ASITP

INSTITUTE OF THEORETICAL PHYSICS ACADEMIA SINICA

AS-ITP-94-37
August 1994

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ABSTRACT

The exotic event observed in 1972 at Yunnan Cosmic Ray Station (YCRS) has been re-interpreted as a collision between a high energy heavy particle with a nucleon, with three charged particles identified as the final products. If no other missing neutral particles were produced in this collision, then one of the three particles C^+ could be assigned with mass M_{c^+} >43 Gev, and life-time $\tau > 0.406 \times 10^{-9}$sec. If C^+ is unstable, it can decay via weak interaction to C^0 and a pair of leptons. The mass difference between C^+ and C^0 is estimated as less than .270 GeV. The relevance of this event with the dark matter problem in the Universe is also discussed.

*The project supported in part by National Natural Science Foundation of China.

1. The exotic event observed in cosmic ray.

In 1972, an exotic and rare event had been observed in the $150cm \times 150cm \times 30cm$ cloud chamber at Yunnan Cosmic Ray Station(YCRS)[1]. It consists of three tracks of charged particles coming from a common point, that indicates that all of them are produced in a single collision. It was then determined that the ionizations I_a, I_b and I_c of these three particles a, b and c are related, respectively, to the minimal ionization I_0 as the following:

$$I_a = (1.53 \pm 0.18)I_c,$$

$$I_b = (1.59 \pm 0.19)I_c,$$

$$I_c = (0.88 \pm 0.11)I_0.$$

The maximal measurable momemtum in the chamber was

$$P_{max} = 48\ GeV/c,$$

and from the curvature of these tracks in the magnetic field the apparent momenta of particles a, b and c were determined, respectively, as

$$P_a = 6.6 {}^{+1.0}_{-0.8}\ GeV/c,$$

$$P_b = 62\ GeV/c,$$

$$P_c = 110\ GeV/c.$$

Furthermore, the angles between every pair of these tracks were also measured as

$$\Theta_{ab} = 3°25', \quad \Theta_{bc} = 1°25', \quad \Theta_{ac} = 4°55',$$

so that it was realized that all these tracks are coplanar. Moreover, since these angles are very small, it is reasonable, as we shall see, to treat them as in one direction approximately.

Based upon the momenta and ionizations, particle a was identified as π^--meson, particle b as a proton. However, particle c is quite different from all particles known to exist by then. To be more concrete, from measurement particle c can be assigned as to have an apparent momentum which is far bigger than the maximal measurable momentum, namely

$$P_c > 49.8 GeV/c, \qquad c.l. = 70\%,$$

and

$$P_c > 52.6 \ GeV/c, \qquad c.l. = 68.3\%.$$

As the ionization of particle c is in the region of minimal ionization with $\beta\gamma \approx 3.4$, and given the uncertainty in the ionization determination, we, therefore, may take $\beta\gamma$ of c to be in the following range.

$$2.18 < \beta\gamma < 6.22, \qquad c.l. = 93\%.$$

Then using the lower limit for the momentum of 49.8 Gev/c, one gets the lower limit of mass for particle c:

$$M_c = 14.6 \ GeV/c^2 \qquad for \ \beta\gamma = 3.4$$

and

$$M_c = 8.3 \ GeV/c^2 \qquad for \ \beta\gamma = 6.0.$$

So that 8.3 GeV was taken to be the lower bound of the mass for c.

The decay of particle c had not been found within the track length L=150 cm.. That sets a lower bound for the life-time of c- particle as $t_{mes} = L/c$ in the laboratory system of references. Therefore one immediately gets the lower limit for the life-time in the rest system of references as

$$t_0 = t_{mes}/\beta\gamma = L/\beta\gamma c,$$

that corresdonds to an average life-time for c-particle as

$$\tau > \tau_{min} = 1/\beta\gamma \times 2.172 \times 10^{-9} sec., \qquad c.l. = 90\%.$$

We have listed in Table 1 the lower limits of the average life-time for different $\beta\gamma$-values for c-particle.

Thus, from the single event obtained in the cloud chamber we have collected the following informations concerning c-particle:

1), with a unit and most probably positive charge;

2), the momentum and the speed of particle c in this event are:

$$P_c > 49.8 GeV/c, \qquad c.l. = 70\%$$

$$2.18 < \beta\gamma < 6.22, \qquad c.l. = 93\%;$$

3), the estimated mass limit is

$$M_c > 8.2 GeV/c^2, \qquad c.l. = 70\%;$$

4), the lower limit for the life-time is

$$\tau > 0.362 \times 10^{-9} sec., \qquad c.l. = 90\%.$$

Thus one may conclude that particle c is an unknown and long-lived heavy particle with an unit positive charge. From now on we shall denote this particle by C^+.

