Cosmological Relics of the High Energy Cold Dark Matter Particle in the Universe

Xue-Qian Li$^{1,3}$ and Zhijian Tao$^{1,2}$

1. China Center of Advanced Science and Technology, (World Laboratory)
   P.O.Box 8730 Beijing 100080, China.

2. Theory Division, Institute of High Energy Physics, Academia Sinica
   Beijing 100039, China

3. Department of Physics, Nankai University, Tianjin, 300071, China.

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Abstract

We demonstrate that if the universe is dominated by the massive cold dark matter, then besides the generally believed thermal distribution of the dark matter relics, there may exist some very energetic non-thermal relics of the dark matter particles in the universe from some unknown sources, such as from decay of supermassive X particle released from topological defect collapse or annihilation. Very interesting, we point out that these high energy dark matter particles may be observable in the current and future cosmic ray experiments.
There is a great deal of evidence to indicate that the dominant component of the universe matter density is dark matter. The most direct evidence for existence of dark matter is from the astronomical observation of velocities of the spiral galaxies [1]. In our own galaxy, for example, in order to explain the observation, a local dark matter density $\rho_{DM} = 0.3\text{GeV/cm}^3$ is determined [2]. In addition, the inflation theory predicts a flat universe, i.e. $\Omega = 1$. The standard big-bang nucleosynthesis implies that the ordinary matter can contribute at most 15 percent of the critical density. It means that 90 percent of the matter in our universe may be dark [3]. The most attractive candidate of the dark matter is from the particle physics. One of them is the weakly-interacting massive particle (WIMP). The WIMP serves as a natural cold dark matter candidate to the universe, since if the WIMP is at a weak-scale mass it naturally provides a near closure density to the present universe as required by the inflation theory. In the present universe the WIMP dark matter particle is statically distributed. Its density is controlled by the Boltzman equation and the evolution of the universe, so it is called thermal relic abundance. So far experimental effort to search for the cold dark matter is made to find the signals of this distribution. The most promising experiments involve the direct detection at low background detectors, which look for the signal of dark matter particle as it collides with detector matter, and the indirect detection through observation of energetic neutrinos emerging from annihilation of cold dark matter particles which are accumulated in the Sun and the Earth [1]. Having not seen any signal in these experiments the parameter space of the WIMP models is seriously restricted. However to discover the WIMP dark matter particles or rule out the WIMP models much more efforts are needed, hopefully the next generation detectors will cover much larger parameter space of the WIMP models.

Instead, in this letter we discuss another possibility to search for cold dark matter. We start from a question, whether there exists a significant flux of very energetic cold
dark matter particle in the universe. Since the thermal relics of cold dark matter are statically distributed in the universe, we are actually studying some non-thermal relics. It is believed that if heavy particles are produced at a temperature of the universe which is not much lower than the mass scale of the particle, the number of the high energy relics would reduce very fast due to thermalization processes and the expansion of the universe. As a result at present time there would be no heavy particles with high energies. However, there indeed is a possibility of existence of non-thermal relics at present universe. Its reason is not well understood, but they may wander around at present time. For example, at a later stage of the universe evolution when its temperature is sufficiently low, some topological defects, such as monopoles, cosmic strings are decoupled from the thermal bath of the universe. Later the superheavy fields, which form the defects, decay into some heavy particles. Since the parents are out of thermal equilibrium, the products are also non-thermally distributed over the space. That could serve as a new source for such non-thermal relics in our universe. Quite similar to the fact that there exists large flux of high energy cosmic ray components of nucleon and other stable particles of the standard model, it is natural to expect an existence of energetic cold dark matter particle in the cosmic rays as the dark matter particles dominate the universe density. The question is how much this kind of energetic dark matter particles remain in our universe. If the amount of the particles are very small, it is not interesting at all to study the potential of search for them. By a general and reasonable analysis we are suggesting there may exist a large amount of this kind of particles in the universe. Since the WIMP is electrically neutral and heavy, so the ordinary accelerating mechanisms for nucleon and neutrino in the cosmic rays cannot work for WIMP’s. Two mechanisms for generating energetic cold dark matter particles in the universe are considered below. One is through the collision of cosmic ray particles and statically distributed dark matter particles. Since the energy of the cosmic ray ranges from
low to very high, the collision will result in some high energy cold dark matter particle fluxes. Another one is that high energy cold dark matter particles can also originate from the very early universe. Some examples are the decays of superheavy X particle released from destruction of topological defects formed during phase transition in the very high energy scale, like the grand unification scale. Recently some decays of the superheavy X particles with mass close to the grand unification scale released from topological defect to standard model light particles have been interpreted as a new mechanism to explain the observed extremely high energy cosmic rays, though it seems that the simple version of the topological defect model is not able to fit all the observed cosmic ray spectrum [4, 5]. Similarly, the very massive X particle may also decay to cold dark matter particles resulting in the energetic particles in the universe. By considering these two sources we derive an evolution equation for the flux of the energetic cold dark matter in the universe. We assume an equilibrium solution to the equation, then we find that the flux of the high energy WIMP’s is sizable, therefore it should be detectable in some future large detectors. We stress that our scenario can also provide a possible explanation for the exotic event observed in Yunnan Cosmic Ray Station (YCRS) [6, 7], if it is confirmed.

