Result of search for low velocity exotic particles*

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Abstract The L3+C experiment, taking advantage of the L3 muon magnetic spectrometer, measured the spatial tracks of charged cosmic ray particles to obtain rigidity as well as velocity. One possible low velocity exotic particle is observed. The existing uncertainties are discussed, and the flux upper limit of the low velocity exotic particles from this observation is deduced based on the assumption of a null observation. The result is 6.2×10^{-10} cm^{-2}·s^{-1}·sr^{-1} at 90% confidence level in the velocity range from $0.04c$ to $0.5c$.

Key words exotic particle, cosmic ray, L3+C

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1 Introduction

Several theoretical assumptions proposed the possible existence of slow-moving particles in cosmic rays. One example is the strange quark matter (SQM)[1—3] (also called strangelet or nuclearite) predicted by the standard model of particle physics. A strangelet consists of almost an equal number of up, down and strange quarks, and has different features from the normal nuclei, e.g., higher stability, with a large mass range, low charge-to-mass ratio Z/A, and possibly with a wide range of velocity including very slow velocity values. Other examples include GUT magnetic monopoles (MMs)[4, 5] and massive cosmic neutralinos. MMs are assumed to be generated in the early universe and have very heavy mass (about 10^{16} GeV/c^2) and very low velocity $\beta=10^{-3}$. It is estimated[6, 7] that at present the intermediate mass magnetic monopoles (IMMs) might be the main part of MMs. IMMs may have lower mass (much lower than 10^{16} GeV/c^2) and possibly be accelerated to higher velocity (higher than $\beta=10^{-3}$ but still slow-moving particles) in the galactic magnetic field. Massive cosmic neutralinos, as one kind of candidate particles of cold dark matter, may collide with high energy cosmic rays and create secondary particles within which charged, massive and slow-moving particles might exist[8]. In the last decades, several cosmic ray experiments[9—18] have been performed underground, on the ground, on mountains or in space to search for such particles. As reviewed in Ref. [19] there has not get been experimental evidence that can confirm the existence of these exotic particles. In this paper we report an attempt to search for low velocity exotic particles using L3+C data.

2 The L3+C experiment

The L3+C experiment[20] uses the muon chamber of the L3 magnetic spectrometer (Fig. 1) to detect cosmic ray muons and search for exotic particles in cosmic rays. The L3 spectrometer, set up underground with an overburden of 30 m, consists of a magnet, drift chambers, and central detectors. The volume of the magnet is 1000 m^3 with the magnetic field 0.5 T. The drift chambers consist of P chambers

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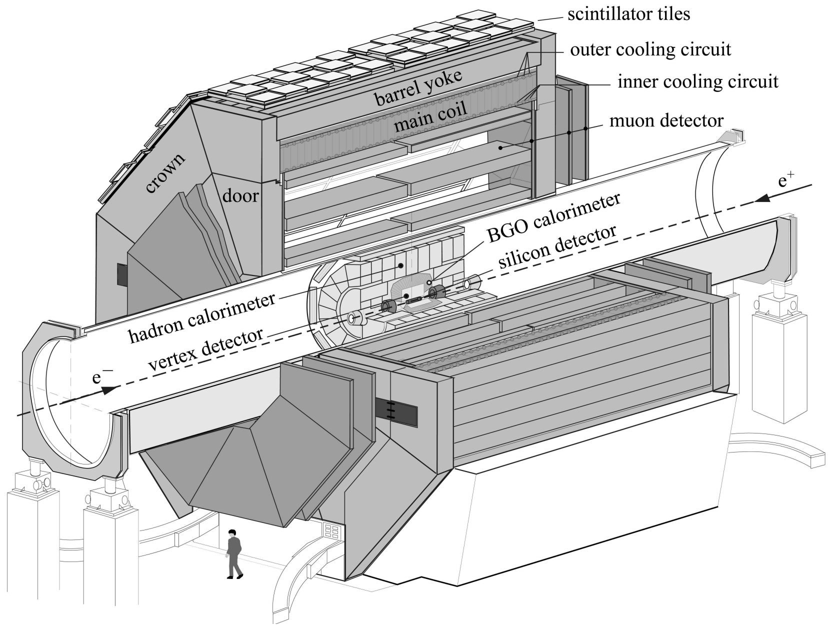

