An Estimation of Muons that are Produced on the Ground

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Abstract

I find that some experiments can be used to estimate numbers of the muons that produced on the earth's surface except of that come from cosmic ray particles in the atmosphere. However, calculation showed that the high energy muons on the ground mainly come from cosmic rays. The ground should lack of mechanisms to produce high-energy muons.

Key words

Muons; Neutrinos; Cosmic Ray

The passed experiments shown that there are numerous muons existed in the earth's surface. The old theories claim that all of those muons are come from the high altitude atmosphere. The height is about 15km. The muons are the secondary cosmic ray particles, which produced by the primary cosmic ray that interacting with the oxygen or nitrogen atoms and molecules. That is, after interacted with atoms or molecules in the atmosphere, the primary cosmic ray will produce mesons, neutrons and etc. The mesons will decay to muons.

Since muons' life time is very shorter, it will need to consider the special relativity effects to reach at the ground. It also becomes the important evidence to support the special relativity theory. [1]

However, I found that the interactions among neutrinos and electrons can also have the abilities to produce numerous muons besides the cosmic ray in the high altitude atmosphere in my previous works. [2, 3] On the other hand, the neutrinos can interact with electrons on the ground besides in the atmosphere. It is different from the older theories. So it can be proofed by the experiments. I will analysis it by an undergraduate experiment in this paper.

1 Wu's experiments on muons' lifetime

Since there are large amount of muons on the earth's surface and there are also mature detecting technologies, many instruments had been designed [4~6] to detect the muon's lifetime over the past few decades. Some instruments are designed specifically for undergraduate students. Because the popularity is very wide, a large number of students involved in the experiment, so the results are also very reliable.

Here I use the results of Wu et al. [6] to analysis this question. Wu and his co-workers designed an apparatus to measure the life time of muons naturally produced in the air in 2010. This apparatus can be used for teaching undergraduate students knowledge of muons. 其他作者的装置基本类似。

The device of Wu et al. is mainly a plastic scintillator of about 0.3 meters long, and when a muon passes through the scintillator, it will produce electrons and fluorescent photons in the scintillator. At this point the muon produces a fluorescent trace that is a straight line. It can be detected immediately.

The experiment detection time window is set to 20 μs, that is, if two pulses can be detected continuously in a time period of 20 μs, it can be judged as a decay event of the muon. It is very small probability for two low-energy muons fly into the scintillator in the same time.

High-energy muons can pass directly through the scintillator without decay. But muons with lower energy at about 100MeV cannot wear out the scintillator and decay in them ultimately due to the occurrence of a large proportion of the energy loss. After decay, it will produce electrons as well as electron and muon neutrinos.

The electrons that produced by the muon decay process will interact with the scintillator to produce fluorescence. Since the electrons after decay are not necessarily in the same direction as the motion of the muons, and the decay process will also take times, it can be easily distinguished from the trajectories of the incident muons.

The external electronic device can measure when the muons incident scintillator and when the muons decay. After then, the time difference can be calculated to determine how long the muons decay.

2 Experiment results

Wu at el. collected 18296 events. Their results shown that the muons' decay time is about 2124.6±9.6ns. It is close to the actually lifetime 2197.03ns of muons.

In addition, the apparatus detects the muons frequency up to 10 Hz. The scintillator base area of about 0.045 m^2, which means that the flux of muons on the ground is about

$$\frac{10}{0.045} = 222(m^{-2}sr^{-1}s^{-1}) = 13320(m^{-2}sr^{-1}min^{-1})$$

Besides Wu's experiment, there are many other authors had done this experiment back in the 1970s.

Coan, T et al. Designed a apparatus that detected a total of 28,963 muons decay events in 480 hours in 2005. The average lifetime of these low-energy muons is $\tau_\mu = 2.19703 \pm 0.00004$μs. It can be estimated that the fluxes of the low-energy muons that can decay in their experiments are

$$\frac{28963}{480 \times 3600 \times \pi 0.152^2} = \frac{0.23}{m^2 sr\ s}$$

Hall [7] and others designed a simple apparatus to measure cosmic ray muons lifetime in 1970. The apparatus is composed of a scintillator that can detect income and decayed muons. After 695 hours, they obtained the results that showed a mean decay time of 1.64 μs, which was quite different from the data measured by other authors in the later period. In addition, their experiments show that the flux of the Earth's surface muons is about

$$\frac{0.02}{\mathrm{cm^2 sr\ s}} = \frac{200}{\mathrm{m^2 sr\ s}}$$

Another experiment was done in 1978 by Owens et al. In contrast to Hall et al., Owens used a simpler apparatus that required only a plastic scintillator. Their apparatus' time window set at 10 μs. They detected a total of 18000 events, the result is that the muons mean decay time is 2.32μs. This is also close to the actual life of the muons. In addition, in their apparatus, six muon incident events can be detected per second, while the decay event is about 50 per hour. The flux of the muon can be calculated as

$$\frac{6}{\pi 0.15^2} = \frac{85}{m^2 sr\ s}$$

This result is less than the usual values. It is possibly due to the fact that their apparatus is surrounded by 10 cm thick lead to block the entrance of some muons.