It is a very interesting question to derive the effective density or flux of the high energy neutral WIMP particle in the present universe. We denote $E$ as the kinetic energy of the WIMP. For the static distribution of the thermal relic WIMP’s, $E = 0$. Our task is to derive the density of WIMP’s with $E \neq 0$, say from GeV to much higher energy. We assume that there already exists a non thermal relic density of WIMP’s with nonzero kinetic energy $n(E)$. As we stated, this density may result from some early universe sources, like decays of X particle released from topological defect. In principle, the scattering between the WIMP’s (including both static thermal and high energy non-thermal relics) and the energetic cosmic protons can make a new equilibrium with the existing high energy density $n(E)$. 

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We denote the differential WIMP density in the energy region from $E_2$ to $E_2 + \Delta E_2$ as $\Delta n(E_2)$. The scattering cross section $\sigma(E_1, E_2, E'_1, E'_2)$ for a cosmic proton and WIMP into a WIMP plus other final state particles can be estimated, provided the model of WIMP interaction is given, here we just keep in mind this scattering is a weak interaction process. The equation for the distribution evolution of $n(E_2)$ is derived as the following

$$\frac{d\Delta n(E_2)}{dt} = -\int \frac{d\sigma(E_1, E_2, E'_1, E'_2)}{dE'_2} \frac{dF(E_1)}{dE_1} dE_1 \Delta n(E_2)(1 - \delta_{E_2 E'_2})$$

$$+ \int \frac{d\Delta \sigma(E_1, E''_2, E'_1, E_2)}{dE''_2} \frac{dF(E_1)}{dE_1} dE_1 n(E''_2)(1 - \delta_{E''_2 E_2})$$

(1)

where $E'_1, E'_2$ are the kinetic energies of the outgoing hadron and WIMP, $dF(E_1)/dE_1$ is the energy density of the charged cosmic ray particle flux and $\Delta \sigma(E_1, E''_2, E'_1, E_2) = \frac{d\sigma(E_1, E''_2, E'_1, E_2)}{dE''_2} \Delta E_2$. The first term on the left-hand side of the equation reduces $\Delta n(E_2)$ because a certain number of dark matter particles with energy from $E_2$ to $E_2 + \Delta E_2$ are stricken out of the energy range by cosmic ray collision. On the other hand some dark matter particles with energy outside the range are stricken into the range by the cosmic ray collision. So the second term increases $\Delta n(E_2)$. We notice that the incident cosmic ray flux should include all possible sources in cosmic rays, charged particles, cosmic photons, neutrino background and etc. However the cross section of the WIMP and the very low temperature photon or neutrino scattering is much suppressed, so the effect can be neglected here. For the same reason we also neglect the contribution of cosmic rays with energy much lower than 1 GeV. The flux of energetic charged cosmic ray particles is measured on the earth and it has the spectrum in the outer space as $F(\Lambda)(E_1/\Lambda)^{-2.7}$ while $0.4 \text{GeV} \leq E_1 \leq 10^6 \text{GeV}$, the parameter $\Lambda$, $F(\Lambda)$ and the spectrum form for higher energy can be found in reference [8]. For our purpose the most relevant energy range should not be much higher than the weak scale, since for very high energy scale both the cosmic ray flux and the initial
density $n(E_2)$ are too much suppressed (see below).

Obviously, after infinitely long evolution time, $d\Delta n(E_2)/dt = 0$ to reach an equilibrium. However for a finite life time of the universe as long as $10^{10}$ years, the equilibrium is not necessarily reached. Our investigation is divided into two steps. Here we first assume the equilibrium condition is satisfied. We will come back to this point later. Moreover since the dominant density of dark matter is the static thermal relics, as a very good approximation one may use $n(E''_2) = n(0)\delta_{E''_2}$ in the above equation so one has

$$\frac{\Delta n(E_2)}{\Delta E_2} = \frac{n(0) \int \frac{d\sigma(E_1,0,E'_1,E_2)}{dE_2} \frac{dF(E_1)}{dE_1} dE_1}{\int \sigma(E_1,E_2) \frac{dF(E_1)}{dE_1} dE_1},$$

(2)

where $n(0)$ is the local Galactic halo density contributed by the WIMP dark matter, and $\sigma(E_1,E_2)$ means that all possible final state energies have been integrated over.

