Search for a dark matter particle family

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I suggest a simple signature for new particles which are unstable partners of a dark matter particle. The suggested mass range is from 8 TeV to 3 PeV, the former being the mass of the dark matter particle and the latter being the knee energy mass scale from the cosmic ray energy spectrum. It can be the energy spectrum of a specific particle such as a muon, a neutrino, jets or any other particles produced in cosmic ray showers, as long as the spectrum is measured. As for the detection of a 3 PeV particle by the neutrino energy spectrum, all dark matter targets throughout the galaxy that are bombarded by high energy cosmic rays and high energy dark matter particles contribute to the process. This is new in the study of dark matter physics.

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I. INTRODUCTION

LHC experiments are underway with the hope that new particles in a dark matter family might be observed. So far no new particles have been discovered. From high energy gamma ray searches the prognosis for the existence of a relatively low mass (less than 1 TeV) dark matter particle (DMP) seems unlikely. HESS[1] concluded that there is no gamma ray peak below 2 TeV, while above 2 TeV up to 10 TeV, there is gamma ray excess above the power law extension from the lower energy data. This suggests that the discovery of new particles in a DMP family might require various kinds of cosmic ray detectors, as was the case for the discovery of strange particles in the pre-1950 era, a golden age of cosmic ray physics. All new particles were found exclusively in cosmic ray detectors, before the arrival of the accelerator era. In the next section, I summarize the expected mass range for a DMP family to see what we are dealing with. The method which we develop for detection is of more general application, however.

II. MASS RANGE FOR DMP SPECIES

In the standard model, all particles are unstable except the particles of lowest mass, protons, electrons and neutrinos. Similarly, a supersymmetric theory suggests that all particles of a family are unstable except for the lowest mass state, in this case the DMP. There may be multiple DMP’s, counterparts of protons, electrons and neutrinos in the standard model. In order to specify a possible mass range for DMP partners, I discuss a theory where the mass scale has been explicitly derived from observational data. In a series of articles[2]-[10] since 1985, the author has presented a model for the emission of high energy particles from AGN. The following is a summary of the model.

1) Quantum effects on gravity yield repulsive forces at short distances[2],[4].
2) The collapse of black holes results in explosive bounce back motion with the emission of high energy particles.
3) Consideration of the Penrose diagram eliminates the horizon problem for black holes[5]. Black holes are not black any more.
4) The knee energy for high energy cosmic rays can be understood as a split between a radiation-dominated expansion and a matter-dominated expansion, not unlike that in the expansion of the universe. (See page 10 of the lecture notes[2]-[4].)
5) Neutrinos and gamma rays as well as cosmic rays should have the same spectral index for each AGN. They should show a knee energy phenomenon, a break in the energy spectral index at 3 PeV, similar to that for the cosmic ray energy spectrum.
6) The recent announcement by Hawking rescinding an earlier claim about the information paradox[11] is consistent with this model.

It is worthwhile to mention that this model has been supported by recent data from the Pierre Auger Observatory, which has found a possible correlation between the sources of high energy cosmic rays and AGN.

Further discussion of the knee energy in the model yields the existence of a new mass scale in the knee energy range, in order to have the knee energy phenomenon in the cosmic ray spectrum[12]. The following are additional features of the model.
7) The proposed new particle with mass in the knee energy range (at 3 PeV) may not be stable, as in the case of the standard model. The standard model has particles at the 100 GeV mass scale, such as W and Z bosons, which are
unstable. If it is a member of a supersymmetric multiplet and weakly interacting with ordinary particles, the stable particle of lowest mass becomes a candidate for a DMP. The only requirement is that such particles must be present in AGN or black holes so that the phenomenon of the knee energy is observed when cosmic rays are emitted from AGN.

8) Using the supersymmetric theory of GLMR-RS (Giudice-Luty-Murryama-Rattazzi; Randall-Sundrum)\[13, 14\], the lowest mass corresponding to a knee energy mass of 3 PeV is 8 TeV. It is shown that the sum of 8 gamma ray observations from unknown sources\[17\] has a definite peak at $7.6 \pm 0.1$ TeV\[18, 19\].

