Anisotropy of μ-Rich Air Showers

S. Sakakibara and Y. Sekido
Department of Physics, Nagoya University, Nagoya, Japan
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The data of μ-meson-rich air showers of cosmic rays observed at Tokyo and Yaizu were analyzed. The result showed that the arrival direction is nearly parallel to the Galactic arm, and the primaries are coming from the direction of the spiral out of the arm.

ANISOTROPY of μ-meson-rich air showers of cosmic rays was reported by Hasegawa *et al.*[1,2] They showed the direction of each μ-rich air shower in a map of the equatorial coordinates, and found that the distribution in right ascension α was not uniform, i.e., the maximum was at $\alpha=(3\sim 15)$h and the minimum was at $\alpha=(15\sim 18)$h. From this anisotropy, they tentatively concluded that the maximum corresponded to the general direction perpendicular to the Orion arm. This interpretation was based only on the α dependence along the band around the declination $\delta=35°$N, without any treatment on the effect of atmospheric absorption. However, we can expect the α dependence also from an assumption that the primaries are coming from the direction of the spiral out along the Galactic arm. In order to know whether the anisotropy is perpendicular or parallel to the Galactic arm, the intensity distribution in δ or some suitable coordinate systems should be examined. Their map does not directly show the intensity distribution, for the distribution in the other coordinates than α is largely affected by the atmospheric absorption. In this paper, their data were analyzed with various coordinate systems after taking the effect of the atmospheric absorption into account. In this analysis, the effect of the nonuniform distribution of operating hours in sidereal time was also taken into account, and the data were revised adding some number of showers. The result showed that the arrival direction is rather parallel to the Galactic arm. This important change of the interpretation of the anisotropy mainly comes from the consideration about the distribution in the other coordinates than α, for α dependence is not appreciably changed from that of the Hasegawa *et al.* result.

The basic data concerning 94 μ-rich air showers, observed in the period from 1959 to 1961, were supplied from the two stations, Tokyo and Yaizu. The number of showers in a range of size N and in a range of zenith distance z is shown in Table I together with the range of $O(t)$ which is the number of days when the equipment was operating at the sidereal time t. The discrimination of data is the same as those in Refs. 1 and 2. The expected number j_0 of μ-rich air showers in a particular range of N and z, in a finite solid angle ($\alpha_1<\alpha<\alpha_2$, $\delta_1<\delta<\delta_2$) in the equatorial coordinates is calculated for the isotropic incidence by the following equation:

$$j_0(\alpha_1,\alpha_2,\delta_1,\delta_2,)=\int_{t=0}^{24}\int_{\delta_1}^{\delta_2}\int_{\alpha_1}^{\alpha_2} 0(t)F\cos^m z\cos\delta d\alpha d\delta dt\,, \quad (1)$$

where F is the vertical flux and the integration is limited in the range of N and z. The dependence of the power m on the relative content of μ mesons was checked with the N–n_μ diagram of Tokyo. The difference in m values for μ-rich and the other air showers was in the error of ± 2. The zenith angle distribution of 74 multiple penetrating particles (m.p.p.) air shower at Yaizu gave $m=5\pm 2.5$. The error of j_0 values due to the error of m is not more than several percent. Therefore, the m values for μ-rich air showers are assumed as follows: $m=8$ for $N>10^6$ Tokyo; $m=13$ for $N>10^5$ Tokyo, and $m=5$ for $N>10^6$ Yaizu.

Table I. Observation of μ-rich air showers showing number of events and days.

	$N>10^7$ $z<40°$	10^7-10^6 $<40°$	10^6-10^5 $40°-50°$	Sum	$0(t)$
Tokyo	15	55	8	78	128–173
Yaizu	8	8	...	16	213–249
Sum	23	63	8	94	

The observed number j, the expected number j_0, and their ratio, $y=j/j_0$, are shown in Figs. 1(a) and (b). The former shows a remarkable variation with the right ascension. A χ^2 test gives the probability P of such a deviation from uniformity to be smaller than 0.01%. The result of harmonic analysis is

1st $\alpha_{\max}=6.8\pm 1.0$ h, amplitude $=(62\pm 15)\%$

2nd $\alpha_{\max}=9$ and 21 h, amplitude $=40\%$

$$\text{two terms combined}\begin{cases}\text{1st max.} & \alpha=8\pm 1\text{ h}\\ \text{2nd max.} & \alpha=21\pm 1\text{ h}.\end{cases}$$

The variation with the declination, shown in Fig. 1(b)

[1] H. Hasegawa, T. Matano, I. Miura, M. Oda, S. Shibata, G. Tanahashi, and Y. Tanaka, J. Phys. Soc. Japan, Suppl. **17**, A-III, 86 (1962); S. Higashi, T. Kitamura, Y. Mishima, S. Miyamoto, H. Shibata, and Y. Watase, J. Phys. Soc. Japan, Suppl. **17**, A-III, 89 (1962).

