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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Neutrino radiation from supernovae

J.A. Grifols

Grup de Física Teòrica, Universitat Autónoma de Barcelona, 08193 Bellaterra, Spain

In a supernova event about 10^{53} erg of gravitational binding energy are released, the bulk of which is carried off by neutrinos. The neutrino burst detected in February 1987 recorded a supernova explosion that took place in the Large Magellanic Cloud some 50 kpc away from the earth and confirmed the basics of models of stellar collapse. Indeed, the neutrino luminosity inferred from observation agrees with the luminosity predicted by detailed model calculations of neutrino transport. However, there is some room (within the uncertainties of both theory and observation) for extra exotic sources of energy drain. Among them, there are right-handed neutrinos, which appear in almost any extension of the minimal standard model of electroweak interactions. In particular, if neutrinos are massive Dirac particles, the right-handed degrees of freedom should be copiously emitted in a supernova collapse. Using SN1987A data one can place bounds on neutrino masses or on the magnetic moment of the neutrino. Furthermore, independently of the energetics of stellar dynamics, the actual detection of neutrinos at IMB and Kamioka has led to relevant limits on neutrino mass, neutrino lifetime, and neutrino charge.

1. Gravitational collapse: energy loss via neutrinos

Supernova 1987A was a type II supernova, i.e. a 15–20 $M_\odot$ star collapses and ejects most of its mass leaving a neutron star behind. In the final stage of its life, when nuclear fuels are exhausted, with silicon having transformed into iron, the nuclear reactions stop and the Fermi pressure of the electrons can no longer stand the gravitational pressure and the Fe–Ni core collapses.

The neutronization process $e + p \to n + \nu$ is an important trigger for the collapse (the electron Fermi pressure suddenly decreasing). Photodissociation of iron, $^{56}Fe \to 13\alpha + 4n$, which is an endothermic reaction, is the other. Independently of the details of stellar evolution dynamics and collapse, the gravitational binding energy

$$E_B \approx GM^2/R \approx 3\times 10^{53} \quad \text{erg} \tag{1}$$

must have been released [1] to form a neutron star.

The total luminosity in electromagnetic radiation plus kinetic energy in a supernova explosion is less than 10^{51} erg. Emission in gravitational radiation is, at most, 1%. The bulk of the binding energy ($\geq 99\%$) is in form of neutrinos. In the neutronization burst 10^{52} erg of energy are emitted (i.e. less than 10% of the total energy) which is emitted essentially in form of thermal neutrinos. Two physically distinct time scales govern the process of energy radiation. The first is the hydrodynamical collapse scale: this is almost the free-fall time $(G\rho)^{-1/2}$ which is of the order of milliseconds; the initial ν_e burst corresponds to this time scale. The second scale is the diffusion scale of the thermal neutrinos. As the temperature and density of the inner core increase, more neutrinos are being produced via e^+e^- annihilations and via bremsstrahlung in the nucleon–nucleon collisions. These neutrinos are trapped in the core (where the density exceeds 2×10^{11} g/cm^3) and diffuse in a random walk through the very opaque material. After suffering very many scatterings they reach the neutrino sphere from where they are black-body-radiated. The diffusion time is $\tau_{diff} \approx R^2/\lambda^2$, where λ is the mean free path of a typical neutrino. This time is of the order of seconds and is therefore several orders of magnitude slower than for hydrodynamical collapse.

The mean free path is given by $\lambda = 1/\sigma n$ where σ is the cross section for neutrino scattering of matter and n is the number density of the scatterers. The relevant cross sections for the neutrino energies involved are quadratic in the neutrino energy. To compute the neutrino sphere we shall define a properly energy-averaged mean free path. In the diffusion regime – for the neutrinos trapped in the core – the radiative transfer problem can be formulated in terms of a "heat equation" (assuming local thermal equilibrium)

$$F_\nu(r) = -\frac{7\pi^2}{180}\bar{\lambda}_\nu T^3 \frac{\partial T}{\partial r} \tag{2}$$

