Measurements of the charge ratio and polarization of 1.2-TeV/c cosmic-ray muons with the Kamiokande II detector

M. Yamada,* K. Miyano, H. Miyata, and H. Takei
Department of Physics, Niigata University, Niigata 950-21, Japan

M. Mori, Y. Oyama, A. Suzuki, and K. Takahashi
National Laboratory for High Energy Physics (KEK), Ibaraki 305, Japan

K. S. Hirata, T. Kajita, T. Kifune, K. Kihara, M. Nakahata, K. Nakamura, S. Ohara, N. Sato,* Y. Suzuki, Y. Totsuka, and Y. Yaginuma
Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan

M. Koshiba
Tokai University, Tokyo 151, Japan

T. Suda and T. Tajima
Department of Physics, Faculty of Science, Kobe University, Hyogo 657, Japan

Y. Fukuda, Y. Nagashima, and M. Takita
Department of Physics, Osaka University, Osaka 560, Japan

K. Kaneyuki and T. Tanimori
Department of Physics, Tokyo Institute of Technology, Tokyo 152, Japan

E. W. Beier, E. D. Frank, W. Frati, S. B. Kim,† A. K. Mann, F. M. Newcomer, R. Van Berg, and W. Zhang‡
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

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We measured the charge ratio and the polarization of the high-energy cosmic-ray muons arriving with zenith angles from 0° to 90° in the large underground water Cherenkov detector, Kamiokande II. The charge ratio $[R(\mu^+/\mu^-)]$ and the polarization (P_0) are found to be 1.37±0.06(stat)±0.01(syst) and 0.26±0.04(stat)±0.05(syst), respectively, at the sea-level momentum of 1.2 TeV/c. This result for the charge ratio is in good agreement with those previously obtained in experiments using magnetic spectrometers at sea level and underground. This is the first measurement of the polarization of the cosmic-ray muons in the TeV region.

Cosmic-ray muons originate from the decay of mesons produced by the interactions of high-energy cosmic-ray primaries with atmospheric nuclei at high altitudes. Since the cosmic-ray primaries consist mostly of free protons (~93%), the charge ratio of muons reflects not only the charge of primaries but also the details of the high-energy hadronic interactions. Therefore, measurements of the muon charge ratio have provided experimental constraints on primary cosmic-ray components and models of high-energy hadronic interactions. Exotic states, such as the quark-gluon plasma (QGP), might be created in ultrahigh-energy nuclear reactions induced by cosmic-ray primaries, which cannot be produced by present accelerators. Study of the polarization of cosmic-ray muons [1–4] is one method to obtain information about these exotic states. However, the polarization of cosmic-ray muons has previously been measured only below 10 GeV/c.

We have measured the charge ratio and the polarization of cosmic-ray muons at 1.2 TeV/c with a large-volume underground water Cherenkov detector, Kamiokande II. The polarization has been deduced from the angular distribution of electrons and positrons emitted from muons stopped in the detector. In this paper we report the results obtained from the analysis of data taken from January 1987 until April 1990. In most of this paper, when mention is made of electrons, we imply both electrons and positrons.

The Kamiokande II detector is a large water Cherenkov detector located at 1000 m underground [2700 m of water equivalent (mwe)] in the Kamioka mine, 300 km west of Tokyo, Japan. Details of the detector have been described elsewhere [5]. The detector volume containing 2140 tons of ultrapure water is viewed by 948 20-in.-diameter photomultiplier tubes (PMT's) on a 1-m×1-m grid on the entire inner surface covering almost 20% of the detector surface. The water purification system ensures that the attenuation length of water for Cherenkov radiation (300–5000-nm wavelength) has been kept at about 45 m. A 4π solid-angle anticounter, a water Cherenkov counter with 123 PMT, surrounds the inner detector completely. The mean thickness of the water in the anticounter is 1.5 m which serves as shielding from low-energy γ rays and neutrons coming from rocks outside of the detector.