Fig. 1. The L3+C detector. The muon detector and the magnet of the L3 spectrometer, and the covered scintillators are used.

and Z chambers. The former are arranged in three layers around the beam line in an octagonal structure with the LEP beam colliding vertex in its center. The P chambers measure the track coordinates in the direction perpendicular to the magnetic field. On the two surfaces of the inner and outer layers of the P chambers, the Z chambers are mounted to measure the track coordinates in the plane along the direction of the magnetic field. In order to select cosmic ray events a layer of plastic scintillators is added on the top of the spectrometer, and an independent triggering and data taking system is applied. The trigger system of L3+C is designed for cosmic ray muons that pass through the scintillator layers and enter the muon chambers. About 95% triggered events are known to be single muons. The low velocity exotic particles that we are searching for are assumed to possess some muon-like features but with low velocity and heavy mass. Therefore, the single-muon sample serves as the background sample of our research, and the exotic particles, if any, are assumed to have the same triggering efficiency as single-muons and to be mixed in the single-muon sample.

When cosmic ray charged particles trigger the system their three-dimensional helix tracks in the magnetic field are used to evaluate their rigidity. In principle, the time-of-flight of particles, and then their velocities can be measured by the scintillator layer and the drift chambers. From the information of rigidity and velocity the charge-to-mass ratio of particles can be calculated. However, in the practical case of the L3+C experiment the particle velocity cannot be obtained in a normal way. In this work, a special method that measures the drift time difference of a track in different layers of the P chamber is applied to get the particle velocity which is shown to be effective for slow-moving particles. Our search for slow-moving particles is done from the single muon event sample. The dataset used in this analysis contains 9.5×10^9 events taken from July 15, 1999 to November 13, 2000.

3 Method

Obviously, the scintillator layers set up on the top of the spectrometer can be used to measure the arrival time of particles. However, in our analysis we found that there were an amount of noise hits in the scintillator layers due to the synchrotron radiation environment of the LEP collider that made a high accidentally coincident rate with particle tracks seen in the drift chambers. From our data the ratio of such accidentally coincidental events to the total events is known to be about 10^{-3}. Therefore, use of scintillator information might form some false slow-moving particles. To avoid these cases, only the drift chamber, but not the scintillator, information is used in this data analysis. Though the time resolution of the drift chamber is worse than that of scintillator, it will be shown below that the time resolution of the L3 drift chambers is still good for the low velocity measurement under some special circumstances.

In order to determine the velocity by the drift chambers the particle track should be long and pass through at least two layers of the chambers. Besides, we will show below that in each chamber layer the track segment must cross the wire plane, i.e. the track segment must be the so-called wire-plane-crossing (WPC) segment (Fig. 2).

In the following we take the collider vertex as the coordinate origin, the plane perpendicular to the magnetic field as the xy plane and the line crossing all sensitive wires of a cell of the chamber layer as the y axis. Since the thickness of a chamber layer is only 15—22 cm (15 cm for the inner and outer chambers, and 22 cm for the middle chambers), for a long track a segment in the xy plane can be approximately expressed by a straight line

$$x = ay + b\,, \tag{1}$$

where a and b are the slope and the intersection of the straight line, respectively, that are the unknown parameters to be determined. In one layer of the P chambers a cell includes 16—24 sense wires (16 for the inner and outer chambers, and 24 for the middle ones). Assuming we observed a track segment containing n hits $(y_i,\ t_i)$ $(i = 1,\ 2,\ \cdots,\ n)$, where y_i is the known position of the ith wire and t_i is the drift time recorded by the ith wire, we calculate x_i by

