第29卷 第8期 高 能 物 理 与 核 物 理 Vol.29, No.8
2005年8月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Aug., 2005

Study on the Muon Background in the Underground Laboratory of KIMS *

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Abstract KIMS is a group aiming at the search for WIMP. In WIMP search experiment, the muon is one important background. We measure the muon flux in Yangyang laboratory where is located at 700m underground. The structure and performance test of muon detector is described. The analysis on muon hit position and angle distribution has been performed. The simulations of muon flux have been done. The muon flux in the laboratory is found to be about $(7.0 \pm 0.4) \times 10^{-8}/\mathrm{s/cm^2/sr}$.

Key words dark matter, WIMP, muon, position reconstruction

1 Introduction

It is known that dark matter is the main component of the universe[1, 2], and the Weakly Interacting Massive Particle (WIMP) is one of the most possible candidates. There are several experimental groups trying to find it, such as DAMA, ZEPLIN-I, GENIUS, EDELWEISS, CDMS, and so on[3—7]. They already got some result to estimate the limit of WIMP mass; especially DAMA published a much exciting result by using the annual modulation effect of WIMP.

The KIMS (Korea Invisible Mass Search group) experiment is also a group aiming at the search for WIMPs. The experimental program is in collaboration between China and Korea. One special point of the KIMS collaboration is that it is the first group to use CsI(Tl) crystal as detection material in the experiment, while the other groups mainly use NaI(Tl) crystal or low temperature detector.

Because the interaction between WIMP and nucleon is weak, the cross section of the interaction is extremely low ($< 10^{-41}\mathrm{cm^2}$). So the low background environment is necessary for the experiment, usually this kind of experiment is located at underground to reduce the neutron and muon background. The KIMS experiment is at 700 meter deep underground. Even at underground, the muons from cosmic ray can not be completely prevented because of its very high energy ($> 1\mathrm{GeV}$).

A high energy muon can generate neutrons by interacting with surrounding rocks, and shielding materials. Those neu-

Received 24 November 2004, Revised 25 February 2005
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trons are very harmful for the experiment, because the nuclear recoil signal of neutron and that of WIMP is indistinguishable. So we need to know about the muon background level of our underground laboratory.

2 Structure of muon detector

Beside of arranging the experiment at underground, we also need good shielding to reduce background level. The structure of the shielding is — from inside to outside — 10cm copper, 5cm PE (polyethylene), 15cm lead and 30cm mineral oil (as muon detector), and inside of copper box are CsI(Tl) crystals — the main material to search WIMPs.

The outermost layer made of mineral oil acts as a muon detector as well. There are totally 8 quadrate detectors surrounding the other materials in 4π angle from 6 directions (Fig.1). There is a detector for every direction except for the bottom which has 3 smaller detectors to support the heavy shielding materials. It is also a shielding of neutrons of environment.

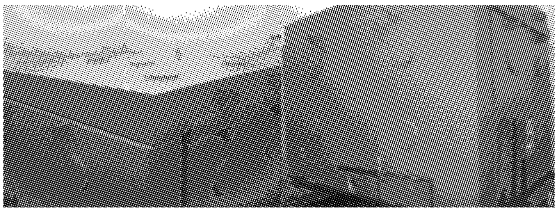

Fig.1. Size of muon detector and the readout windows.

The container of muon detector with 30cm thickness is made of steel. The capacity of all the 8 detectors is about 7800 liters. We use 95% mineral oil plus 5% homemade liquid scintillator (Pseudocumene + PPO + POPOP) as detector material.

There are glass windows on the surface of every detector for signal read out. For the detector at top, it has 6 windows on the surface; for the detectors of 4 sides, each detector has 4 windows; for the 3 detectors at bottom, they all have 2 windows at both sides. So there are totally 8 detectors and 28 windows. For each window, we use two 2 inch PMTs for read out.

3 Performance of muon detector

Before we install all the detectors at underground laboratory, one of them has been tested at ground experimental laboratory, which should be at bottom and has two windows at both sides.

3.1 Attenuation length test

When the scintillation light transmits in the liquid it will be attenuated as distance increase. To know the exact relation between light intensity received by a PMT and distance between the light source and the PMT, we do the test using cosmic ray muons with moving a 0.5 liter BC501A trigger detector to change the distance between the trigger point and the PMT, and record the corresponding PMT signal, then we can get the result (Fig.2).