So long as the equilibrium condition is satisfied, the equilibrium solution indicates that the differential spectrum of WIMP’s in our galaxy is proportional to the local halo density. And it is independent of the details of the mechanism of the early universe evolution. No matter what the mechanism it is, it only needs to provide certain large initial $n(E_2)$ for the evolution equation, so that the equilibrium condition can be satisfied.

Without using detail information of any WIMP models we can very roughly estimate the equilibrium differential density spectrum of WIMP’s with large kinetic energy. If $E_2$ is much smaller than $10^6$ GeV while larger than a certain value, say 1 GeV, simply by dimension analysis one estimates

$$\frac{dn(E_2)}{dE_2} \sim \frac{n(0)}{E_2} \frac{(1\text{GeV})}{E_2}^{2.7}.$$

(3)

this corresponds to a flux $j(E_2 \geq 10^2\text{GeV}) \sim 1\text{cm}^{-2}\text{s}^{-1}$. Though this flux is much smaller than the static dark matter flux across the Earth, which is about $10^5\text{cm}^{-2}\text{s}^{-1}$. This high energy WIMP flux may still cause some detectable signals in future large detectors, since it
is a high energy involved process. To calculate the capture rate in the high energy process, one needs to specify a concrete WIMP model. However since the capture process is typically a weak interaction process, by assuming a weak interaction cross section as $10^{-35} - 10^{-38}\text{cm}^2$, we can reasonably estimate a capture rate as $10^{-5} - 10^{-8}\text{s}^{-1}$ per ton of target. The expected events in one year are 100 and 0.1 respectively.

There could be many new signatures to distinguish the desired processes from other background processes. We mention one possible signature which is to produce a heavy charged particle when the neutral dark matter hitting on the matter surrounding or inside the detector. For instance in SUSY model, if neutralino is the dark matter particle, there exist some charged supersymmetric particles. The mass difference of the charged particle and the neutralino should be comparable with the mass of neutralino itself, so if the incident kinetic energy of the neutralino is larger than the mass difference, the charged supersymmetric particle could be produced. Because the charged particle is heavy and unstable, it decays to some light products afterwards. The kinematics and decay properties of the charged particles may provide some clues for the incident dark matter particles.

In 1972, in the cloudy chamber of the YCRS, an exotic event with a heavy charged particle being tracked was observed [6]. In fact, three charged prongs were recorded and they correspondingly possessed three-momenta as $p_a = 6.6_{-0.8}^{+10}\text{GeV/c}$, $p_b = 62\text{GeV/c}$ and $p_c = 110\text{GeV/c}$ with the spanned angles as $\theta_{ab} = 3^\circ 25', \theta_{bc} = 1^\circ 25' \text{and} \theta_{ac} = 4^\circ 55'$, namely they were coplanar trajectories. Later the tracks $a$ and $b$ were identified as $\pi^-$ and proton while $c$ remained unknown. A careful re-analysis which was done recently by Chen et al.[7] indicates that the unidentified positively charged particle has a heavy mass as

\[ M^+ > 43 \text{ GeV} \]

The authors of reference [7] have suggested that the unknown charged heavy particle may
be identified as a heavy elementary particle which was produced by a bombard of a heavy neutral particle coming from the universe on a proton. Obviously, in this case, the kinetic energy of the unknown neutral particles must be greater than the threshold $M^+ - M^0 + M_\pi$ where $M^0$ is the mass of the neutral particle. For so large momenta measured in the case, the neutral particle must be very energetic. If their postulation is valid, it would be a direct evidence for the existence of large flux of massive and high energy neutral particle in the cosmic ray, even though with a remarkable uncertainty. They also claimed to have found similar evidence at the data obtained by other experiments [7]. Numerically the flux should be around $10 \text{cm}^{-2}\text{s}^{-1}$ in order to explain the observed capture rate. The question was where the high energy neutral particle flux is from. We see that the high energy WIMP flux derived above can give the necessary amount of flux.