$$x_i = v_{\rm d}[(t_i - t_0) - y_i/(v_{xy}\sqrt{1+a^2})]\,, \tag{2}$$

where $v_{\rm d}$ is the drift velocity that is a known value from the performance measurement of the chamber, t_0 is an assumed particle arrival time at an arbitrarily given $y = y_0$ plane, and v_{xy} is the fraction of the particle velocity in xy plane. Here t_0 and v_{xy} are two further parameters to be determined. In order to determine all parameters, a, b, t_0 and v_{xy} the data are fitted using the straight line (1), requiring a minimum value of the function D that is defined as

$$D = \sum_{i=1}^{n}\left[v_{\rm d}(t_i - t_0) - \left(a + \frac{v_{\rm d}}{v_{xy}}\sqrt{1+a^2}\right)y_i - b\right]^2 . \tag{3}$$

To minimize D four equations are obtained. It is seen[1)] that only two of them are independent. In more detail, a and v_{xy} cannot be determined simultaneously, and t_0 and b as well. However, if the track segment is a WPC one, substituting (1) we will have two straight lines (see Fig. 2)

$$\begin{aligned} x &= ay + b, \\ x &= -ay - b \end{aligned} \tag{4}$$

that correspond to hits $(y_i,\ t_i)$, $i = 1,\ \cdots,\ m$ and $(y_j,\ t_j)$, $j = m+1,\ \cdots,\ n$, respectively. Now, (3) is substituted by

$$D = \sum_{i=1}^{m}\left[v_{\rm d}(t_i - t_0) - \left(a + \frac{v_{\rm d}}{v_{xy}}\sqrt{1+a^2}\right)y_i - b\right]^2 + \sum_{j=m+1}^{n}\left[v_{\rm d}(t_j - t_0) - \left(-a + \frac{v_{\rm d}}{v_{xy}}\sqrt{1+a^2}\right)y_j + b\right]^2 . \tag{5}$$

In this case all four parameters a, b, t_0 and v_{xy} can be determined by four independent equations coming from the minimization of the function D, showing that the particle velocity could be obtained.

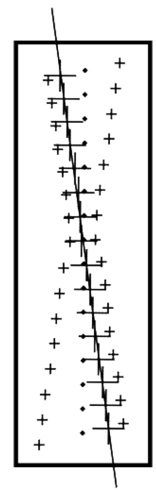

Fig. 2. An example of the WPC segment in a drift chamber cell. The ambiguity hits at some sense wires can be excluded via the track direction. The dots are sense wires, the small crosses are hits before time shifting, the large crosses are hits after time shifting and the line is the track.

Thus we specially choose those tracks having at least two WPC track segments for this study. In our practice the following way is used to determine the particle velocity between two WPC track segments. In fact, Eq. (2) cannot describe precisely the relation between the drift time t_i and the hit position $(x_i,\ y_i)$ when the drift chambers are operated in the magnetic field. Therefore, the relation between t_i and (x_i, y_i) has to be determined experimentally. This has been obtained with the so-called 'cellmap' of the chambers. For a WPC segment a least square linear fitting was applied to the data $(x_i,\ y_i)$, $i = 1,\cdots,m$ and $(x_j,\ y_j)$, $j = m+1,\ \cdots,\ n$. From Fig. 2 it can be easily seen that in the first step fitting a bad χ^2 value must be obtained. Then a small time shift is added to all $t_i (i = 1,\ \cdots,\ n)$ values to improve the χ^2. This

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procedure is repeated until an optimized time shift is obtained that corresponds to a minimum χ^2. The final time shift t_1 is assumed to be the particle arrival time (or called the WPC time) at the center of this chamber segment. In the fitting procedure the ambiguity of hit positions can be excluded via the track direction. In the same way, the particle arrival time t_2 at the center of the next chamber segment could be obtained. The flight velocity β_{12} of a particle between these two WPC segments can be calculated by

$$\beta_{12}^{-1} = \frac{t_2 - t_1}{d/c}\,, \tag{6}$$

where d is the track length between the two segments that is temporarily taken as the straight line distance between these two segment centers. The error of d is so small that it can be ignored compared with the error from the arrival time measurement. Obviously, the longer the track length, the smaller the velocity resolution.