9) There are several other particles with mass between 8 TeV and 3 PeV in the GLMR-RS theory. We assume that the target mass range for the search is from 8 TeV to 3 PeV. In particular, the 3 PeV target is of prime importance, since it is a starting point for the discovery of a new mass scale. Moreover, it provides bases for matter-dominated expansion of black holes and possibly of the universe. It is expected that such particles are produced abundantly in the process of cosmic ray production from AGN as well as in the process of universe expansion. But most particles produced in AGN decay. They are produced in pairs in high energy cosmic ray showers and subsequently decay. In this article, we aim to find a signature for such particles.

One may call the new particle system the Cion system. This is an acronym for Cosmic Interface Particle. It is also taken from the Chinese word for knee, Xi (pronounced as shi). The particle at 3 PeV may be called a prime-Cion and the DMP particle at 8 TeV a dm-Cion.

### III. JET PRODUCTION IN HIGH ENERGY COLLISIONS

It is quite common to observe many jets in a high energy collision. Jets seem more frequent than would be dictated by phase space considerations. In other words, a high energy collision produces a relatively small number of jet entities rather than producing many particles which share the momenta. Ignoring small momenta perpendicular to the jet direction, a jet may be approximated as a single particle. By the same token, the decay of a massive particle may be approximated by a relatively fewer number of jet or particle decays. In such a situation, significant probability is shared by the smallest number of particles, i.e., two body decay. If one assumes two body decays, one finds particles carrying half the energy of the parent mass in the rest frame of a parent particle.

The next simplest decay mode is three body decay. The phase space for three body decay has a triangular form at the highest energy, which is half the mass of the parent particle. This is generally true unless the matrix element vanishes at the highest energy. In that case, the peak shifts to a lower energy.

### IV. MASS SPECTRA OF THE GLMR-RS SUPERSYMMETRIC THEORY

Since the knee energy of the cosmic ray energy spectrum implies a new mass scale in nature, according to the theory proposed by the present author in 1985, and the model predicted a correlation between high energy cosmic rays and AGN that was observed by the Pierre Auger Observatory\[16\], it seems natural to expect new physics at a mass scale of 3 PeV. Then one would look for a supersymmetric theory which has a big mass ratio, so that a relatively low mass for a dark matter particle can be predicted from a practical observational point of view. From that consideration, the author came to the conclusion that the analysis of the GLMR-RS theory\[13, 14, 15\] was the most appropriate. In that theory, the basic mass relations are given by the gaugino mass parameters,

\begin{align*}
M_1 &= \frac{11\alpha}{4\pi \cos^2 \theta_W} m_{3/2} = 8.9 \times 10^{-3} m_{3/2}, \\
M_2 &= \frac{\alpha}{4\pi \sin^2 \theta_W} m_{3/2} = 2.7 \times 10^{-3} m_{3/2}, \\
M_3 &= -\frac{3\alpha_s}{4\pi} m_{3/2} = -2.6 \times 10^{-2} m_{3/2},
\end{align*}

before loop corrections, where $\alpha$, $\alpha_s$ and $\theta_W$ are the fine structure constant, strong coupling constant and the weak interaction angle respectively.

With the assumption for the largest mass,

\[ m_{3/2} = 3 \text{ PeV}, \]

the lowest mass in the above list becomes

\[ M_2 = 8.1 \text{ TeV}. \]
FIG. 1: Sum of gamma ray energy spectra of 8 unidentified sources [17], in units of $10^{-12} (\text{TeV})^{0.4} (\text{erg cm}^{-2} \text{s}^{-1})$.

This becomes a prediction for the mass of a dark matter particle. This is consistent with the earlier finding of HESS [1]. One attractive nature of the GLMR-RS theory is that the mass ratios listed above are expressed in terms of fundamental constants in nature.