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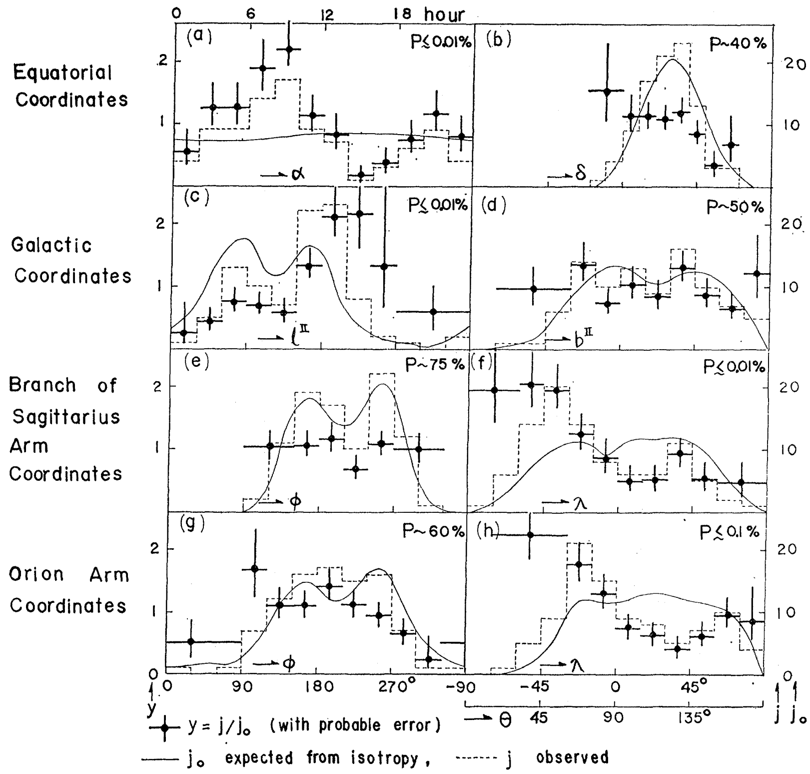

FIG. 1. Distribution of the relative intensities, y, of μ-rich air showers in celestial coordinates. P gives the significance level of anisotropy.

seems to indicate a larger intensity at lower declination, though it is not statistically significant.

The distributions in Galactic coordinates obtained by similar process are shown in Figs. 1(c) and (d). The longitude effect in Fig. 1(c) is significant, but not for the latitude effect in Fig. 1(d). The longitude l^{II} of the maximum intensity seems to be at or somewhat larger than 210°.

In order to see whether the anisotropy that appeared in Figs. 1(a) and (c) is perpendicular or parallel to the Galactic arm, the data were analyzed with a new coordinate system in which the direction of spiral-in was defined as the pole where the latitude $\lambda=+90°$ and the longitude ϕ was measured from one of the cross points of $\lambda=0°$ and $b^{II}=0°$. These directions are shown in Table II, by assuming the branch[3] of the Sagittarius arm or

TABLE II. Galactic arm coordinates (λ,ϕ).

	Sagittarius branch	Orion
Pole $\lambda=+90°$	$l^{II}=37°$	$l^{II}=70°$
$\phi=0°$, $\lambda=0°$	$l^{II}=307°$	$l^{II}=340°$

the Orion arm to be the axis. The intensity distributions in these coordinates are shown in Figs. 1(e)–(h). The longitude effect is not significant as shown in Figs. 1(e) and (g), but (f) and (h) show remarkable variation with λ. This latitude effect implies that the anisotropy is rather parallel to the Galactic arm, and the larger intensity from the direction of spiral out $(\lambda<0)$ is statistically significant. It is difficult to say, at present, which arm is better to interprete the anisotropy, though the branch of the Sagittarius arm seems to be preferable from Fig. 1(c). The 2nd maximum in Fig. 1(a) corresponds, respectively, to those in Figs. 1(c) $(l^{II}\approx 70°)$, (f) $(\lambda_{Sgr}\approx 40°)$, and (h) $(\lambda_{Ori}\approx 70°)$, but none of them is statistically significant.