In order to see the intrinsic fluctuation existing in the time shifts obtained by the above method we assume that the particle flies from the first WPC segment to the second one with $\beta=1$. Subtracting the time-of-flight TOF=d/c between these two segments from t_2, a value $t_1' = t_2 - \mathrm{TOF}$ is obtained. Thus $\Delta t = t_1 - t_1'$ should contain twice the intrinsic fluctuation existing in the time shifts. Making Δt distribution for all WPC segment pairs a time resolution $\sigma = \sigma_{\Delta t}/\sqrt{2} = 4$ ns is obtained for the time shifts of WPC segments.

If a track contains several WPC segments the velocity showing in Eq. (6) can be measured several times from all segment-pair combinations. We used the weighted mean value method for β calculation, that is, by taking $\frac{1}{\sigma_i^2}$ as the weight between two WPC segments,

$$\beta^{-1} = \frac{\sum_i \beta_i^{-1}\frac{1}{\sigma_i^2}}{\sum_i \frac{1}{\sigma_i^2}}\,, \tag{7}$$

where σ_i is the velocity resolution calculated from Eq. (6) taking the 4 ns time shift resolution into account, and the summation in Eq. (7) runs over all segment-pair combinations. The obtained β is treated as the first approximation of the particle velocity because so far the helix track in the magnetic field has not been considered in getting the flight distance d. In the next step, using this β as an input value the whole track is reconstructed by the L3+C reconstruction program. After that the particle rigidity is obtained, and a new β value can be re-calculated by executing Eq. (6) and Eq. (7) once more. In this step the real track length d of the helix track is used in Eq. (6).

4 Data analysis

With the method described in the last section it is seen that only those drift chamber tracks with long flight length, with multi-WPC segments and with good track quality can be used to measure the particle velocity. Due to the limitation of the track reconstruction capability, a number of events are reconstructed as single track events, but in reality they are multi-muon events, events with secondary tracks or events with noise. All these events should be ruled out. Moreover, the quality of the track reconstruction is also limited by the hit conditions. Consequently, the following data selection criteria including WPC segment selections and event selections are taken.

For WPC segment selections:

1. In each side of the sense wire plane there are at least 4 continuous hits and there are no ineffective (or inefficient) hits between these two track sections of two sides;

2. The segment is fitted with $\chi^2/\mathrm{dof} \leqslant 2$, and has $0.1 \leqslant \mathrm{slope} \leqslant 0.5$ which demands the segment be close to the sense wire and have a good time resolution.

For event selections:

1. It is a single track event and the number of WPC segments $\geqslant$4;

2. The total hits in the P chambers must be less than 400 and those in the Z chambers, less than 100;

3. The track must pass through at least two octants of the drift chambers to ensure its flight length;

4. In order to further rule out events containing secondary tracks or tracks suffering serious scattering, the deviation from any segment to the finally reconstructed track must be less than 10 cm in the P chambers, less than 50 cm in the Z chambers, and the number of hit cells must be less than 10;

5. In order to remove events with large WPC time fluctuation, for a WPC segment, the time difference between the WPC time and the calculated time from the track must be less than $5\times\sqrt{2}\sigma$ where σ is the resolution of the time shifts of WPC segments, i.e. 4 ns.