V. EVIDENCE FOR A DARK MATTER PARTICLE

HESS has reported a systematic search for high energy gamma rays from 8 unknown sources [17]. Unknown sources could be promising for a dark matter gamma ray search, since they might be dominated by dark matter, such as a massive black hole made by the collapse of a predominantly dark matter object. Such an object might not have the AGN signature. This is because the AGN signature requires ordinary atomic matter, while that for unknown sources may be deficient in ordinary matter. I have reported that the total sum of 8 data samples shows a distinctive peak at $7.6 \pm 0.1 \text{ TeV}$, as shown in Fig.1. This is consistent with Eq. (5). This agreement propels further pursuit of other particles in this model.
VI. SIGNATURE FOR UNSTABLE MEMBERS OF A DARK MATTER FAMILY: A BUMP IN THREE BODY DECAY

The family members of the dark matter particle, $M_2$, listed above have masses

$$M_1 = 27 TeV, \quad (6)$$
$$M_3 = 78 TeV, \quad (7)$$

and, of course,

$$m_{3/2} = 3 PeV. \quad (8)$$

All particles except $M_2$ are unstable, as is the case in the standard model. There are other members in the family at the high end of the mass range, such as scalars. So the above mass values represent a typical family member in the lower mass range. Let us use $F$ to denote unstable particles. They are typically produced as pairs in high energy cosmic ray showers. The simplest kind of decay is

$$F^0 \rightarrow M_2 + \mu^+ + \mu^- \quad (9)$$
$$F^0 \rightarrow M_2 + \nu + \bar{\nu} \quad (10)$$
$$F^0 \rightarrow M_2 + jet + jet \quad (11)$$

for a neutral component, and

$$F^\pm \rightarrow M_2 + \mu^\pm + \nu \quad (12)$$

for a charged component.

If $F$ pairs are produced at rest in a shower, from the phase space of 3 body decay one would expect for a decay particle a triangular distribution bounded by half the parent mass. This can be seen from the gamma ray energy distribution in 3 gamma decay of orthopositronium, or the electron energy distribution in muon decay\[20],

$$\mu^- \rightarrow e + \nu + \nu. \quad (13)$$

A triangular three body decay distribution is also exhibited in more compact form in a log-log graph. Since most energy spectra in cosmic ray studies are exhibited in log-log scale in order to accommodate the large energy range and power law behavior of background processes, this feature is favorable for the discovery of a three-body-decay bump. Predominantly on the high energy end, the motion of the parent particle widens the bump, since initial cosmic rays have a high incident energy. This phenomenon should appear for muons as well as neutrinos. In other words, the three particles, $M_1$, $M_3$ and $m_{3/2}$, would show up as bumps near 13.5 TeV, 39 TeV and 1.5 PeV in the energy spectra of the muon, neutrino and jet. The only exception would be in the case where the interaction matrix element suppresses the high energy end of the spectrum, so that its maximum would appear in the middle of the energy range. This would happen for mu-e decay for V+A theory. If one were to observe a bump near 1.5 PeV as evidence for $m_{3/2}$, one would know the ratio of the observed bump with an expected value of half the $m_{3/2}$ mass, 3 PeV.

Fig. 2 of Frejus 94\[21] shows the energy spectrum for a vertical stopped muon between 10 TeV and 68 TeV obtained with the Frejus detector. It clearly suggests that there are enhancements at around 17 TeV and 38 TeV, consistent with the expectation from bumps\[21] due to the $M_1$ and $M_3$ particles. Definitely one needs more accurate data before drawing a conclusion. However, it is remarkable that data from two decades ago can provide such a useful hint. A renewed effort to make an accurate measurement is encouraged.

Beyond an underground depth of 10,000 kwe, neutrino induced muons start to dominate, so that energy measurement by stopped muons does not work for the atmospheric muon spectrum. Therefore, muons beyond 100 TeV cannot be measured in this manner. In such a case, energy measurement of neutrinos should replace that of muons for discovering a bump for a dark matter excited state in three body decay. Alternatively, a different method of measuring muon energy such as IceCube and Antares should be used.