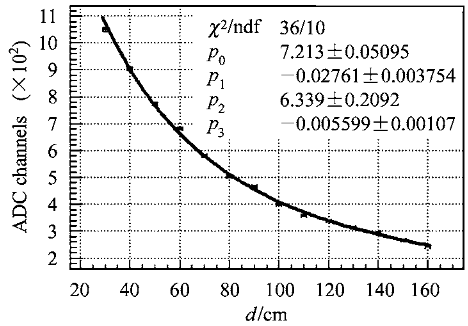

Fig.2. Double exponential function fitting for attenuation length test.

Attenuation curve shown in Fig.2 is fitted with a double exponential function:

$$E = k \times (e^{p_0+p_1 d} + e^{p_2+p_3 d}),$$

Here E means the light intensity received by PMT, k is scale constant, d is the distance between the trigger point and the PMT, and p_0 to p_3 is fitting parameters which gives ratio and attenuation length for two exponential components.

3.2 Detection efficiency

Two trigger detectors have been used for the measurement of muon detection efficiency, a 0.5 liter BC501A detector and a 20cm × 20cm plastic scintillator. The former one has been put on the muon detector and the latter has been put under the muon detector. The coincidence of the two detectors' signal gives a trigger to select events in which muons pass through all 3 detectors. Then we look at the pulse spectrum of muon detector and find the inefficient events, and then the detection efficiency can be calculated.

We take a data more than 100000 events. In order to get real muon events, we cut out low energy area and 26442 events remain. There are 25942 events have passed through all 3 detectors. So the detection efficiency of muon detector is about 98%. Considering of the large gamma background the accidental coincidence of two trigger detectors should be estimated. The count rate of whole system is about 1—2Hz, while that of BC501A detector is about 60Hz and that of plastic scintillator is about 140Hz, and the gate width of discriminator is 60ns. So the trigger rate of accidental coincidence can be calculated as $2\times 60\text{ns}\times 140\text{Hz}\times 60\text{Hz}\approx 0.0015\text{Hz}$. Compare to total count rate, this level is neglectable.

4 Measurement and data analysis

4.1 Electronics system

Because we have 28 channels, and each channel has two PMT, so the electronics could be a little complicated (Fig.3).

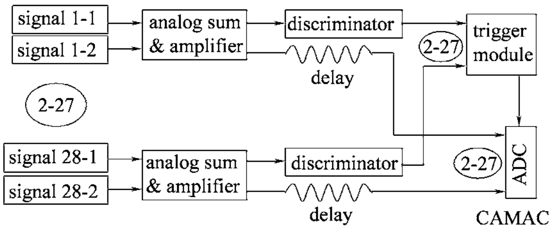

Fig.3. Diagram of electronics system for muon detector.

To form a muon event trigger we take logic AND for any of two window for each detector then logic OR of all detectors. That means, if there is 2 or more channels give a trigger at same time inside of one detector, we think this detector gives a positive signal; if there is at least 1 detector gives a trigger, the whole system has been triggered. Most events triggered in this way are from gamma ray produced by the radioactive decay of surrounding rocks hitting near the PMT. To find real muon events we require two or more muon detectors give trigger signal in one event. Using this requirement, we got a muon rate in the underground laboratory about $380/\text{d}/\text{m}^2$. It is equal to $7.0\times 10^{-8}/\text{s}/\text{cm}^2/\text{sr}$ of muon flux. The statistic error is about 5.13%, and the error from muon efficiency test is about 0.62%. Also there should be error from some other high energy particle such as proton and neutron, but compare to the first two, it's negligible. So the muon flux can be summarized as $(7.0\pm 0.4)\times 10^{-8}/\text{s}/\text{cm}^2/\text{sr}$.

4.2 Reconstruction of muon hit position

One importance of muon detector is to do anticoincidence with CsI(Tl) crystal signal since muon could produce prompt neutrons. Knowing the direction of muons would help to understand background caused by muons. The direction of a muon can be found by the accurate determination of the muon hit positions.

The method of minimum chisquare has been used[8] to find out the hit position. For example, in each event we can get six signals $E[1]$ to $E[6]$ from the top detector which has six windows. Suppose E_m for measured value and E_c for expected value. The procedures are following:

1) We can get 15 relative difference ratio $R_m[1]$ to $R_m[15]$ and the variation $ERR_m[1]$ to $ERR_m[15]$ from measured value $E_m[1]$ to $E_m[6]$ respectively:

$$R_m[k]=(E_m[i]-E_m[j])/(E_m[i]+E_m[j]),$$

$$ERR_m[k]=\sqrt{(E_m[i]^2+E_m[j]^2)/(E_m[i]+E_m[j])^2}$$

$$(i,j=1\sim 6 \text{ and } i\neq j, k=1\sim 15).$$

2) Once we choose a point in the detector and calculate the distances between this point and the six windows, then we can get the estimated value $E_c[1]$ to $E_c[6]$ according to the double exponential function introduced in section 3.1 and the relative difference ratio $R_c[1]$ to $R_c[15]$ and the variation $ERR_c[1]$ to $ERR_c[15]$ from above formula.