From the latitude effect in the Galactic arm coordinate described above, the following picture may be imagined. Suppose the primaries of the μ-rich air showers are heavy nuclei according to the Hasegawa *et al.*[1,2] idea, the Galactic magnetic field is uniform and parallel to the Galactic arm, and a source sufficiently larger than the gyroradius ($\sim 10^{19}$ cm) is in the side of spiral-out at a distance L. By assuming heavy nuclei, emitted from a source with the intensity $I_t=I_0\exp(-t/\tau)$ at the time t, are coming to the earth at the time T along a helical path with a pitch angle $\theta=90°+\lambda$, the directional intensity J is obtained approximately.

$$J=0, \qquad (\theta>\theta_c)$$
$$\ln J=A+B\sec\theta\,(\theta\leqslant\theta_c), \qquad (2)$$

where

$$\sec\theta_c=cT/L,$$
$$A=\ln I_T=\ln I_0-T/\tau,$$

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and

$$B=(1/\tau-1/\tau_a)L/c.$$

I_T and I_0 are the source intensity at the time $t=T$ and 0, respectively, and τ_a is the life time of heavy nuclei. From Eq. (2) and the latitude effect shown in Figs. 1(f) and (h), we can estimate $\theta_c=60°\sim70°$, $I_T=10\sim20\%$ of air showers, and $B=-0.5\sim0.5$. Assuming the collision mean free path of the heavy nuclei, $m_a\approx5$ g/cm^2 and the matter density in the Galactic arm, $\rho\approx1$ proton/cm^3, we obtain $\tau_a=m_a/\rho c\approx10^{14}$ sec. Provided L is smaller than the dimension of the Galaxy, the result $B<0.5$ gives the conditions $\tau\gtrsim2L/c\approx T$ and $I_0=10\sim60\%$ of air showers. This implies that a source at a distance L light years has been emitting heavy nuclei since about $2L$ years ago, with an initial intensity $10\sim60\%$ of ordinary air shower and with a decay time longer than $2L$ years.

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Complete Spin Tests for Fermions

M. ADEMOLLO AND R. GATTO

Istituto di Fisica dell' Università di Firenze, Firenze, Italy and Laboratori Nazionali di Frascati del Comitato Nazionale per l'Energia Nucleare, Frascati, Roma, Italy

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Complete spin tests for fermions of arbitrary spin, produced from a spin-zero boson on an unpolarized spin-$\frac{1}{2}$ fermion and decaying into a spin-zero boson and a spin-$\frac{1}{2}$ fermion, are derived. The tests constitute a set of necessary and sufficient conditions for a particular spin assignment, in the absence of more detailed dynamical information. Essential use is made of the R invariance of the parity conserving production process. More general tests, applicable to arbitrary production processes, are also discussed.

1. INTRODUCTION

It is the main purpose of this paper to derive necessary and sufficient conditions for a spin assignment to a fermion that is produced from a spin-zero boson on an unpolarized spin-$\frac{1}{2}$ fermion and subsequently decays into a spin-$\frac{1}{2}$ fermion and a spin-zero boson. Our conclusions for this case are summarized in Sec. 4.2 in a form allowing their direct practical use.

Also, in this paper we discuss spin tests applicable to more general production processes. Our conclusions for the general case are summarized in Sec. 4.1.

The derivation of the necessary and sufficient conditions for the case of production from a spin-zero boson on an unpolarized spin-$\frac{1}{2}$ fermion is made possible by the application of the R transformation to the production density matrix. Such a method was recently applied by Peshkin,[1] and is also related to work by A. Bohr[2] and by Eberhard and Good.[3] We obtain necessary and sufficient conditions as a consequence of a theorem that characterizes the most general density matrix for production of a fermion of spin s from two incoherent helicity states related by an R transformation.

For the general production process we obtain various tests, some of them involving the longitudinal and transverse polarizations. These results are closely related to results by Lee and Yang,[4] by Durand, Landovitz, and Leitner,[5] by Spitzer and Stapp,[6] by Gatto and Stapp,[7] by Capps,[8] by Ademollo and Gatto,[9] and by Byers and Fenster.[10]

2. THE DENSITY MATRIX FOR PRODUCTION FROM SPIN-ZERO BOSON ON UNPOLARIZED SPIN-1/2 FERMION

2.1

We consider the production process

$$a+f\rightarrow F+b, \tag{2.1}$$

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