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The KARMEN anomaly, light neutralinos and type-II supernovae

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Abstract: The KARMEN experiment observes a time anomaly in events induced by pion decay at rest. This anomaly can be ascribed to the production of a new weakly interacting particle X with mass $m_X \approx 34\,\mathrm{MeV}$. We show that a recently proposed identification of the X particle with the lightest neutralino χ in the frame work of the MSSM with broken R parity is in contradiction to optical observations of type-II supernovae.

Keywords: Neutrino and Gamma Astronomy, Related Astrophysics (Neutron Stars, Supernovae etc.), Rare Decays, Supersymmetric Effective Theories.

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Contents

1. Introduction

The experiment KARMEN has investigated a variety of neutral and charged current neutrino interactions finding excellent agreement between measured cross-sections and the predictions of the standard model. However, the analysis of the time distribution of events induced by neutrinos from π^+ and μ^+ decays at rest has revealed an anomaly: the measured distribution for subsequent events differs substantially from the expected exponential distribution with a time constant equal to the muon lifetime of $2.2\,\mu$s [1]. As a possible explanation for this anomaly, the KARMEN collaboration proposed that their signal is a superposition of a gaussian distribution centered at $3.4\,\mu$s and the exponential distribution describing muon decay. The gaussian distribution is interpreted as time-of-flight signature of a hypothetical particle X produced at the spallation target, passing through 7 m steel shielding and then decaying in the detector. A maximum likelihood analysis of this hypothesis showed that the probability that the gaussian signal is a statistical fluctuation is only 10^{-4}. The best-fit values for the mass of the particle X are $m_X \approx 33.9\,\mathrm{MeV}$, while the branching ratio $\mathrm{BR}(\pi^+ \to \mu^+ + X)$ and the decay rate Γ_{vis} of X into photons and electrons have to fulfill the relation $\mathrm{BR}(\pi^+ \to \mu^+ + X)\Gamma_{\mathrm{vis}} \approx 3 \cdot 10^{-11}\,\mathrm{s}^{-1}$. Furthermore, the KARMEN data disfavor two-body decays of the X particles, because no peak at 17 MeV has been seen in the energy spectra of the anomalous events.

There have been several theoretical works discussing candidates for the new particle X [2, 3, 4, 5]. Proposed candidates are an active or sterile neutrino [2], a scalar boson [3] and a light neutralino [4, 5]. While an active neutrino seems to be excluded by the new experimental limit for $\mathrm{BR}(\pi^+ \to \mu^+ + X)$, a sterile neutrino was found to be, within stringent limits on its mixing parameters, a viable candidate for the X particle. In ref. [3], a scalar boson with mass ≈ 104 MeV was proposed as

X particle. Since the energy deposited by the decaying X particle in the calorimeter of the KARMEN experiment is only between 11 and 35 MeV, additional light scalars have to be invoked to dilute the energy via cascade decays. Although the model seems to be compatible with laboratory constraints, it looks somewhat artificial. In ref. [4], the X particle was identified with the lightest neutralino χ in a supersymmetric model with broken R parity. However, the proposed decay mode of the neutralino was a two-body decay, $\chi \to \gamma + \nu_\mu$, and is therefore now disfavored by the KARMEN data. Recently, the authors of ref. [5] reconsidered this proposal. They introduced two R parity violating operators instead of one, explaining the anomalous pion decay by $L_2 Q_1 D_1^c$ and the neutralino decay $\chi \to e^+ e^- \nu_{\mu,\tau}$ by $L_e L_\mu E_e^c$ or $L_e L_\tau E_e^c$. They found that this scenario is consistent with accelerator bounds provided that the neutralino is dominantly a bino and has a lifetime $\tau_\chi = 0.24 - 100\,\mathrm{s}$. Moreover, they showed that regions exist in the MSSM parameter space which allow such a bino without excessive fine-tuning. The same conclusion was obtained already earlier in ref. [6].