2. The behavior and property of particle C^+.

The observed life-time of C^+ is rather long, that suggests that if it decays, it can only through weak interaction to a neutral heavy particle C^0 with small phase space. If the mass difference between C^+ and C^0 is less than 0.3GeV, the main decay modes are

$$C^+ \to C^0 + e^+ + \nu_e,$$

and

$$C^+ \to C^0 + \mu^+ + \nu_\mu.$$

In addition, the decay width can be expressed as

$$\Gamma = G_F{}^2/15\pi^2 \times (M_+ - M_0)^5 \lambda(M_+ - M_0),$$

where $\lambda(m)$ is a slowly varying function of m, with $\lambda = 1$ for $m < 0.11GeV$, and increases slowly with m. In Table 2 we have presented the calculated average life-times for C^+ versus $M_+ - M_0$. Then one may conclude that if C^+ is unstable, and decays to C^0, the mass difference between C^+ and C^0 is constrained by

$$M_+ - M_0 < 0.270\ GeV$$

3. Kinematics consideration for the event.

As we have already mentioned, that in this single event three charged particles in the final state have been identified. If we assume further that no missing neutral particles emitted in this process, then the event can be described as a collision between a high-energy incident particle i coming from the cosmic ray and a target particle t:

$$i + t \to \pi^- + p + C^+.$$

And it is not difficult to realize that among the initial particles one must have positive unit charge, and the other is neutral. For the energy range characteristic for this event, all the nucleons in a comlex nucleus can be viewed

as independent and free. Then the first possible candidates for i and t seem to be two nucleons. However, simple kinematics consideration has shown that this is impossible because the energy and mimentum conservations can not be fulfilled . The next is to consider i as a energetic proton, and t is a heavy unkown particle. And our analysis has shown that the energy and momentum conservation law also can not be satisfied. Thus we are forced to assume that t is a proton or a neutron, both are abundant in our atmosphere, while the incident particle is a high-energy heavy and exotic particle C^+ or C^0. Now treating all the three produced in the final state particles as in one direction, one can write down the energy and momentum conservations as

$$P_i = P_\pi + P_p + P_+,$$

$$E_i + M_p = E_\pi + E_p + E_+,$$

where all the symbols are self-evident. Denoting $\delta M = M_+ - M_i$, one can easily solve the equations as:

$$M_+ = A/B,$$

$$A = M_p(E_p - M_p) + M_pE_\pi - E_pE_\pi + P_pP_\pi - M_\pi{}^2/2 + (\delta M)^2/2,$$

$$B = (E_p - M_p)\gamma_+ - P_p\beta_+\gamma_+ + E_\pi\gamma_+ - P_\pi\beta_+\gamma_+ + \delta M.$$

It is noted that although the mass of C^+, M_+, depends on δM, but it varies rather slowly with δM in the range from 0 , say, to 0.2 GeV

Taking for the final particles the observed momenta and speed as

$$P_\pi = 6.2\ GeV,$$

$$P_p = 62\ GeV,$$

$$\beta_+\gamma_+ = 2.18\ -\ 6.22,$$

and considering that δM is in between 0 and 0.3 GeV, then the energy trigger used in this experiment $E_i > 300\ GeV$ sets a lower bound for $\beta_+\gamma_+$. Moreover, the requirement that M_+ must be positively definite, i.e. $B > 0$, sets a upper limit for $\beta_+\gamma_+$. To be precise, we are led to the following results:

$$5.27 < \beta_+\gamma_+ < 6.01, \quad for\ \delta M = 0,$$

$$5.31 < \beta_+\gamma_+ < 6.06, \quad for\ \delta M = 0.100\ Gev,$$

$$5.35 < \beta_+\gamma_+ < 6.12, \quad for\ \delta M = 0.200\ Gev,$$

$$5.38 < \beta_+\gamma_+ < 6.16, \quad for\ \delta M = 0.270\ GeV$$

And within these intervals of δM, M_+ is a function of $\beta_+\gamma_+$, the values of M_+ are listed in Table 3. From the values given in Table 3 one sees that the lower bound of M_+ can be taken to be 43 GeV. Moreover, using the corresponding value of $\beta\gamma$, the lower limit for the life-time has been re-estimated as $0.406 \times 10^{-9} sec$.

To conclude this section, we note that the event of YCRS might be interpreted as a collision between an heavy particle with high energy coming from the cosmic ray and a nucleon. This collision results in a production of three charged particles, among them the proton and the π-meson have been identified previously. Based upon the energy and momentum conservations, the third one can be interpreted as the heavy particle C^+. Its mass and life-time can be assigned as:

$$M^+ > 43\ GeV, \quad and \quad \tau > 0.406 \times 10^{-9}\ sec$$

respectively. If C^+ is unstable, it may decay via weak interaction to its neutral partner C^0, with the mass difference estimated as less than 0.270 GeV.