Now we come back to discuss the equilibrium condition which is assumed before. We notice that an initial condition must be satisfied, otherwise the equilibrium cannot be reached for the present age of our universe. The condition is that the initial density $n(E_2)$ with $E_2$ being greater than a certain value is large enough. If one assumes that the initial $n(E_2)$ is negligibly small, from the evolution equation we can roughly estimate the order of the magnitude of the density, which is many order of the magnitudes smaller than the equilibrium density we obtained above. It means that by the collision of the high energy cosmic ray and the static WIMP dark matter particle alone, the produced high energy WIMP density in the universe is negligible. Therefore we need a large initial condition for the evolution equation. This implies that some new sources for generation of such initial condition should exist. We have named some possibilities such as decay of X particle released from topological defect[4]. Here the question is if these new mechanisms are indeed able to produce large enough $n(E_2)$ in the early universe. Certainly we are not trying to investigate all the possibilities, but considering only the case of cosmic string collapse [9] and annihilation of
monopole-antimonopole pairs [10]. Following reference [5], the rate of release of massive particle X forming the topological defect from destruction of the defect can be expressed as

$$\frac{dn_X(t)}{dt} = k m_X t^{-3}$$

(4)

where $m_X$ is the mass of the X particle, $t$ is the Hubble time, and $k$ is a dimensionless constant which is restricted to be less than about 0.2 by the cosmic ray spectrum observation [5]. It corresponds to $p = 1$ in the equation (1) of reference [5]. Moreover, by assuming the massive particle X decay with a sizable branching ratio to stable WIMP particles, we can use the same formula of equation (5) in this reference for the differential particle flux $j(E_0)$. For the weak interaction feature of the WIMP we omit the energy loss effects when the particle propagates in the universe from some early time $t_i$ to the present time $t_0$, namely $dE_i/dE_0$ is dominantly determined by the expansion effect of the universe in the equation, here $E_i$ and $E_0$ are the energies of the particle at time $t_i$ and $t_0$ respectively. Then the flux is estimated as

$$E_0 \frac{d j(E_0)}{d E_0} \simeq c k m_X \frac{m_X}{E_0} t_0^{-2}$$

(5)

where $c$ is the speed of light and $t_0$ is the age of the universe. Taking $m_X = 10^{16}$ GeV, and $k = 0.1$ we obtain the differential flux due to the X particle decay as

$$E_0 \frac{d j(E_0)}{d E_0} \sim \frac{100 \text{GeV}}{E_0} \text{cm}^{-2} \text{s}^{-1}$$

(6)

This flux is comparable with the equilibrium flux obtained above, so we conclude that it is possible to satisfy the equilibrium condition with the X particle decay as the source of high energy WIMP density in the early universe.

In this work we suggest to directly detect WIMP dark matter particles in the cosmic ray. The point is that we show that there may exist some sizable flux of high energy WIMP particles in the universe. Even though the flux is much smaller than that occurring in
the direct dark matter search experiments, the detector for high energy experiments can be much bigger than that built for the low energy direct search experiments, therefore the numbers of events in high energy experiments are not necessarily less than that in the low energy experiments. And the YCRS event may be an indication of this kind of signal, even if the measurement on the event is not very reliable and needs new experiments to check. In fact some cosmic ray experiments in L3 are undergoing, one of the experimental purposes is to search for this kind of events [11]. Once the characteristics of those events are confirmed, the observation can be viewed as a strong evidence supporting the existence of the stable WIMP’s of high energy in the universe.

In order to understand where the high energy WIMP dark matter particles come from, we have derived an evolution equation for the differential density. With assumption of the equilibrium condition we estimate the differential density numerically and find that this density is interestingly large for future and even some current cosmic ray experiments. The interesting property of the equilibrium is that it does not depend on the details of any sources in the early universe, so long as the equilibrium condition is satisfied. We use the grand unification scale supermassive X particle released from \( p = 1 \) type topological defect decay as an example to show that the equilibrium is possibly reached. One should have noticed that all the numerical estimation in this work is somehow crude, they may be one or two orders of magnitudes deviating from the stated values. And the decay mode of X particle is not clear, while we simply assume that it decays dominantly to the WIMP dark matter particle. Though there are those uncertainties, however, we believe that the qualitative features we discuss in this work are correct and may be very interesting to experimentalists. Finally we emphasize that the possibility of existence of high energy cold dark matter particle in the universes deserves much attention of both theoreticians and experimentalists. If the equilibrium state is not reached in the real world, so the flux is not
as large as the equilibrium result we derived, the desired flux or density of the cold dark matter particle in the universe from some new sources, like X particle decay from topological defect destruction, can still be large enough for the future experimental detection.

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References