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for the neutrino energy flux F_ν. The star has been assumed spherically symmetric and the mean free path $\bar{\lambda}_\nu$ is defined as

$$\bar{\lambda}_\nu = \frac{\int \mathrm{d}E(\sigma n)^{-1}E^4\frac{\mathrm{e}^{E/T}}{(1+\mathrm{e}^{E/T})^2}}{\int \mathrm{d}E\, E^4\frac{\mathrm{e}^{E/T}}{(1+\mathrm{e}^{E/T})^2}}. \qquad (3)$$

This approach goes under the name of Rosseland approximation [2]. Given a temperature profile $T(r)$ and a density profile $\rho(r)$ for the stellar core, and given the microscopic neutrino cross sections one obtains $\bar{\lambda}_\nu(r)$. The neutrino sphere, R_ν, is obtained then by requiring that the optical depth

$$\tau(r) = \int_r^\infty \frac{\mathrm{d}r}{\lambda} \qquad (4)$$

be $\tau(r=R_\nu)=\frac{2}{3}$, i.e., from the neutrino sphere onwards the "physical" neutrino path coincides with the geometrical path. We choose the simple model by Turner [3],

$$T(r) = \begin{cases} 15\ \mathrm{MeV}\ c_1\rho_{14}^{2/3} & \text{for} \quad \rho_{14} \geq 2, \\ 20\ \mathrm{MeV}\ c_1\rho_{14}^{1/3} & \text{for} \quad \rho_{14} < 2, \end{cases} \qquad (5)$$

for the core temperature, where $\rho_{14}=(r/1.5\times10^6\ \mathrm{cm})^{-7}$ for the core density in units of 10^{14} g/cm^3. c_1 is a parameter that takes into account uncertainties in the core adiabat. The neutrino cross section on nucleons is

$$\sigma(\nu_\mu N) = \tfrac{1}{4}\sigma_0(E_\nu/m_e)^2, \qquad (6)$$

with $\sigma_0 = 1.76\times10^{-44}$ cm^2. We restrict the discussion to ν_μ for simplicity. Detailed model calculations of neutrino transport indicate an approximate equipartition among neutrino species as far as energy flux is concerned [4]. With this input we obtain $R_\nu \simeq 29$ km for the neutrino sphere.

The total luminosity including three generations of neutrinos and their antineutrinos is,

$$L_{\mathrm{TOT}} = \frac{7\pi^3}{40}T_\nu^4R_\nu^2 \simeq 9\times10^{52}\quad \mathrm{erg/s} \qquad (7)$$

in agreement with the luminosity inferred from IMB and Kamiokande data [5].

2. Massive neutrinos

Almost any modification or extension of the standard model (SM) includes the existence of new particle degrees of freedom. In particular, Dirac neutrinos with nonzero mass [6] require right-handed (RH) neutrino fields to exist. Actually we know of no theoretical reason (e.g. a symmetry principle) that forbids a neutrino to be massive. In this respect, a particle physics model that contains RH neutrinos is far more natural than the strict SM with only left-handed (LH) neutrinos. In the context of supernova physics, the existence of light particles not present in the SM allows for additional sources of energy drain.

The theory of gravitational collapse implies $E_B \leq 4\times10^{53}$ erg. Observational data [5] tells us that $E_\nu \geq 2\times10^{53}$ erg emitted over a diffusion time 1–10 s. Therefore, the exotic luminosity output is bounded above by

$$L_{\mathrm{exotic}} \leq 2\times10^{53}\quad \mathrm{erg/s}. \qquad (8)$$

Actually, in the emission of light particles one should distinguish two physically different regimes: diffusion and free streaming. If the mean free path of the particles is much less than the size of the core, then the particles diffuse through matter (e.g. ordinary SM LH neutrinos). If their mean free path is larger then the size of the core, then the particles escape freely without further rescattering once produced.

