Detecting the Ambient Neutralino Dark Matter Particles at Accelerator[*]

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Abstract   In this work, we present a new strategy to investigate the possibility of direct detection of the ambient neutralino matter at accelerator. We calculate the cross sections for both elastic and inelastic scattering processes of the dark matter particles with the beam particles at e^+e^- and hadron colliders.

Key words   dark matter flux, direct detection, accelerator

1   Introduction

The recent astronomical observation suggests that about 1/4 of the energy density in universe is contributed by dark matter which does not participate in electromagnetic and strong interactions. In fact, the dark matter particles only interact with other matter particles via weak interaction and as well among themselves, thus they are named as the WIMPs[1].

Modern cosmology indicates the dark matter is "cold" rather than "hot". The leading candidate of the cold dark matter particles in the minimal supersymmetric standard model with R parity conserved is neutralino $\widetilde{\chi}^0$[2].

The traditional method to detect the dark matter on Earth is to use detectors with huge-volume. As the dark matter flux comes into detector, an elastic scattering of neutralino with proton in the detector: $\widetilde{\chi}^0 + p \rightarrow \widetilde{\chi}^0 + p$, makes the proton recoiling. Since proton is charged, a trajectory can be detected by sensitive electronics. However, the kinetic energy of the neutralino is too small to cause inelastic scattering such as $\widetilde{\chi}^0 + p \rightarrow \widetilde{\chi}^+ + X$.

For such low energy, where the dispersive velocity of the dark matter particles is less than 1000km/s[4], inelastic processes are impossible, from other side, the cross section of the elastic process $\widetilde{\chi}^0 + p \rightarrow \widetilde{\chi}^0 + p$ is small and its theoretical prediction its order of magnitude is smaller than 10^{-6}—10^{-7}pb. The recent experiment of SOUDAN sets an upper bound of the cross section as $\sigma \leqslant 10^{-7}$pb. Because of the small cross section and difficulty of the detection, one may turn to search for other ways to directly detect the dark matter flux. Erede and Luk discussed a possibility of detecting the SUSY particles in the cosmic rays at TEVATRON[5]. Some authors suggested to associate the SUSY dark matter search with collider physics[3].

In this paper we study a new mechanism to detect cold dark matter by using the accelarator beam particles to collide with the ambient neutralino dark matter particles. Obviously, direct detection of the dark matter particles via inelastic scattering is very beneficial because the products of the scattering can involve a heavy charged SUSY particle whose trajectory would be clear thus easy to detect. Moveover, in the elastic scattering of $\widetilde{\chi}^0 + p \rightarrow \widetilde{\chi}^0 + p$, the background is hard to be fully eliminated, namely the contami-

nation from the background proton or other charged particles makes the experimental identification of $\tilde{\chi}^0$ even more difficult. The inelastic scattering does not suffer from such problems.

In this work we investigate a possibility of direct detection of the dark matter flux at accelerators via elastic and inelastic processes. The accelerators available at present or will be available in the near future are LEPII, TEVATRON, LHC and ILC. The concrete inelastic processes are that one uses the beam of extra high energy at accelerator to bombard on the dark matter particles which come into the detector and even the beam tube and then charged SUSY particles $\tilde{\chi}^+$ are produced via the scattering, i.e. the processes such as $\tilde{\chi}^0 + e^- \to \tilde{\chi}^- + \nu_e$, $\tilde{\chi}^0 + e^- \to \tilde{\chi}^- + \gamma$ or $\tilde{\chi}^0 + p \to \tilde{\chi}^+ + X$ etc.

The detection rate is

$$N = \rho_{\rm dm}\rho_{\rm beam}|v_{\rm rel}|\sigma slt\alpha \; , \qquad (1)$$

where $\rho_{\rm dm}$ is the dark matter density in the ambient space of our Earth, $\rho_{\rm beam}$ is the flux of e^- or proton at the accelerator, $v_{\rm rel}$ is the relative velocity of the beam and dark matter flux, but as the previous study indicates, the velocity of dark matter cannot exceed 1000km/s, thus compared to the velocity of the beam particle which is very close to the speed of light c, one can treat the dark matter particle to be at rest in the laboratory frame as $|v_{\rm rel}| \sim c$. σ is the scattering cross section which we evaluate in this work. s is the cross section of the beam, l is the length of the detector and t is the time duration of the experiment, and α is the detection efficiency.