VII. MUONS AND NEUTRINOS BY NEUTRINO DETECTORS

Neutrino detectors such as IceCube and Antares can measure muons and neutrinos at high energy by the Cerenkov method. IceCube has reported a partial spectrum for high energy muons. A spectrum\[22],\[23], with average energy 20 TeV has a peak at 10 TeV. This is consistent with a bump at 10-20 TeV, as is suggested by the Frejus data and
the $M_1$ bump. An IceCube spectrum with average energy 400 TeV has a peak at 600 TeV. This is consistent with a bump on a nearby bump at higher energy, such as 1.5 PeV for $m_{3/2}$. One would like to have IceCube analyze all energy spectra for muons, say at sea level. As one saw from the previous section, their results might have important implications for the high energy component of a dark matter family. A most important task for IceCube and Antares would be to examine whether bumps similar to those of Frejus 94 can be found in their data. The reason they didn’t examine this process is that they did not realize the significance of the Frejus bumps.

If the energy spectrum for atmospheric neutrinos were to be measured accurately in the 10 TeV–10 PeV range, along with that for muons, it might reveal a dark matter family, and might lead to a new era of particle discovery through cosmic ray studies.

VIII. PRODUCTION OF THE KNEE ENERGY PARTICLE, $m_{3/2}$

In order to produce $m_{3/2}$ with a 3 PeV mass, one needs an incident particle of energy $E$ in the lab frame

$$E = (3 \text{PeV})^2/2M$$

where $M$ is the target mass. For $M = 10$ GeV (a Nitrogen nucleus), one needs

$$E = 4.5 \times 10^{20} \text{eV},$$

i.e., one needs cosmic rays with energy beyond the GZK cutoff. This may be possible if high energy particles contain dark matter particles. Such a scenario requires the acceleration of neutral particles. Being a gravitational acceleration, the model proposed since 1985 by the author does that, and DMPs are emitted with intensities similar to that of cosmic rays. However, such intensities are not so high.

If one considers as a target DMPs that reach our neighborhood, one can take the target mass to be

$$M = 8 \text{ TeV}.$$  

Then the energy required for the production of a knee energy particle of 3 PeV is

$$E = 5.6 \times 10^{17} \text{eV},$$

which has a higher intensity than that of the energy in Eq. (15). If one considers dark matter incident particles, then dark matter–dark matter interactions are supposed to be strong, so that a significant amount of $m_{3/2}$ particle production can be expected. Also, the distribution of target dark matter is widely spread beyond the Earth, so that muons and neutrinos as decay products of unstable $m_{3/2}$ particles may come from a vast region. It would be a good idea to set up muon or neutrino detectors in a space station in the future.

If one tries to find a 1.5 PeV peak in the muon spectrum, the lifetime of the relevant muon becomes 33 seconds from the relativistic effect, so that dark matter targets within $10^{12} \text{cm}$ can contribute to the process. If one considers similar events in the neutrino energy spectrum, all dark matter targets in the whole galaxy can contribute. This implies that the 1.5 PeV peak in the neutrino energy spectrum should be very large. This phenomenon will provide decisive evidence for the existence of $m_{3/2}$ at 3 PeV, and at the same time, it will show the effect of dark matter targets in the whole galaxy.

The same argument can be applied to the production of a $m_{3/2}$ particle by the collision of dark matter on dark matter, as well as by the collision of cosmic rays on dark matter. Both processes are strong interactions at this high energy. The discovery of such a phenomenon is an exciting possibility for the near future. Definitely, it is worthwhile to see whether a bump at 1.5 PeV can be observed in present neutrino detectors such as IceCube and Anteras.