The electronics system provides multihit time and charge measurements for each PMT. The system records signals larger than 0.35 photoelectrons (p.e.) in a given PMT when an event trigger is present. The detector is triggered by at least 20 hit PMT's within 100 nsec. The trigger accepts electrons of 8 MeV (7 MeV) with approximately 50% efficiency in the total volume of the detector (in the 565 ton fiducial volume, described below). After the PMT gain was increased in June 1988, the trigger accepts electrons of 7 MeV (6 MeV) with 50% efficiency in the total volume (in the fiducial volume). A loss of triggers due to dead time of the electronics system was estimated to be negligible for successive events with the time interval longer than 0.9 μsec. Therefore, event pairs with time intervals longer than 0.9 μsec were used in this analysis. The time interval was measured by a clock pulsing every 20 nsec, which is much shorter than the muon lifetime in vacuum, $\tau_\mu = 2.197\,03 \pm 0.000\,04$ μsec [6]. The frequency of the 50-MHz clock is calibrated with an accuracy of 10^{-6} using Loran-C signals. The raw event trigger rate is 0.6–1.2 Hz (depending on the adjustable discriminator threshold) of which 0.37 Hz is due to cosmic-ray muons. The remaining rate is mainly due to radioactive contamination in the detector and to external low-energy γ rays.

The energy calibration for low-energy events is performed with electrons of energy up to 52.8 MeV from the decay of the stopped cosmic-ray muons. From this calibration the absolute energy normalization is known to be better than 3%. The energy resolution for an electron is expressed by $22\%/\sqrt{E_e/10\text{ MeV}}$.

Event pairs consisting of a stopped muon and a decay electron (μ-e decay events) were selected out of 1.96×10^8 raw events taken in 978 effective days from January 1987 through April 1990. The selection procedure for μ-e decay events is described as follows.

(1) The time interval between the prompt event (muon) and the delayed one (electron) should be less than 30 μsec.

(2) The total number of photoelectrons (p.e.) deposited by the prompt event in the inner detector should be greater than 400 p.e. and less than 9000 p.e. This condition picks up events which travel between 1 and 15 m in water.

(3) The greatest number of photoelectrons in any PMT of the inner detector should be more than 10 p.e. and less than 200 p.e., for removing typical electronic noise events and through-going muon events from the sample.

(4) If a prompt event satisfies both (2) and (3), the delayed event is accepted as a decay electron event candidate.

The events selected as muon candidates were reconstructed with an algorithm based on the Cherenkov ring pattern of hit PMT and electron candidates were reconstructed with an algorithm based on time information and position of hit PMT. The entrance position for stopped muon events was determined with an uncertainty less than 0.8 m and the angular resolution is less than 6°. The vertex position resolution for decay electrons is 0.8 m (1.6 m) for 50 MeV (10 MeV). The angular resolution is 15° (32°) largely due to multiple Coulomb scattering of an electron of 50 MeV (10 MeV). These numbers were obtained by a Monte Carlo calculation, which well reproduces the calibration data of electrons from the decay of stopped muons. The electronic noise events remaining after the above selection procedure were removed by means of the quality parameters from event reconstruction. By an eye-scan check of a sample of events, the electronic noise events rate is found to be less than 0.2%. After event selection, 157 310 pairs of events remained as $\mu \to e$ decay candidates in the total volume.