While the flux of low energy muons that can decay is

$$\frac{50}{3600 \times \pi 0.15^2} = \frac{0.2}{m^2 sr\ s}$$

This is consistent with the results of Coan et al.

3 Analysis

From the above analysis, combined with the known data, we can simply estimate numbers of muons that can reach the ground produced by the atmosphere cosmic ray.

Taking into account the fact that most of atmosphere cosmic rays particles are exceed the energy of 1GeV, we can estimate the lower limit flux of atmosphere cosmic rays particles

$$10^4 (m^{-2} sr^{-1} s^{-1})$$

According to the average speed of 0.995c, muons falling from the height of 15km will take time to

$$\frac{15000}{0.995 \times 3 \times 10^8} = 50(\mu s)$$

By considering the relativistic effects, the lifetime of the muons can be extended to 20μs. So that muons that can reach at ground is about

$$10^4 \times 0.5^{\frac{50}{20}} = 1768(m^{-2}sr^{-1}s^{-1})$$

We can roughly estimate the loss rate of the muons since they will interact with the atoms or molecules in the air. According to Frisch[1] et al. experiment, Muons interact with the atoms or molecules in the air will result in the effect of time dilation from 10 times to 8.8 times after 2km.

That means the speed decreases by about 0.7% after about 2km. So according to Frisch's method, we can calculate the mean value of the slowdown coefficient of each segment (2km long)

$$\frac{1}{7}\sum_{i=0}^{6} \frac{1}{\sqrt{1-0.995^2(1-0.007)^{2i}}} = 5.28$$

That is, the lifetime of muons can be extended to 10.5μs.

The number of muons that reach the ground is thus:

$$10^4 \times 0.5^{\frac{50}{10.5}} = 369(m^{-2}sr^{-1}s^{-1})$$

It can be seen that the theoretical calculation results are in good agreement with the experimental results.

So the conclusion of the high energy ground muons are come from atmosphere cosmic rays is correct.

Of course, high-energy cosmic ray particles may also be affected by the Earth's magnetic field, taking into account the Earth's magnetic field strength:

$$25 \times 10^{-6}T$$

The force adding to a unit charged particle is:

$$\mathrm{e} \times \mathrm{v} \times \mathrm{B} = 1.6 \times 10^{-19} \times 3 \times 10^8 \times 25 \times 10^{-6} = 1.20 \times 10^{-15}(N)$$

If we take into account the muon's mass

$$1.88 \times 10^{-28}kg$$

The acceleration that a muon obtain from the magnetic force is

$$\frac{1.20 \times 10^{-15}}{1.88 \times 10^{-28}} = 6.38 \times 10^{12} (\frac{kgm}{s^2})$$

It can be seen that the acceleration is very large. Without regard to the relativistic effect, such a large acceleration will cause the muon run away in 50μs

$$\frac{1}{2} \times 6.38 \times 10^{12} \times 50^2 \times 10^{-12} = 7975(m)$$

If the relativistic effect is taken into consideration, the mass of the high-speed motion muon will increase by a factor of 10. So the offset distance caused by geomagnetic field is much smaller.

We can see that although the Earth's magnetic field can take great impact on the muons, but will not lead to too many muons loss. The geomagnetic field has a serious effect only on cosmic ray particles far enough away from the earth.

4 Conclusion

It is shown that the high energy muons on the ground mainly come from cosmic rays. The ground should be the lack of mechanisms to produce high-energy muons.

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Appendix: Chinese Version

产生于地面的 μ 子数量估算

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摘要：*通过一个大学本科物理实验装置可以大致估算地球表面数量众多的 μ 子，除了来自高空大气层宇宙射线粒子，还有部分 μ 子是地面产生的。不过计算结果显示，地面的高能 μ 子主要还是来自大气层的宇宙射线。*

关键词：*μ 子；中微子；宇宙射线*

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Key words

Muons; Neutrinos; Cosmic Ray

现有的实验已经证明，在地球表面存在大量的 μ 子。一般认为这些 μ 子主要来自大气层上空大约 15km 处，宇宙射线粒子与大气层中的氧和氮原子相互作用以后的产物。属于宇宙射线的二次粒子。即宇宙射线中的质子等粒子与大气层原子相互作用以后，形成 π 介子等粒子，这些 π 介子进一步衰变，就可以形成 μ 子等二次粒子。