The possibility that KARMEN has observed already over several years a supersymmetric particle is intriguing. In particular, the scenario of ref. [5] with its rather constrained parameter space would have impact on searches for supersymmetry at accelerators as well as on searches for dark matter. It is therefore of interest to check this model against all possible constraints. In this brief note, we discuss the influence of neutralino emission on core collaps supernovae (SN). We find that the production of neutralinos with $m_\chi \approx 34\,\mathrm{MeV}$ is practically not suppressed in the SN core. The energy deposited in the SN envelope by decaying neutralinos is for all allowed squark masses larger than the value allowed by observations of the light curves of type-II supernovae.[1] We conclude that a light neutralino with lifetime $\tau_\chi = 0.24 - 100\,\mathrm{s}$ is in contradiction to observations.

2. Neutralino production

In the SN core, neutralinos are mainly produced in nucleon-nucleon bremsstrahlung $NN \to NN\chi\chi$ and in e^+e^- annihilations. The spin-averaged squared matrix element of the latter process is for a bino-like neutralino, degenerated selectron masses $M_{\tilde{e}}$ and $m_e = 0$ [8]

$$|\bar{M}|^2 = \frac{g'^4}{2}(Y_L^4 + Y_R^4) \left\{ \left(\frac{t - M_\chi^2}{t - M_{\tilde{e}}^2}\right)^2 + \left(\frac{u - M_\chi^2}{u - M_{\tilde{e}}^2}\right)^2 - \frac{2sM_\chi^2}{(t - M_{\tilde{e}}^2)(u - M_{\tilde{e}}^2)} \right\}. \quad (2.1)$$

Neglecting the Pauli-blocking factors of the neutralinos, the cross-section times the relative velocity is

$$v\sigma = \frac{1}{(2\pi)^2} \frac{1}{8EE'} \int \frac{d^3k}{2\omega} \frac{d^3k'}{2\omega'} |\bar{M}|^2 \, \delta^{(4)}(p + p' - k - k'), \quad (2.2)$$

[1] This argument was first used by S.W. Falk and D.N. Schramm in ref. [7] to restrict radiative decays of neutrinos.

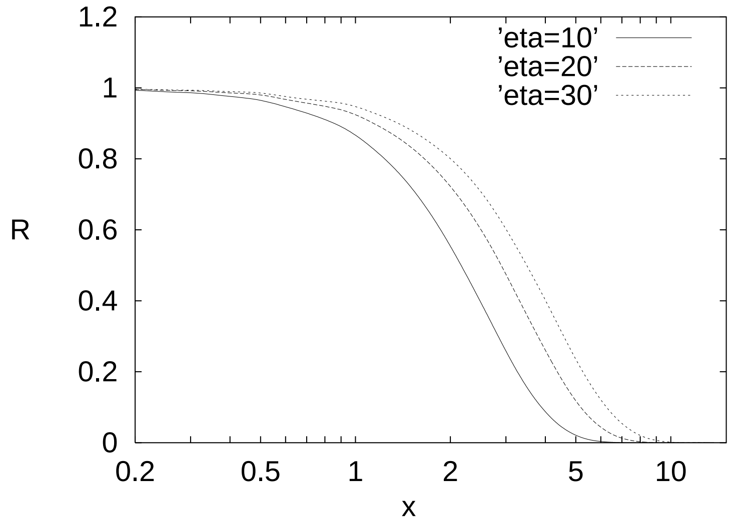

Figure 1: The ratio $R = \varepsilon(x)/\varepsilon(0)$ as function of $x = m_\chi/T$ for $\eta = 10, 20$ and 30.

where $p = (E, \vec{p})$, $p' = (E', \vec{p}')$ are the four-momenta of the electron and positron and $k = (\omega, \vec{k})$, $k' = (\omega', \vec{k}')$ of the neutralinos, respectively. The emissivity $\varepsilon(e^+e^- \to \chi\chi)$ follows as

$$\varepsilon(e^+e^- \to \chi\chi) = \frac{1}{2\pi^4} \int dp dp' d\vartheta \sin\vartheta \, \frac{p^2}{e^{(E-\mu)/T}+1} \, \frac{p'^2}{e^{(E'+\mu)/T}+1} \, (E+E') \, v\sigma \,, \quad (2.3)$$

where T is the temperature and μ the chemical potential of the positron-electron plasma. The integration over the angle $\vartheta = \angle(\vec{p}, \vec{p}')$ can be performed analytically, but results in lengthy expressions. Therefore, we have preferred to evaluate directly eq. (2.3). In figure 1, we show the ratio $R = \varepsilon(x)/\varepsilon(0)$ as function of $x = m_\chi/T$ for different values of the degeneracy parameter $\eta = \mu/T$. Typical values found in simulations for the temperature and the electron degeneracy inside the SN core are $T = 10 - 40\,\mathrm{MeV}$ and $\eta = 10 - 30$ [9]. For an average temperature of $T = 20\,\mathrm{MeV}$, i.e. $x = 1.7$, the neutralino production is even for the low value $\eta = 10$ only reduced by 40%. A significant suppression of the neutralino production requires $x \gtrsim 10$, i.e. temperatures well below those believed to exist in SN cores.