Finally, 3.4×10^6 events are selected, which are 3.6×10^{-4} of the total events. The β^{-1} distribution of selected events is shown in Fig. 3 that is fitted by a Gaussian with mean value 1.01 and standard deviation 0.18. The β measurement range is determined by the drift time range, the flight distance and the resolution of WPC times. It is known that the longest flight distance in the L3 drift chamber is 12 m and the largest drift time in a cell of the P chamber is 1μs, so the least measurable β is 0.04. On the other hand, the β^{-1} resolution of 0.18 decides that only particles with $\beta < 0.5$ can be distinguished from the normal cosmic ray muons. Therefore, the β measurable range of the L3+C drift chamber is from 0.04 to 0.5 using the method in this work.

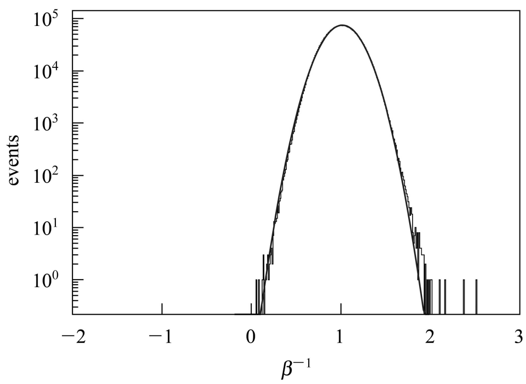

Fig. 3. The β^{-1} distribution of the total selected events. The line shows a Gaussian fitting. Four events are seen to be out of the main Gaussian distribution which are named as No. 1, 2, 3 and 4 from right to left, respectively.

A Gaussian of β^{-1} distribution with mean value 1.01 means that most events selected are common cosmic ray muons having light velocity and our method and analysis procedure work essentially well. Four events are outside the main distribution. By eye-scanning, it is judged that events No.2, No.3 and No.4 are ones having a secondary interaction with medium in the drift chambers to generate a secondary particle. In the event selection stage the events containing secondary tracks should already be ruled out by the computer program for data analysis. However, from the eye-scanning of these three events, we find that that sometimes tracks containing a short secondary track segments cannot be ruled out effectively. The deviation to a gaussian in the $\beta = 1.5$—2.0 region in Fig. 3 might possibly be caused by the same reason. Therefore, after eye-scanning, we further rule out these three events. Event No.1 (Fig. 4) is a single track event without secondary particles. The particle passes through four WPC segments, and leaves the detector after passing through the inner layer of a lower octant. The measured velocity of this particle by this method is $\beta = 0.40 \pm 0.03$. The particle has positive charge. Its measured rigidity R is 8.01 GV/c with a relative error 3%[21] or an absolute error 0.24 GV/c. From the relation

$$\frac{Z}{A} = \frac{\beta\gamma_{\mathrm{P}}}{R} \qquad (8)$$

its charge-to-mass ratio is thus obtained to be 0.052 with an error of 0.006. Knowing the standard deviation 0.18 of the β^{-1} distribution the random probability of the event with β=0.40 is obtained to be 2.7×10^{-17}. Taking the number of trials 3.4×10^{6} into account the probability 9.1×10^{-11} of the event being formed by background is deduced.