由于 μ 子的寿命非常短，只有 2μs，要穿行十几千米达到地面，需要考虑狭义相对论效应。

这也成为了支持狭义相对论的一个重要证据[1]。

不过我在前期分析粒子结构的工作[2,3]中发现，除了宇宙射线粒子（除了中微子）能够产生大量 μ 子以外，中微子直接同物质中的电子相互作用也同样能够产生大量的 μ 子。而且中微子可以直接在地面上直接与电子相互作用产生 μ 子，这极大地丰富了地球表面 μ 子的来源。本文将通过分析一个实验案例来证明新的理论。

1μ 子寿命测量实验

由于地球表面 μ 子数量非常丰富，检测 μ 子的技术也非常成熟，国内外很早就已经设计了相应的装置[4~8]，提供大学本科生测量 μ 子寿命以及探讨相对论效应之用。由于普及面非常广，参与实验的大学生数量众多，因此其结果也非常可靠。

这里以 2010 年，中国科技大学的吴雨生等人设计了一个专门测量地面自然产生的 μ 子寿命的实验装置[6]为例来进行分析。其他的装置基本类似。

吴雨生等人的装置主要是一个大约 0.3 米长的塑料闪烁体，当 μ 子穿过该闪烁体的时候将在闪烁体中产生电子和荧光光子。此时 μ 子所产生的荧光轨迹是一条直线。这是可以被立即检测出来的。

实验检测时间窗口设定为 20μs，即如果在 20μs 的时间中能够连续检测到两个脉冲，则可以判断为一次 μ 子的衰变。因为在这么多的时间中同时有两个低能 μ 子进入闪烁体的几率是非常小的。

高能 μ 子可以直接穿过闪烁体而不会发生衰变。但是能量在 100MeV 的 μ 子由于与闪烁体发生作用发生大比例的能量损失，最终无法穿出闪烁体而在其中产生衰变。衰变以后将产生电子以及电子和 μ 子中微子。

其中 μ 子衰变产生的电子又将与闪烁体相互作用产生荧光。由于衰变以后的电子其运动轨迹与 μ 子运动方向不一定相同，且衰变需要一定得时间，因此可以很容易将其与入射 μ 子的轨迹区分开来。

通过外部的电子装置测量 μ 子入射闪烁体的时间以及 μ 子发生衰变的时间，二者之差就是低能 μ 子的衰变时间。

2 实验结果

吴雨生等人收集了 18296 个结果，经过数据处理和分析以后，得出所测量的 μ 子衰变时间为 2124.6±9.6ns，该结果非常接近 μ 子实际的平均寿命 2197.03ns，说明结果还是比较可靠的。

另外该装置检测所有 μ 子的频率达到 10Hz, 该闪烁体底面积大约 0.045m^2，也就是说这些地球表面 μ 子的通量大约是

$$\frac{10}{0.045} = 222(m^{-2}sr^{-1}s^{-1}) = 13320(m^{-2}sr^{-1}min^{-1})$$

除了吴雨生等人的实验以外，早在 20 世纪七十年代开始就已经陆续有很多作者开展了这方面的实验。

Coan, T 等人在 2005 年设计了一个装置，该装置在 480 个小时中一共检测到 28963 个事件。得到这批低能 μ 子的平均寿命为 $\tau_\mu = 2.19703 \pm 0.00004\mu s$. 可以估算出他们的实验中能够发生衰变的低能 μ 子的通量为：

$$\frac{28963}{480 \times 3600 \times \pi 0.152^2} = \frac{0.23}{m^2 sr\, s}$$

Hall[7]等人在 1970 年设计了一个测量宇宙射线 μ 子寿命的简单装置。该装置由多个闪烁体构成，分别检测入射和衰变后的 μ 子。他们的装置在运行了 695 个小时之后获得的结果表明，μ 子平均衰变时间为 1.64μs, 该数据与后期其他作者测量的数据有比较大的差距。另外他们实验表明地球表面 μ 子的通量大约为

$$\frac{0.02}{\mathrm{cm^2 sr\, s}} = \frac{200}{\mathrm{m^2 sr\, s}}$$

另一个实验则是 Owens[8]等人在 1978 年完成的，与 Hall 等人的装置不同的是，他们使用了一个更简单的装置，只需要使用一个塑料闪烁体，时间窗口设定在 10μs，即在满足 10μs 时间中基本上没有同时两个 μ 子衰变的前提下，只要检测到在这么短的时间中出现两次脉冲，就可以判断出现了一个 μ 子衰变的事件。他们一共检测到了 18000 个事件，得到的结果是 μ 子平均衰变时间为 2.32μs. 这也比较接近 μ 子的实际寿命。另外在他们的装置中，每秒中可以检测到 6 个 μ 子入射的事件。而衰变的事件则是每小时 50 个。可以计算出 μ 子的通量为：