It is natural to assume that the bremsstrahlung process $NN \to NN\chi\chi$ is suppressed roughly by the same factor $f \sim 0.5$. This assumption allows us to obtain the emissivity simply from the one for the related processes with neutrinos [10], e.g.,

$$\frac{\varepsilon(nn \to nn\chi\chi)}{\varepsilon(nn \to nn\nu\bar{\nu})} \approx f \, \frac{16 m_W^4 \tan^4\vartheta_W}{M_{\tilde{q}}^4} \left(\frac{\sum_{i=u,d,s} (Y_{L,i}^2 + Y_{R,i}^2) \Delta q_i}{\Delta u - \Delta d - \Delta s} \right)^2 , \quad (2.4)$$

where Δq_i denotes the spin fraction carried by the quark i. Using for $\varepsilon(NN \to NN\nu\bar{\nu})$ the expression given in ref. [11] for non-degenerate nucleons and the spin fractions of ref. [12], the total energy E_χ emitted into neutralinos from the SN in the free-streaming regime is given by

$$E_\chi \approx 2.7 \cdot 10^{22} \, \frac{\mathrm{erg}}{\mathrm{g\,s}} \, f \left(\frac{250\mathrm{GeV}}{M_{\tilde{q}}}\right)^4 \left(\frac{T}{25\mathrm{MeV}}\right)^{5.5} \frac{\rho}{2\rho_0} \, \tau_{\mathrm{burst}} \, M_{\mathrm{core}} \,. \tag{2.5}$$

With $f = 0.5$, $T = 25\,\mathrm{MeV}$, $\rho = 2\rho_0 \approx 6 \cdot 10^{14}\,\mathrm{g/cm}^3$, a duration of the neutrino and neutralino burst of $\tau_{\mathrm{burst}} = 10\,\mathrm{s}$ and $M_{\mathrm{core}} = 1.5 M_\odot$, we find $E_\chi = 4.0 \cdot 10^{56} \mathrm{erg}(250\,\mathrm{GeV}/M_{\tilde{q}})^4$ in the free-streaming regime.

3. Energy deposition in the SN envelope

An emitted neutralino with lifetime τ_χ has the probability $P \approx 1 - \exp(-R/\tau_\chi \gamma)$ to decay inside the SN progenitor with radius R, where $\gamma = E_\chi/m_\chi$. We will use conservatively as radius for the progenitor stars of type-II supernovae the value $R \approx 1000$ s [13]. Thus for all allowed lifetimes $\tau_\chi = 0.24 - 100\,\mathrm{s}$ a large fraction of the neutralinos decays inside the envelope, depositing its energy there during the first 10 s after core collapse. There are several possibilities how this energy deposition can be used to restrict or exclude a light, decaying neutralino. First, the electromagnetic displaying of the SN which is expected to start 3 hours after the neutrino burst, when the shock wave reaches the photosphere, should start much earlier. Second, model calculation for SN1987A find that the total energy of the shock is $E_{\mathrm{sh}} \approx 3 \cdot 10^{51}$ erg. This number can be used as upper limit for the energy E_{en} released by the neutralinos in the envelope.

Assuming that the neutrino carries away one third of the energy, neutralinos deposit the energy $E_{\mathrm{en}} = \frac{2}{3} E_\chi P$ in the SN envelope. With $P > 0.63$, we can exclude those parts of the parameter space of the model [5] which give rise to $E_\chi \gtrsim 7 \cdot 10^{51}$ erg. Thus, squark masses smaller than $\approx 4\,\mathrm{TeV}$ are excluded in the free-streaming regime.