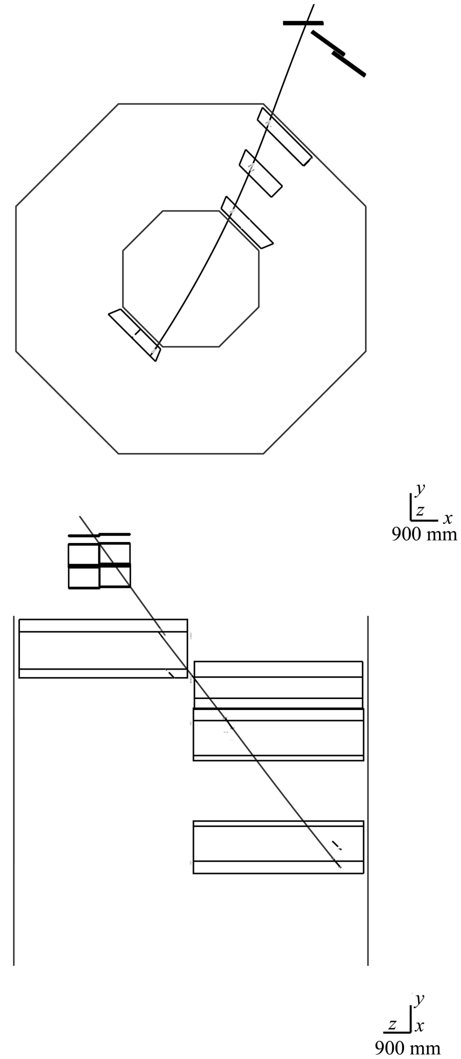

Fig. 4. Scanning of event No.1. Upper: track projection in the xy plane. There are four WPC segments. Lower: track projection in the yz plane.

This event is noticed by its low velocity. However, considering the following reasons we are not able to definitely confirm this event as a slow-moving exotic particle: the statistics is poor — it is the only event we have obtained; it is a lack of more measurable information besides its velocity and rigidity; since this particle passed the edge of the central detectors, the contribution from energy loss and elastic scattering cannot be simply ruled out; and, it is not possible to rule out secondary particles produced in the insensitive part of the drift chambers. Therefore, the flux upper limit of a null observation is estimated.

For single-μ events that satisfy the on-line selection condition of the L3+C experiment, the effective acceptance of the drift chamber is known to be 2.0×10^6 cm^2·sr[20]. The life time corresponding to our data set is 2.1×10^7s. Thus the total exposure $L=4.2\times10^{13}$cm^2·s·sr is obtained. It is mentioned that the selection efficiency for the event sample used in Fig. 3 is 3.6×10^{-4}. There is one more efficiency 0.25 used in the eye-scanning ruling out procedure. Though we are not able to do the eye-scanning for all events, for a conservative and safe consideration this efficiency is applied for the whole sample. Threfore, the overall selection efficiency $p=0.25\times3.6\times10^{-4}=9.0\times10^{-5}$ is used. The upper flux limit of the low velocity exotic particles is calculated as follows. If k low velocity events are observed within N incident events k follows the binomial distribution[22]

$$P(k)=\frac{N!}{k!(N-k)!}p^k(1-p)^{N-k}\,, \qquad (9)$$

where $p=9.0\times10^{-5}$. Taking 90% as the possibility of which at least one slow-moving event within all the incident events is observed, the probability of no one slow-moving event being observed is

$$P(k=0)=(1-p)^N=1-90\%=0.1\,. \qquad (10)$$

Then the event number upper limit at the 90% confidence level is

$$N_{0.9}=\frac{\lg 0.1}{\lg(1-p)}=2.6\times10^4\,. \qquad (11)$$

Therefore, the corresponding flux upper limit at 90% c.l. is

$$I_{0.9}=\frac{N_{0.9}}{L} \qquad (12)$$

which is 6.2×10^{-10}cm^{-2}·s^{-1}·sr^{-1}.

5 Conclusion

In the L3+C experiment, making use of the L3 muon magnetic spectrometer, spatial tracks of cosmic ray charged particles are measured to obtain the particle rigidity. A method based on the measurement of the time shift difference of WPC track segments of the drift chambers to determine the particle velocity is developed, and is shown to be effective in detecting slow-moving particles. One event possibly showing the feature of a low velocity exotic particle is observed with the apparent velocity $\beta=0.40\pm0.03$, rigidity (8.01 ± 0.24) GV/c and charge-to-mass ratio 0.052 ± 0.006. However, limited by the present experimental conditions no firm conclusion is made. It is treated at the present work as a null observation and the upper flux limit of the low velocity exotic particle is estimated to be 6.2×10^{-10}cm^{-2}·s^{-1}·sr^{-1} at a 90% confidence level in the β range from 0.04 to 0.5.

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