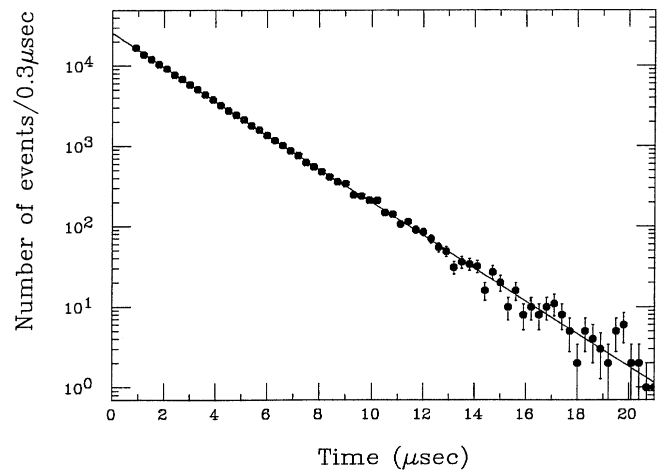

FIG. 1. The decay curve of stopped muons. The solid curve was obtained by fitting a two component decay function with lifetimes of $2.197\,03 \pm 0.000\,04$ μsec (for μ^+) and 1.7954 ± 0.0020 μsec (for μ^- in pure water.)

In the analysis of the charge ratio, the fiducial volume for the electron vertex was set at 0.5 m from the front surfaces of the PMT of the inner detector. Event pairs which satisfy the spatial condition that the distance between the muon track and the electron vertex should be shorter than 3.0 m were employed in the analysis. The decay curve of muons obtained from the time interval information between a muon event and a subsequent electron event is shown in Fig. 1. For positive muons, which are free from nuclear capture in water, the mean lifetime is equal to τ_μ. On the other hand, the mean lifetime of negative muons in a medium is shorter than τ_μ, because of nuclear capture. Many measurements for the mean lifetime of negative muons in various media have been performed [7]. The mean lifetime of negative muons in pure water is found to be $\tau_{\mu^-} = 1.7954 \pm 0.0020$ μsec according to Ref. [7]. The observed decay curve, therefore, has to consist of two components: τ_{μ^+} $(=\tau_\mu)$ and τ_{μ^-} mean lifetimes.

The decay curve is fitted by the equation

$$N(t-(t+\Delta t))=N_+[1-\exp(-\Delta t/\tau_{\mu^+})]\exp(-t/\tau_{\mu^+})+N_-[1-\exp(-\Delta t/\tau_{\mu^-})]\exp(-t/\tau_{\mu^-}) , \quad (1)$$

where Δt is the binning width of the decay-curve histogram set to be 0.3 μsec, and N_+ and N_- represent the total number of positive and negative muons, respectively. The nuclear capture fraction for negative muons in pure water (Λ_c) is [7]

$$\Lambda_c=0.184\pm0.001 . \quad (2)$$

Combining the above equations, the muon charge ratio $R(\mu^+/\mu^-)$ is given by

$$R(\mu^+/\mu^-)=\frac{N_+}{N_-/(1-\Lambda_c)} . \quad (3)$$

From fitting of the decay curve based on μ-e decay pairs observed in 978 days of live detector time data, N_+ and N_- were obtained to be 117 158±1 915 and 69 941 ±2 087, respectively. Consequently, the charge ratio $R(\mu^+/\mu^-)$ of cosmic-ray muons at the sea-level momentum of $1.2^{+0.2}_{-0.4}$ TeV/c is found to be 1.37±0.06(stat)±0.01(syst). This momentum value was estimated from the thickness of rock (the density of rock is 2.7 g cm^{-3}) which muons pass through. The charge ratio of cosmic-ray muons obtained by the present method is plotted in Fig. 2 together with the results of other experiments using magnetic spectrometers [8,9] and the agreement is seen to be good.

In the analysis of the polarization, the fiducial volume was set at 2.5 m from the PMT surfaces of the inner detector (565 tons). Event pairs with electron energy greater than 14.0 MeV were employed in the analysis. Above this threshold energy, the trigger efficiency is almost 100% for electrons in the fiducial volume. The angular distribution of decay electrons is fitted by the shape

$$\frac{dN}{d(\cos\theta)}\propto(1-2x_0^3+x_0^4)-\left[\frac{1}{3}+\frac{2x_0^3}{3}-x_0^4\right]P_{\rm ob}\cos\theta , \quad (4)$$

where x_0 is the relative threshold energy chosen to be 14.0/52.8 for the analysis of decay electrons, $P_{\rm ob}$ stands for the polarization observed in the detector, and θ is the angle between the momentum vectors of muon and electron. Figure 3 shows this angular distribution. $P_{\rm ob}$ is 0.12±0.02 (stat) from fitting of this angular distribution. The polarizations for positive and negative muons are equal but the sign is inverted at production. Since the depolarization mechanism in water is different for posi-

