proper distance D_p can be expressed as $\Phi_\nu \simeq 1.5 N_n \tau / 4\pi D_p^2$, where N_n denotes the isotropic-equivalent number of neutrons in the flow, τ is the np interaction probability, and we have taken the average number of neutrinos (adding flavors and antiparticles) per np scattering equal to 1.5.[14] Using $N_n \simeq \xi_0/(1 + \xi_0) \times E/(\eta m_n c^2)$, where ξ_0 is the initial neutron-to-proton flux ratio (cf. eq. (4)), E is the total isotropic-equivalent burst energy, η is the baryon loading parameter (cf. eq. (3)), and m_n the neutron mass, we find the following neutrino fluences for a burst at redshift $z = 1$ for the fireball model and the AC model, respectively:

$$\Phi_\nu^{\mathrm{FB}} \simeq 10^{-4}\,\mathrm{cm}^{-2} \left(\frac{\tau}{0.05}\right) \left(\frac{2\xi_0}{1 + \xi_0}\right) \left(\frac{E}{10^{53}\mathrm{erg}}\right) \left(\frac{\eta}{10^3}\right)^{-1} ; \tag{6}$$

$$\Phi_\nu^{\mathrm{AC}} \simeq 2 \times 10^{-5}\,\mathrm{cm}^{-2} \left(\frac{\tau}{0.01}\right) \left(\frac{2\xi_0}{1 + \xi_0}\right) \left(\frac{E}{10^{53}\mathrm{erg}}\right) \left(\frac{\eta}{10^3}\right)^{-1} . \tag{7}$$

Using the fact that pions are created near threshold, and assuming a roughly isotropic distribution in the center-of-mass frame, one finds that the typical observed neutrino energy is $\sim$50 GeV for the fireball model and $\sim$70 GeV for the AC model.[14] The typical energy for the AC model is slightly higher because charged pions will be accelerated by the plasma before decay.

For the fireball model, the flux estimate (6) is roughly an order of magnitude below previous estimates[13]. This difference can be attributed to a more accurate treatment of the np interaction (in Ref.[13] it is assumed that $\tau \simeq 1$). For the AC model, the interaction probability is smaller by another factor $\sim$5. This difference results from the more gradual acceleration of the flow and is thus directly linked to its nature. Unfortunately, the detection prospects with the upcoming km^3 neutrino detectors such as IceCube are very poor due to the relatively low neutrino energy: for reference values of the parameters we expect less than 1 event per year for a combined, diffuse flux of 1000 GRBers per year for either model. This GRB rate is rather optimistic if one takes into account that np decoupling only occurs for sufficiently pure (high-η) GRBers. We thus conclude that realistic detection prospects for the neutrino flux studied here requires a detector with larger effective area at sub-100 GeV energies than the upcoming km^3 detectors.

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[a]We refer the reader to Ref.[14] for the adopted approximation for σ.

4 Discussion

Neutrino emission offers a promising way to further our understanding of gamma-ray bursters. Neutrinos carry information that is complementary to electromagnetic emission because they can escape from optically thick regions and because they predominantly trace the hadronic component of GRB sources. This offers a unique way to constrain the nature of the relativistic outflow associated with GRBs. However, due to their feeble interactions in detectors at Earth, it remains a challenging task to identify concrete realizations of this potential.

Here we have discussed neutrino production in inelastic neutron-proton collisions that occur when neutrons have decoupled from the outflow associated with GRBs. We have estimated the characteristic neutrino flux within the widely used fireball model and the more recently introduced AC model. The characteristic neutrino fluxes and energies are distinctively different for the two models, directly reflecting the dynamics and hence the nature of the flow. Unfortunately, the relatively low neutrino energy precludes any realistic detection prospects with the upcoming km^3 detectors such as IceCube.

Apart from neutrino production through charged pion decay, one also expects the production of gamma rays through the decay of neutral pions produced in np interactions. The plasma is optically thick to these gamma rays, and hence they cannot directly leave the plasma. In fact, the energy that is injected in the flow through this mechanism is reprocessed (through synchrotron radiation, pair production, and Inverse Compton scattering) and emitted in a different energy band. The typical energy of this reprocessed emission is $\sim$10 GeV for the fireball model and $\sim$100 keV for the AC model, and the expected fluence is detectable up to large redshifts with the GLAST satellite.[14] Detection of this emission would favor the fireball model, and constrain the baryon loading of the flow.

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