$$\frac{6}{\pi 0.15^2} = \frac{85}{m^2 sr\, s}$$

该结果少于通常的数值，主要原因可能在于他们的装置外围包裹了 10cm 厚度的铅，阻挡了部分 μ 子的入射。

而能够衰变的低能 μ 子通量则为：

$$\frac{50}{3600 \times \pi 0.15^2} = \frac{0.2}{m^2 sr\, s}$$

这与 Coan 等人的结果基本一致。

3 分析

通过上面的分析，结合已知的数据，可以简单估算一下大气层宇宙射线产生的 μ 子到达地面的数量。而超出这一数值的则可能就是地面某种机制产生的 μ 子。

考虑到大气层宇宙射线以能量为 1GeV 的粒子为主，则可以估算出大气层宇宙射线的通量下限大约为：

$$10^4(m^{-2}sr^{-1}s^{-1})$$

则按照平均 0.995c 的速度来计算，从 15km 高空掉落下来需要时间为：

$$\frac{15000}{0.995\times 3\times 10^8}=50(\mu s)$$

考虑相对论效应，则 μ 子的寿命可以延长为 20μs. 这样达到地球表面所有能量的 μ 子数量为：

$$10^4\times 0.5^{\frac{50}{20}}=1768(m^{-2}sr^{-1}s^{-1})$$

即便考虑到地球磁场效应等，可以判断地球表面的 μ 子都是来自宇宙射线的。但是同实验结果相比，不过这一数量超出了地球表面 μ 子的通量。如果仅仅依靠在空气中的衰减来看，可以大致估算 μ 子的损失率：

即便按照 Frisch[1]等人的实验，μ 子与空气中的原子或分子产生相互作用，导致时间变慢的效应从 10 倍降低到 8.8 倍，仍然可以计算出到达地面的 μ 子数量达到每平方米每秒 1397 个，是实验测得的数据的 6 倍。

当然也可以考虑 μ 子到达地面的时候，速度整体上减慢了，故相对论效应还会降低一些。这样按照 Frisch 等人的实验情况，如果这种相互作用一直呈现线性的关系，则每经过大约 2km 距离，速度从 0.995c 减慢到 0.988c，速度大约降低 0.7%，则可以计算出达到地面时，速度已经降低的比较低了。

按照 Frisch 的方法，取各段距离时间变慢系数的平均值，这样可以计算出 μ 子到达地面，时间变慢的系数为

$$\frac{1}{7}\sum_{i=0}^{6}\frac{1}{\sqrt{1-0.995^2(1-0.007)^{2i}}}=5.28$$

即 μ 子的半衰期可以延长到 10.5μs

这样到达地球表面的 μ 子的数量为：

$$10^4\times 0.5^{\frac{50}{10.5}}=369(m^{-2}sr^{-1}s^{-1})$$

可以看出理论计算的结果与实验结果基本一致。

因此地面 μ 子来自地球上空的宇宙射线的结论是正确的。

当然高能宇宙射线粒子还可能受到地球磁场的影响，考虑到地球磁场强度为：

$$25 \times 10^{-6} T$$

则一个带电量为 e 的粒子受到的力为：

$$\mathrm{e} \times \mathrm{v} \times \mathrm{B} = 1.6 \times 10^{-19} \times 3 \times 10^{8} \times 25 \times 10^{-6} = 1.20 \times 10^{-15} (N)$$

如果考虑到 μ 子的质量为：

$$1.88 \times 10^{-28} kg$$

可以计算出 μ 子因为地磁场获得的加速度为：

$$\frac{1.20 \times 10^{-15}}{1.88 \times 10^{-28}} = 6.38 \times 10^{12} (\frac{kgm}{s^2})$$

可以看出加速度是非常大的。不考虑相对论效应，这么大的加速度将导致 μ 子在 50μs时间内横向偏移

$$\frac{1}{2} \times 6.38 \times 10^{12} \times 50^2 \times 10^{-12} = 7975(m)$$

如果考虑相对论效应，高速运动的 μ 子质量将增加 10 倍，则 μ 子因为地磁场横向偏移的距离还要小很多。

可以看出尽管地球磁场对 μ 子的影响很大，但是不会导致太多 μ 子损失。地磁场只对那些离地球足够远的宇宙射线粒子有很严重的影响。

4 结论

通过计算表明地面上的高能 μ 子主要来自宇宙射线。地面上应该缺少产生高能 μ 子的机制。

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