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[1] HESS Collaboration, Acero, F. et al., ArXiv:astro-ph.0911.2709 (2009).
[2] Tomozawa, Y., Magnetic Monopoles, Cosmic Rays and Quantum Gravity, in the Proc. of 1985 INS International Symposium on Composite Models of Quarks and Leptons (Tokyo, edit. Terazawa, H. and Yasue, M., 1985), pp. 386.

[3] Tomozawa, Y., The Origins of Cosmic Rays and Quantum Effects of Gravity, in Quantum Field Theory (ed. Mancini, F., Ersever Science Publishers B. V., 1986) pp. 241. This book is the Proceedings of the International Symposium in honor of Hiroomi Umezawa held in Positano, Salerno, Italy, June 5-7, 1985.

[4] Tomozawa, Y., Cosmic Rays, Quantum Effects on Gravity and Gravitational Collapse, Lectures given at the Second Workshop on Fundamental Physics, University of Puerto Rico, Humacao, March 24-28, 1986. This lecture note can be retrieved from KEK Kiss NO 200035789 at [http://www-lib.kek.jp/KISS/kiss_prepri.html](http://www-lib.kek.jp/KISS/kiss_prepri.html)

[5] Tomozawa, Y., Gravitational Waves, Supernova and Quantum Gravity, in Symmetry in Nature, (Scuola Normale Superiore, Pisa, 1989) pp. 779, Section 2 and 3.

[6] Tomozawa, Y., Exact Solution of the Quantum Einstein Equation and the Nature of Singularity, in the Proc. 5th Marcel Grossman Meeting on General Relativity (ed. D. Blair et al., Perth, Australia, 1988) pp. 527.

[7] Tomozawa, Y., Black Hole Oscillation, in the Proc. 5th Marcel Grossman Meeting on General Relativity (ed. D. Blair et al., Perth, Australia, 1988) pp. 629.

[8] Majumdar, A. and Tomozawa, Y., Progr. Theoret. Phys. (Kyoto) 82, 555 (1989).

[9] Majumdar, A. and Tomozawa, Y., Nuovo Cimento 197B, 923 (1992).

[10] Tomozawa, Y., Astron. Astrophys. Suppl. Ser. 97, 117 (1993).

[11] Hawking, S., www.newscientist.com/article/dn6151.html.

[12] Tomozawa, Y., MPLA 23, 1991 (2008), arXiv: 0802.0301; High Energy Cosmic Rays from AGN and the GZK Cutoff, arXiv: 0802.2927 (2008).

[13] Giudice, G. F., Luty, M. A., Murayama, H. and Rattazzi, H. R., JHEP 12, 027 (1998).

[14] Randall, L and Sundrum, R, Nuclear Phys. B 557, 79 (1999).

[15] Wells, J. D., Phys. Rev D71, 015013 (2005).

[16] The Pierre Auger Collaboration, Science 318, 938 (2007); Correlation of the Highest-energy Cosmic Rays with the Positions of Nearby Active Galactic Nuclei, arXiv: 0712.2843 (2007).

[17] Aharonian, F. et.al., Astron.&Astrophys. 477, 353 (2008).

[18] Tomozawa, Y., Evidence for a dark matter particle. arXiv: 1002.1938 (2010).

[19] Tomozawa, Y., Cosmic rays from AGN, the knee energy mass scale and dark matter particles. arXiv: 1002.1327 (2010).

[20] e.g., Ehrlich, R. D. et al., Phys. Rev. Lett. 16, 540 (1966) Fig. 2

[21] Rhode, W., Nuclear Phys. B (Proc. Suppl.) 35, 250 (1994).

[22] IceCube collaboration, Abbasi, R. et.al., Apj. 763, 33 (2012).

[23] IceCube collaboration, Abbasi, R. et.al., Astroparticle Phys. 34, 48 (2010).

[24] Greisen, K., Phys. Rev. Lett. 16, 748 (1966); Zatsepin, G. T. and Kuzmin, V. A., Pisma Z. Experim. Theor. Phys. 4, 114 (1966).