RH neutrinos should be produced in the hot supernova core via an helicity-flip mechanism. RH neutrinos in the free-streaming regime immediately leave the star. Otherwise they rescatter in matter. It is the amount of spin flip which determines what happens and this is governed by the neutrino mass. Hence, the mass of the neutrino directly influences the cooling of the supernovae. The relevant spin flip processes are

$$\nu_\mathrm{L}\mathrm{N}\to\nu_\mathrm{R}\mathrm{N},\quad \mathrm{NN}\to\mathrm{NN}\nu_\mathrm{L}\nu_\mathrm{R}\quad \text{and}\quad \mathrm{e}^+\mathrm{e}^-\to\nu_\mathrm{L}\nu_\mathrm{R}.$$

In all these processes the weak neutral current mediated by virtual Z^0-boson exchange is operative. The first two processes are dominant and we shall not consider $\mathrm{e}^+\mathrm{e}^-$ annihilation any further. Since LH neutrinos are trapped and in thermal equilibrium ($\tau_{\mathrm{diff}} \gg \tau_{\mathrm{weak}}$) we can compute the luminosity associated with the $\nu_\mathrm{L}(k_1)\mathrm{N}(\mathrm{p}_1)\to\nu_\mathrm{R}(k_2)\mathrm{N}(\mathrm{p}_2)$ process as

$$L_{\nu_\mathrm{R}} = \mathrm{vol}\times2\int\prod^2\frac{\mathrm{d}^3p_i}{(2\pi)^32E_i}\prod^2\frac{\mathrm{d}^3k_j}{(2\pi)^{32}E_j} \times|M|^2f_1g_1\delta^4(P_i-P_f)E_2 \qquad (9)$$

where M is the quantum-mechanical amplitude for the process, $f_1=[\mathrm{e}^{(\epsilon_1-\mu)/T}+1]^{-1}$, $g_1=[\mathrm{e}^{(E_1-\mu_\nu)/T}+1]^{-1}$ and E_2 is the energy of the RH neutrino. The parameters we use for the central inner core are: $T=60$ MeV, $R=10$ km, and $\rho=8\times10^{14}$ g/cm^3. In the nondegenerate and nonrelativistic limit the result, in the case where the target is a neutron, is

$$L_{\nu_\mathrm{R}} = \frac{4}{3}\pi R^3\frac{G_\mathrm{F}^2}{4\pi^3}m_\nu^2(C_\mathrm{v}^2+3C_\mathrm{a}^2)\frac{X_\mathrm{n}\rho}{m}T^4F(\mu/T) \qquad (10)$$

with

$$F(y)=\int_0^\infty dx\frac{x^3}{e^{x-y}+1}.$$

X_n is the neutron mass fraction and $C_{v,a}$ are the corresponding weak neutral current couplings for the neutron. Adding the corresponding luminosity for proton case and imposing $L_{\nu_R}\leq 2\times 10^{53}$ erg/s we get the upper bound $m_\nu \leq 14$ keV. In much the same way the second process $NN\to NN\nu_L\nu_R$ can be evaluated and one gets

$$L_{\nu_R}(nn)=\frac{4}{3}\pi R^3\frac{2^2}{105\pi^{5.5}}m_\nu^2G_F^2g_A^2 \times(X_n\rho)^2\left(\frac{m}{m_\pi}\right)^4\frac{T^{3.5}}{m^{4.5}}, \tag{11}$$

$$L_{\nu_R}(np)=\frac{4}{3}\pi R^3\frac{2^4}{35\pi^{5.5}}m_\nu^2G_F^2g_A^2 \times\left(X_nX_p\rho^2\right)\left(\frac{m}{m_\pi}\right)^4\frac{T^{3.5}}{m^{4.5}}, \tag{12}$$

in the nondegenerate, nonrelativistic approximation. The corresponding bound is $m_\nu \leq 46$ keV. One can check a posteriori that indeed the RH neutrinos stream out freely from the star since

$$\lambda_{\text{core}}=\frac{1}{n_N\sigma}=8\times 10^2\ \text{km}\left(\frac{50\ \text{keV}}{m_\nu}\right)^2,$$

where n_N is the density of nucleon targets and σ is the cross section for $\nu_R N\to\nu_L N$ (the main source of opacity).

Now, it is obvious that by increasing m_ν sufficiently we shall reach a diffusion regime and, should be m_ν large enough, the time it takes for the RH neutrinos to diffuse will be long enough such that the luminosity is again below the 2×10^{53} erg/s limit. This lower limit can be calculated by using the Rosseland mean and by subsequently computing the thermal RH neutrino emission exactly as was done for ordinary neutrinos. This procedure renders $m_\nu \geq 34$ MeV. Present laboratory limits for the neutrino mass are $m_{\nu_e}\leq 9.4$ eV, $m_{\nu_\mu}\leq 250$ keV, $m_{\nu_\tau}\leq 35$ MeV. So we conclude, $m_{\nu_\tau}\leq$ 14 keV or $m_{\nu_\tau}\geq 34$ MeV and $m_{\nu_\mu}\leq 14$ keV.