In the regular non-accelerator experiments, this equation still holds, but $\rho_{\rm beam}$ is replaced by the density of proton in the detector, $sl = v$ is the volume of the detector and $|v_{\rm rel}|$ is the velocity of the dark matter particles in the lab frame. In that case, the volume of detectors can be very large, but as aforementioned, in this case σ is small and detection efficiency is low. By contrary, in the accelerator case, σ can be enhanced by 6—7 orders, the detection efficiency can be apparently improved, but the effective volume sl is much smaller than that of detectors used for non-accelerator experiments. The purpose of this

work is that if we can swap the loss of the effective volume by the advantages of high cross section and detection efficiency. The key point is how much the cross section is enhanced and the decisive factor is the effective volume provided by the available accelerators and detectors and the dark matter flux.

In this work, we have re-done the calculations on the cross sections of $\tilde{\chi}^0 + e^- \to \tilde{\chi}^- + \nu$ and $\tilde{\chi}^0 + p \to \tilde{\chi}^+ + X$ in light of[6], by the results, we obtain the corresponding detection rates. We take several groups of the parameters for the minimal SUSY model with the mSUGRA scheme. The parameters are determined based on the present collider data and are called the benchmark parameters by the Snowmass.

2　The elastic scattering of neutralino with the electron beam

The process under consideration is

$$\tilde{\chi}_1^0 + e^- \to \tilde{\chi}_1^0 + e^-, \quad \nu_e + e^-, \qquad (2)$$

where we assume that the lightest supersymmetric particle is neutralino $\tilde{\chi}_1^0$.

The traditional method for detecting the dark matter flux which is composed of weakly interacting $\tilde{\chi}_1^0$'s, is to let them collide with the nucleons or electrons in the detector and measure the trajectories of the recoiled charged SM particles. The available energies for the elastic scattering is very low and cross section is small. In accelerator, as one uses the beam particle (electron or positron) to bombard on the dark matter flux, and one can observe that some of the projectile electrons decline from the beam direction, so the signal is clear, and the energies are much higher, resultant cross section may be increased. With various electron beam energies, we obtain the cross sections which are tabulated in Table 1.

Meanwhile, a background may contaminate the situation. The observation is based on measuring the electrons scattered from the SUSY dark matter particles in $e^- + \tilde{\chi}_1^0 \to e^- + \tilde{\chi}_1^0$ and there is a background from the electrons scattered from nucleons of the remnant atmosphere in the vacuumized tunnel, $e^- + n \to e^- + n$. At lower energies, the cross section of scattering can

be easily computed and the amplitude is

$$M = \frac{G_F}{2\sqrt{2}} \bar{n}\gamma_\mu \left[\left(-1 + \frac{4}{3}\sin^2\theta_W \right) + \gamma_5 \right] \times$$
$$n\bar{e}\gamma^\mu [(-1 + 4\sin^2\theta_W) + \gamma_5]e. \qquad (3)$$

Then we can obtain the cross section. At the same length, the background events are at least 1000 times larger than the expected events at 1.0315×10^{-6}pa.

Table 1. The cross section for elastic process $\tilde{\chi}_1^0 + e^- \rightarrow \tilde{\chi}_1^0 + e^-$ with various beam energies.

E_n/GeV	σ_{total}/pbar
0.30×10^1	0.44×10^{-2}
0.50×10^1	0.11×10^{-1}
0.10×10^3	0.23
0.25×10^3	0.46×10^1
0.75×10^3	0.30×10^1
0.20×10^4	0.10×10^1

Recently, Hisano et al.[12], also suggest to measure the number of electron recoil events by neutralino at accelerator. They conclude that if very high current beam is available, the dark matter wind can be observed.

3　The inelastic cases

As discussed above, the elastic scattering may suffer from mis-identification of the signal from the background. We would turn to study if one can measure the dark matter flux via inelastic scattering between the projectile and the neutralinos.

(a) In the e^+e^- colliders.

If the kinematics is permissive, several inelastic reactions such as $e^- + \tilde{\chi}_1^0 \rightarrow \tilde{\nu}_e + W^-(H_1^-)$, $e^- + \tilde{\chi}_1^0 \rightarrow \tilde{e}_i^- + Z^0(H^0, A^0)$ $(i = 1, 2)$ etc. can occur. However, without losing generality, we suppose that $\tilde{\chi}_1^-$ is the lightest charged leptonic SUSY particle, so that at the moment we consider only the inelastic channel $e^- + \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^- + \nu_e$. The expressions of the corresponding amplitudes for the reaction were given in our earlier work[6].