4. A discussion of the YCRS event and its relation with cold dark matter candidate.

The contemporary cosmology study has provided the following important informations, that is, the matter density of our Universe consists of three parts: the baryon matter, the hot dark matter and the cold dark matter. The relative abundances of them are characterized by three dimensionless parameters, namely, Ω_b, Ω_h and Ω_c. The combined astrphysical and astronomical analyses favour a scenary, where Ω_b contributes less than 10% of the total mass, while the dark matter is the dominant component of the mass of our Universe. The most part of the baryon mass is, of course, in nucleons. However, as for the dark matter, since it has no direct electromagnetic interaction, its existence can only be inferred from the gravitational effect. There are many discussions concerning the nature of dark matter, and many candidates have been proposed for the dark matter. As far as the cold dark matter is concerned, the most promising suggestion is a neutral, stable and heavy particle C, the existence of which should be verified by the experiments. If we believe the C^0 we have just discussed is the cold dark matter particle, then the ratio of the number of C^0, i.e. N_c to the number of the nucleons N_n is related to their masses as follows:

$$\frac{N_c}{N_n} = \frac{\Omega_c}{\Omega_n}\frac{M_n}{M_c}.$$

It is now reasonable to assume that particle C^0 exists not only as the dark matter in the Universe, but also in the primary cosmic ray. And it is well-known that the flux of the cosmic ray is a function of energy, so that let us denote the differential fluxes of the cold dark matter particles and that of the baryons in the cosmic ray by $j_c(E)$ and $j_b(E)$ respectively. Then the total fluxes of C^0 and that of baryons with energy bigger than E are, respectively,

$$J_c(E) = \int_E^\infty j_c(E')dE',$$

$$J_b(E) = \int_E^\infty j_b(E')dE'.$$

As from the cosmic ray observations it is known that for $E > 10\ GeV$, $J_b(E)$ can be expressed as

$$J_b(E) = J_b(E_0)(E_0/E)^b,$$

where the parameter b is taken from the experimental fit directly as

$$b = 1.778.[2]$$

There is no any information concerning $J_c(E)$. However, if one assumes that the same ratio of the cold dark matter mass to the baryon mass holds in both the Universe and the primary cosmic ray, and the same energy behavior observed for both the cold dark matter flux and the baryon flux in the cosmic ray, or more explicitly,

$$\frac{J_c(M_c)}{J_b(M_n)} = \frac{N_c}{N_n},$$

and

$$J_c(E) = J_c(E_0)(\frac{E_0}{E})^b.$$

Then from the equations one can easily get the ratio of the number of dark matter particles to the number of baryons with energy bigger than E_0 in the cosmic ray:

$$\frac{J_c(E_0)}{J_b(E_0)} = \frac{J_c(E_0)}{J_c(M_c)}\frac{J_c(M_c)}{J_b(M_n)}\frac{J_b(M_n)}{J_b(E_0)},$$

and consequently,

$$\frac{J_c(E_0)}{J_b(E_0)} = \frac{\Omega_c}{\Omega_b}(\frac{M_c}{M_n})^{b-1}.$$

Now the ratio of the number of collisions with a target nucleon induced by particles C to that induced by baryons is proportional to

$$\frac{J_c(E_0)\sigma_{cn}}{J_b(E_0)\sigma_{pn}},$$

where

$$\sigma_{cn} = \frac{G_F^2}{2\pi}(s - M_c^2)(1 - \frac{M_c^2}{s} + \frac{M_c^4}{s^2}),$$

and

$$\sigma_{pn} = 44mb..$$

Therefore, under the conditions at YCRS, the expected number of events of the cold dark matter particles per year is estimated to be

$$n = J_b(300GeV) \times \frac{J_c(300GeV)}{J_b(300GeV)}\frac{\sigma_{cn}}{\sigma_{pn}} AR_{eff}Sr/2\pi,$$

where A is the effective detection area, R_{eff} is the relative time of detection, and Sr is the solid angle of the detector, namely,

$$A = 2000\ cm^2,$$

$$R_{eff} = 1/3,$$

$$Sr = 0.20\ sr.,$$

$$J_b(1Tev) = 1 \times 10^{-4} cm^{-2} sec^{-1}.[2]$$

Since σ_{cn} is a function of the energy and M_c, we have taken the incident energy to be 300 GeV, and $M_c = 42.5GeV$. The recent observations[3] seem to indicate that $\Omega_b = 0.03$, and $\Omega_c = 0.70$, we are thus led to the expected number of events of the cold dark matter as

$$n = 0.025yr^{-1}.$$

This means that given the acceptance of the detector at YCRS of 0.04 m^2sr., one may have in average one event every 40 years. Therefore, if the acceptance is to be increased, say, to 5 $m^2sr.$, three events per year can be expected.