3) The calculation of the chisquare value χ between R_m and R_c:

$$\chi=\sqrt{\sum_{i=1}^{15}(R_m[i]-R_c[i])^2/(ERR_m[i]^2+ERR_c[i]^2)}.$$

4) Choose other points and repeat step 2 and 3 we can get their chisquare, the point which has minimum chisquare value is what we are looking for: muon hit position.

To verify the validity of this method, we have put an $85\text{cm}\times 20\text{cm}$ plastic scintillator at the center of top for choosing the muon events which only hit the center area of muon detector. After reconstruct the position of muon hit using this method we find that the position variation is about 13cm in sigma.

Besides, the simulation code GEANT4[9] has been used to verify the effect too. Muon has been generated from a rectangular area above the top detector; the size of this area is 2 times of that of the top detector. Muon is generated at random position inside of this area and in random direction (downward 2π angle). The muon which hit on detectors has been recorded, and then we can use the recorded "ADC" information to reconstruct its hit position on each detector. Fig.4 shows the comparison of reconstructed muon hit position and generated hit position.

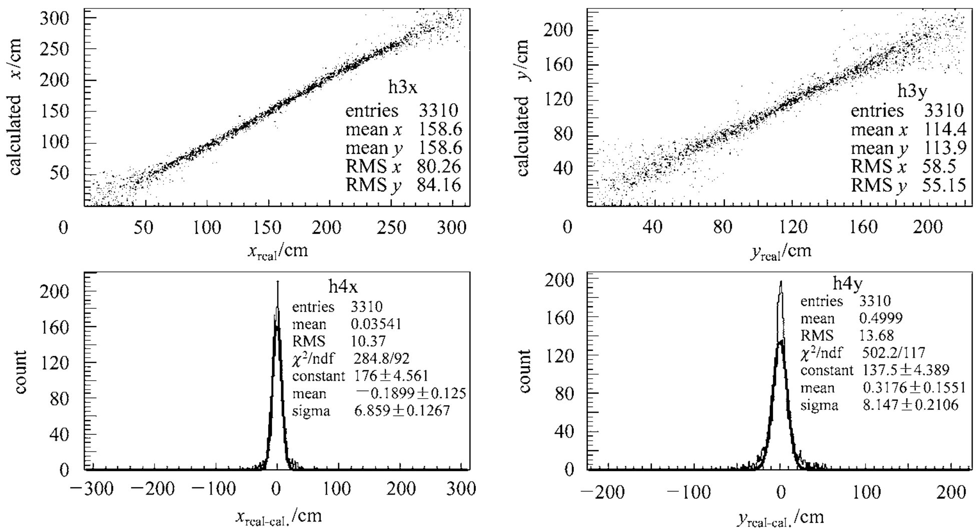

Fig.4. Comparison of reconstructed muon hit position distribution and simulation data in x-axis and y-axis.