The results somehow depend on the mass difference of $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^-$.

As an example, we would like to investigate a special case. In 1972, a peculiar event of heavy cosmic ray particle was observed in the cloudy chamber of the Yunan Cosmic Ray Station (YCRS)[7]. Recently, the event was re-analyzed[8] and it is identified as that a heavy neutral particle C^0 came in and bombarded on a proton to produce a heavy charged particle C^+ as well as a proton and π^-. Their analysis confirmed that the mass of the heavy neutral cosmic ray particle C^0 is greater than 43GeV and the mass difference

$$\Delta M = M_{C^+} - M_{C^0} < 0.270\,\text{GeV}.$$

If taking this result seriously, one would be tempted to conclude that the coming neutral C^0 is a SUSY dark matter particle $\tilde{\chi}_1^0$ and the produced heavy charged particle is $\tilde{\chi}_1^+$ accordingly.

The cross sections are listed in Table 2.

Table 2. The cross section for inelastic process $\tilde{\chi}_1^0 + e^- \rightarrow \tilde{\chi}_1^- + e^-$ with various beam energies.

E_n/GeV	σ_{total}/pbar
0.30×10^1	0.40
0.50×10^1	0.11×10^1
0.10×10^3	0.70×10^2
0.25×10^3	0.13×10^3
0.75×10^3	0.11×10^3
0.20×10^4	0.14×10^3

The number density of the projectile beam is

$$\rho_{beam} = \frac{\text{No. of particles per bunch}}{\text{bunch length} \cdot S}, \qquad (4)$$

the total event number one may expect to observe is calculable. As ρ_{dm} is 0.3GeV/cm^3, with the optimal parameters which we can find from the available accelerators in the world[9], we achieve that

$$N = 8 \times 10^{-5} \text{ events/year},$$

for $l = 1$m.

(b) In the hadron colliders.

It is natural to expect that at the hadron colliders, the situation might be remedied, because the available beam energies are much larger and the number of partons which may contribute to the total inclusive cross sections would be greatly increased. The concerned sub-processes are

$$\begin{aligned}
u + \tilde{\chi}_1^0 &\rightarrow d + \tilde{\chi}_1^+, & d + \tilde{\chi}_1^0 &\rightarrow u + \tilde{\chi}_1^-, \\
s + \tilde{\chi}_1^0 &\rightarrow c + \tilde{\chi}_1^-, & c + \tilde{\chi}_1^0 &\rightarrow s + \tilde{\chi}_1^+, \\
b + \tilde{\chi}_1^0 &\rightarrow t + \tilde{\chi}_1^-, & \bar{u} + \tilde{\chi}_1^0 &\rightarrow \bar{d} + \tilde{\chi}_1^-, \\
\bar{d} + \tilde{\chi}_1^0 &\rightarrow \bar{u} + \tilde{\chi}_1^+, & \bar{s} + \tilde{\chi}_1^0 &\rightarrow \bar{c} + \tilde{\chi}_1^+, \\
\bar{c} + \tilde{\chi}_1^0 &\rightarrow \bar{s} + \tilde{\chi}_1^-, & \bar{b} + \tilde{\chi}_1^0 &\rightarrow \bar{t} + \tilde{\chi}_1^+.
\end{aligned} \qquad (5)$$

The effective lagrangian can be found in literature[2].

In terms of the parton distribution function[10], we use the FDC program[11] to calculate the cross sections for $\tilde{\chi}_1^0 + p \rightarrow \tilde{\chi}_1^\pm + X$. The key point is the various SUSY breaking mechanisms which may result in different values for the cross sections. Let us list the possible parameter space with the two typical breaking mechanisms in Table 3.

Table 3. The parameters adopted for the later numerical computations.

symbols	schemes	m_0/GeV	$m_{1/2}$/GeV	A_0	$\tan\beta$	sign of μ
1	typical values	100	−100	0	10	+
2	region of focus	1450	300	0	10	+
3	region of annihilation	90	400	0	10	+
4	large $\tan\beta$	400	300	0	50	+
5	light $\tilde{t}$	150	300	−1000	5	+
6	non-universal gluino masses	150	300	0	10	+
	GMSB	Λ	M_{mess}	N_{mess}	$\tan\beta$	sign of μ
7	NLSP=$\tilde{\tau}_1$	40,000	80,000	3	15	+
8	NLSP=$\tilde{\chi}_1^0$	100,000	200,000	1	15	+
	AMSB	m_0	$m_{3/2}$		$\tan\beta$	sign of μ
9	small $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$	400	60,000		10	+

In Table 3, we only list the necessary parameters for the SUSY sector, and for the SM sector all the parameters can be found in the data book[9]. In the table, we include two SUSY-breaking scenarios and the corresponding SNOW-MASS 2001 benchmark points suggested by the SNOW-MASS working group.