For very light squarks, nucleon-neutralino interactions become strong enough so that neutralinos are efficiently trapped and E_χ falls below $7 \cdot 10^{51}$ erg. The results of ref. [10] suggest, that this possibility is already excluded by direct accelerator searches. Nevertheless, we will reconsider below the trapping regime for a bino like neutralino.

4. Neutralino opacity

In the calculation of the free-mean path of the neutralino in the SN core, we should take into account the thermal distribution functions of the electrons and nucleons, respectively. A detailed calculation performed in ref. [15] for massless photinos showed that the thermal cross-section of $\chi e^- \to \chi e^-$ can be rather well approximated by the vacuum one. Moreover, the thermal effects can be factored out in neutralino-nucleon scattering, when recoil effects are neglected.

If selectrons are not considerable lighter than the lightest squarks, the dominant opacity source for neutralinos is scattering on nucleons. We estimate the free-mean path l_χ of the neutralino as

$$l_\chi^{-1}(\chi p) \approx 4.2 \cdot 10^{-6}\mathrm{cm}^{-1} \left(\frac{250\,\mathrm{GeV}}{M_{\tilde q}}\right)^4 \frac{(1-Y_n)\rho}{2\rho_0}\,, \tag{4.1}$$

$$l_\chi^{-1}(\chi n) \approx 1.0 \cdot 10^{-6}\mathrm{cm}^{-1} \left(\frac{250\,\mathrm{GeV}}{M_{\tilde q}}\right)^4 \frac{Y_n\,\rho}{2\rho_0}\,, \tag{4.2}$$

where we used as average energy of the neutralino $E_\chi \approx 3T \approx 75\,\mathrm{MeV}$ and a thermal suppression factor 0.7 (cf. [15]). Requiring $l_\chi^{-1}R = 10$ as trapping criteria with $\rho = 2\rho_0$, $Y_n = 0.8$, and $R = 10\,\mathrm{km}$ as size of the core, we find $M_{\tilde q} \approx 160\,\mathrm{GeV}$ as borderline between the diffusion and the free-streaming regime.

In the diffusion regime, we estimate the neutralino luminosity $\mathcal{L}_\chi$ assuming black-body surface emission, $\mathcal{L}_\chi = (\pi^3/15)\,R_\chi^2 T_\chi^4$, from a χ-sphere with radius R_χ. The position of this sphere is calculated from the optical depth τ, $\tau = \int_{R_\chi}^\infty dr\, l_\chi^{-1}(r) = 2/3$, where we use as density profile $\rho(r) = \rho_R(R/r)^n$, as temperature profile $T(r) = T_R(\rho(r)/\rho_R)^{1/3}$ and $Y_n = 0.5$ [11]. We choose density and temperature at the edge of the core as $T_R = 10\,\mathrm{MeV}$ and $\rho_R = 10^{14}\mathrm{g/cm}^3$, respectively. The exponent n of the profiles is rather model dependent, $n \sim 3-7$. Using the scaling relation

$$L_\chi(r) = L_\chi(R)\left(\frac{R}{r}\right)^{4n/3-2} \tag{4.3}$$

and $n = 5$, the neutralino luminosity is small enough for $R_\chi \gtrsim 2.8R$. This is consistent with $\tau(R_\chi) = 2/3$ only if the squark masses would be below 20 GeV.

5. Summary

The production of neutralinos with the mass $m_\chi \approx 34\,\mathrm{MeV}$ is practically unsuppressed in a SN core. The upper bound on the sfermion masses in the model of ref. [5], $M_{\tilde f} \lesssim 1\,\mathrm{TeV}$, together with the lower limit $M_{\tilde f} \gtrsim 100\,\mathrm{GeV}$ from LEPII leaves no room for a decaying neutralino with the required lifetime $\tau_\chi = 0.24-100\,\mathrm{s}$: for all allowed values of $M_{\tilde f}$, the energy deposited in the SN envelope by decaying neutralinos is in contradiction to the optical observations of type-II supernovae.

Note added. The preprint `hep-ph/9912465` by I. Goldman, R. Mohapatra and S. Nussinov discusses also the consistency of a light, neutral, decaying fermion n^0 with SN1987A. Its discussion is model-independent, using however the assumption that the n^0-nucleon cross-section is at least a factor of 10 smaller than the neutrino-nucleon cross-section. This assumption does not hold necessarily in the case of the neutralino.

JHEP02(2000)010

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