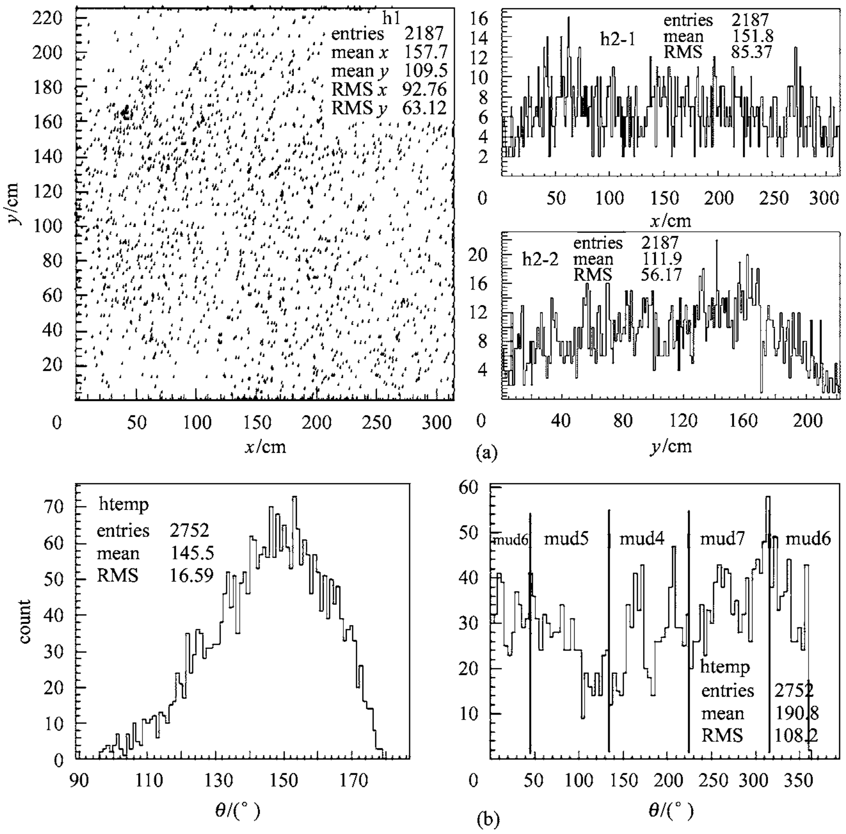

Fig.5. (a) Reconstructed muon hit position on top detector based on background data, the left is 2-dimensional distribution and right is the projection in x-axis and y-axis;
(b) Angle distribution of muon background, left is θ and right is φ.

We compare the reconstructed result and generated one directly in x-axis and y-axis. It seems that the result at center area is fairly good, but the result at edge area is worse. From the projection we can see the sigma value is about 7cm (for x-axis) and 8cm for (y-axis) mainly based on for the center area.

Test on detectors of vertical direction has also been done. Because there are only 4 windows for each detector, the result is much worse. Considering most muon comes from vertical direction, we mainly pay attention on top and bottom detectors.

4.3 Angular distribution

After found the hit position on all the detectors, we can get both position and angle of the muon track. We can also use the simulation data to verify the effect. We use two parameters: θ for vertical direction (0—180 degree, upward is 0 degree) and φ for horizontal (0—360 degree) to define the coordinate of the muon track. From comparison of the reconstructed angle distribution and simulation data we can get angle variation about 8 degrees for θ and 16 degrees for φ.

4.4 Muon cosmic ray background in laboratory

According to the analysis above, it seems our reconstructing method works well. We have studied muon cosmic ray background in underground laboratory. Fig.5(a) shows the position distribution of cosmic ray background, it seems uniform. Fig.5(b) shows the angle distribution of cosmic ray background and one can find non-uniform distribution for angle φ. This is because the laboratory is located at mountain area, and the thickness of the rocks from different phi angle is not the same. The observed phi angle distribution is found to be qualitatively consistent with the shape of the mountain surface.

5 Conclusion

Muon detector made of mineral oil mixed with liquid scintillator has been developed for the KIMS wimp search experiment. The detector is installed in the Yangyang underground laboratory and has been in operation. The reconstruction method and algorithm to find muon hit position has been developed. The effect of the reconstruction method has been tested using a small plastic scintillation counter and we find that the one sigma variation of the difference to be about 13cm. GEANT4 simulations have been done for this purpose and the variation of position between simulation data and calculated result is not more than 8cm in one standard deviation. The angle distribution of muon has also been analyzed. The angle variation between simulation data and calculated result is 8 degree in vertical and 16 degree in horizontal. Using this detector, the muon flux at 700m underground laboratory of Yangyang has been measured to be about $(7.0\pm0.4)\times10^{-8}/\mathrm{s}/\mathrm{cm}^2/\mathrm{sr}$ and angular distribution of incoming muons are also measured.

We are very grateful to the Korea Midland Power Co. and their staffs for providing the underground laboratory space at Yangyang.

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KIMS地下实验中μ子本底的研究*

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摘要 KIMS是寻找和研究暗物质WIMP的实验组.在WIMP寻找实验中,μ子是十分重要的一种本底.我们对地下700m深的Yangyang实验室内的μ子通量进行了测量.介绍了μ子探测器的结构和性能测试.描述了对μ子入射位置和角度分布的分析,并进行了蒙特卡罗模拟.实验室内的μ子通量测量值为$(7.0\pm0.4)\times10^{-8}/s/cm^2/sr$.

关键词 暗物质 WIMP μ子 位置重建

2004-11-24收稿,2005-02-25收修改稿
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