With the parameter as inputs, we calculate the cross section of $\tilde{\chi}_1^0 + p \rightarrow \tilde{\chi}_1^\pm + X$ and the numerical results are tabulated in Table 4.

Table 4. The cross sections of the inelastic scattering $\tilde{\chi}_1^0 + p \rightarrow \tilde{\chi}_1^\pm + X$.

No.	total cross section σ/pb
0	0.73×10^3
1	0.13×10^2
2	0.12×10^1
3	0.56×10^1
4	0.75×10^1
5	0.93×10^2
6	0.76×10^1
7	0.87×10^1
9	0.22×10^1

In Table 4, the first row (No.0) corresponds to the special case where we adopt the parameters determined by the data of the Yunan observatory[7,8] for a comparison. Namely there we set $m_{1/2} = 250\text{GeV}$, $A_0 = -100$, $\tan\beta = 10$, $\mu > 0$ and $m_{\tilde{\chi}_1^0} = 43\text{GeV}$, $m_{\tilde{\chi}_1^-} = 43.27\text{GeV}$. It is obvious that the obtained cross section with this group of parameters is larger than the typical values by one order.

For LHC, the beam energy is about 7000GeV, if we take the maximum cross section to be $\sigma \sim 727\text{pb}$ (No.0 in Table 4), and the ideal situation with the detection efficiency $\eta \sim 1$, one can expect

$$N = 1.4 \times 10^{-5} \text{ events/year.}$$

Moreover, it is impossible to use the elastic scattering to measure the dark matter flux, because in that case the recoil trajectory of the beam particles would be drowned in an incredible background.

As discussed at beginning, the accelerator experiments may provide higher energies which can be used to bombard on the dark matter particles coming to our earth. No matter in the elastic scattering at e^+e^- colliders or inelastic scattering at both e^+e^- and hadron colliders, one can expect clearer signals. Because in the traditional method where the dark matter particles scatter with the proton or electron in the detector and the trajectory of proton or electron recoils are measured. The kinetic energy of the dark matter particle is small (about 0.3 to 0.6MeV) and the corresponding cross section is small too. With this small recoiling kinetic energy, the trajectory of charged particle (proton and electron) is not clear. However, the detector can be made to possess a large volume and the number of particles which may interact with the dark matter particles is large and it can compensate the small reaction cross sections.

On other side, the elastic or inelastic scattering processes of the SM particles and the dark matter

particles at accelerators of very high energies, can result in larger cross sections and provide clear signals which almost cannot be misidentified with the background. However, the volume of the detector which would be the accelerator itself at our proposal, is very limited. Generally, the size of the beam bunch is of order 100mm³ and each bunch may contain at most 10^{12} particles.

Therefore, our conclusion is that unless one can greatly increase the luminosity or the detector length (it seems impossible to enlarge the beam radius) by at least 6 to 7 orders, it is impossible to obtain any data which has substantial significance.

However, it seems not to be the end of the story, because the present knowledge on the distribution of dark matter in the space tells us that the density at the ambient space of our earth might be much larger than the universe-averaged value. If it happens that the dark matter density at the ambient space of our earth is several orders larger than the universe-averaged value which is used in our above computations, the flux may be possible to be observed. It is also noted that because the signal is clean, the requirement on the detector quality is not as rigorous as that for regular experiments. Thus if the detector can be made to be longer than 1m, say, 100m, then we would have a larger chance to directly observe the dark matter flux and the idea is very encouraging. The observation may be a nice complementarity to the direct search for SUSY particles by producing them at accelerators.

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在加速器上探测周围的超对称暗物质*

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摘要 探讨了在加速器上直接检测周围超对称暗物质的可能性，计算了暗物质与 e^+e^- 和强子对撞机上束粒子碰撞的弹性和非弹性散射截面.

关键词 暗物质流 直接探测 加速器