These numbers have a factor 2–3 uncertainty in either direction so that a fair and safe statement should be

$$m_{\nu_\mu,\nu_\tau}\leq 40\ \text{keV} \quad\text{or}\quad m_{\nu_\tau}\geq 10\ \text{MeV}.$$

The uncertainty is associated with the parameters of the supernova. Indeed, the temperature of the inner core varies from 30 to 100 MeV in present model estimates. This uncertainty is correlated with our ignorance of the exact equation of state at super-nuclear densities and reflects an uncertainty in the density by roughly a factor of 2.

3. Neutrino static properties

A massive Dirac neutrino would possess a magnetic moment

$$\langle\nu\,|\,J^\rho\,|\,\nu\rangle_{\text{m.d.m}}=\frac{\mu e}{2m}\sigma^{\rho\lambda}q_\lambda\bar{\nu}_L\nu_R+hc.$$

Only the upper limits for μ are known. The laboratory bounds are obtained from neutrino electron scattering data and are [7], $\mu_{\nu_\mu}\leq 10^{-9}\mu_B$ and $\mu_{\nu_e}\leq 1.1\times 10^{-9}\mu_B$ with $\mu_B=e/2m$, the Bohr magneton.

Better limits can be derived from SN1987A. They are obtained by similar arguments as those given earlier. Indeed, RH neutrinos produced by magnetic transitions $\nu_L\to\nu_R$ in the core of the collapsing star and escaping freely afterwards would carry off too large a fraction of the energy generated in the stellar collapse. These RH neutrinos would remain undetected. The bound thus obtained is [8] $\mu_\nu\leq 2\times 10^{-12}\mu_B$ for any neutrino species.

Neutrinos are electrically neutral. Their neutrality is experimentally sustained to a very high degree of accuracy. In fact, $|q_{\nu_e}|\leq 8\times 10^{-20}e$, where e is the electric charge of the positron. This limit follows from the assumption of charge conservation in neutron β-decay, $n\to p+e^-+\bar{\nu}_e$ combined with the bound $q_n\leq(-1.5\pm 2.2)\times 10^{-20}e$ obtained by studying the deflection of a neutron beam by a strong electric field and combined with the bound $|q_p+q_e+q_n|\leq(0.8\pm 0.8)\times 10^{-21}e$ that was reached in an experiment with levitating steel balls. (This is a Millikan-type experiment where gravity is counterbalanced by a magnetic force exerted on the balls and where their stability is challenged by an electric field applied in the transverse direction.)

A direct limit on the electric charge of the neutrino can be derived from the supernova 1987 event. Neutrinos emitted in a stellar collapse, when crossing the intergalactic and galactic magnetic fields would see their trajectories lengthened, should they be charged. As a consequence their bunching in time would spread beyond what was observed at the terrestrial detectors, if their charge exceeds [9] $|q_\nu|\leq 2\times 10^{-17}e$.

This number is easily obtained from the curvature of trajectories in a magnetic field B,

$$r=\frac{E(\text{GeV})}{0.3B(\text{T})q_\nu},$$

and the implied time stretching

$$\frac{\delta t}{t}=\frac{1}{12}\frac{(0.3Blq_\nu)}{E^2}\frac{\delta E}{E},$$

where l is the distance to the Large Magellanic Cloud and E is the energy of the neutrino. Using as typical numbers

$$\delta t \leq 5\text{s}, \quad l = 50 \text{ kpc},$$
$$E \sim 15 \text{ MeV}, \quad B \sim 1 \ \mu\text{G (galactic field)},$$
$$\frac{\delta E}{E} \sim \frac{1}{2},$$

one gets the limit on q_ν given above.

Other neutrino properties (such as charge radius, lepton number, lifetime,...) can be scrutinized using similar techniques and we refer the interested reader to the existing literature [10].

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