5. Conclusions and discussions.

The rare event with a long-lived heavy particle observed at YCRS might be accounted for by the production of a charged particle C^+ resulted from a collision of a energetic heavy particle coming from the cosmic ray with a target nucleon. The mass and life-time of C^+ can be assigned as

$$M_+ > 43\ Gev, \quad \tau > 0.406 \cdot 10^{-9}\ sec.,$$

provided no other missing particles are emitted. Judging by all possibilities, C^+ is unstable and has to decay to its neutral partner C^0. Then the mass difference between C^+ and C^0 is constrained by its rather long life-time as less than 0.270 GeV.

The incident high energy particle might be an exotic, cold dark matter particle in the primary cosmic ray. If so, one may estimate and expect more such events in an enlarged scale of experiment.

It is well-known that one of the extensions of the standard model in particle physics is the so-called minimized supersymmetric standard model (MSSM). According to this model, every particle in the standard model has a supersymmmetric partner. And because of the spontanious breaking of the supersymmetry, all the supersymmetric particles are rather heavy. However, there exists a lighest supersymmetric particle (LSP), which is neutral and stable. And many people believe that the cold dark matter particle is LSP. If we identify LSP with C^0, then the YCRS event indicates that there exists a charged partner of C^0, i.e. C^+, with almost degenerate mass, which explains its long life-time. Since the experimental bounds obtained at YCRS concerning the property of C^+ are not in contradiction with the limits set by MSSM, therefore, the MSSM not only provides a candidate for the cold dark matter in the Universe, but also gives an attractive interpretation of the event observed more than twenty years ago at YCRS.

References

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[2] Encyclopedia, V.9 Cosmic ray physics, 9-4, (1988), ed. by Cosmic Ray Groups of IHEP and ISP, Science Press.

[3] John N. Bahcall, Nature, 368 (1994) 584; A. Songaila, *et al.*, Nature,368 (1994) 599.

Table 1. The average life-times versus $\beta\gamma$.

$\beta_+\gamma_+$	τ_{min} (10^{-9} sec)	$\beta_+\gamma_+$	τ_{min} (10^{-9} sec)	$\beta_+\gamma_+$	τ_{min} (10^{-9} sec)
2.0	1.086	3.4	0.639	4.8	0.453
2.2	0.987	3.6	0.603	5.0	0.434
2.4	0.905	3.8	0.572	5.2	0.418
2.6	0.835	4.0	0.543	5.4	0.402
2.8	0.776	4.2	0.517	5.6	0.388
3.0	0.724	4.4	0.494	5.8	0.374
3.2	0.679	4.6	0.472	6.0	0.362

Table 2. The average life-times versus $M_+ - M_0$ (Gev).

$M_+ - M_0$ (Gev)	τ (10^{-9} sec)	$M_+ - M_0$ (Gev)	τ (10^{-9} sec)
0.040	2.20×10^4	0.180	5.95
0.060	2.89×10^3	0.200	3.53
0.080	6.87×10^2	0.220	1.46
0.100	2.25×10^2	0.240	0.942
0.120	4.52×10	0.260	0.631
0.140	2.09×10	0.280	0.218
0.160	1.07×10	0.300	0.154

Table 3. The mass of C^+ versus $\beta\gamma$.

$\beta_+\gamma_+$	M_+ (Gev) $\delta M = 0$ (Gev)	M_+ (Gev) $\delta M = 0.100$ (Gev)	M_+ (Gev) $\delta M = 0.200$ (Gev)	M_+ (Gev) $\delta M = 0.270$ (Gev)
5.35	48.87	45.37	42.35	40.47
5.40	53.12	49.01	45.50	43.34
5.45	58.11	53.23	49.12	46.60
5.50	64.08	58.20	53.32	50.36
5.55	71.34	64.13	58.24	54.73
5.60	80.36	71.32	64.12	59.89
5.65	91.86	80.24	71.23	66.05
5.70	107.05	91.58	80.03	73.55
5.75	128.03	106.51	91.20	82.88
5.80	158.89	127.04	105.84	94.79
5.85	208.78	157.04	125.87	110.53
5.90	303.16	205.05	154.95	132.33
5.95	549.49	294.27	200.98	164.50
6.00	2830.41	517.65	284.94	216.78
6.05	—	2095.48	486.56	316.54
6.10	—	—	1632.40	582.46