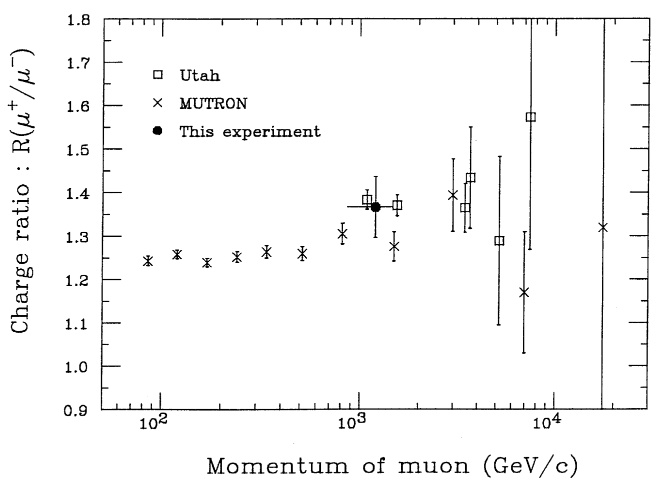

FIG. 2. The present result for the charge ratio of 1.2-TeV/c cosmic-ray muons together with the results from the Utah group and MUTRON. The acceptable regions of zenith angle are from 0° to 90° for Kamiokande II, 40° to 90° for the Utah group, and 86° to 90° for MUTRON. The horizontal axis is the sea-level momentum of the muons.

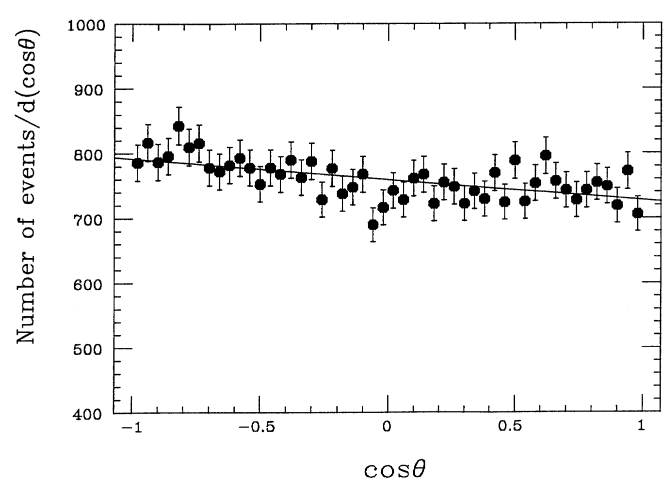

FIG. 3. The angular correlation between the momenta of the stopped muons and the decay electrons.

tive and negative muons, the known effects of depolarization have to be taken into account [10–12]. The polarization P_0 of muons at production is

$$P_0=\frac{P_{ob}[1+R'(\mu^+/\mu^-)]}{(1-\delta)[r^+_{H_2O}R'(\mu^+/\mu^-)+r^-_{H_2O}]}\ , \tag{5}$$

where $R'(\mu^+/\mu^-)$ is the ratio of N_+/N_- (without the correction for μ^- capture), the factor $\delta(\leq 0.005)$ is the magnitude of depolarization of muons in the atmosphere and in rock [13], $r^+_{H_2O}$ and $r^-_{H_2O}$ are the remaining fractional polarization of positive and negative muons in water, respectively. From Refs. [11] and [12], $r^+_{H_2O}$ is 0.720 ± 0.006 and $r^-_{H_2O}$ is 0.051 ± 0.015. P_0 thus obtained in the present measurement is 0.26 ± 0.04 (stat)±0.05 (syst), and is shown in Fig. 4, which shows also the results of previous data [14–21].

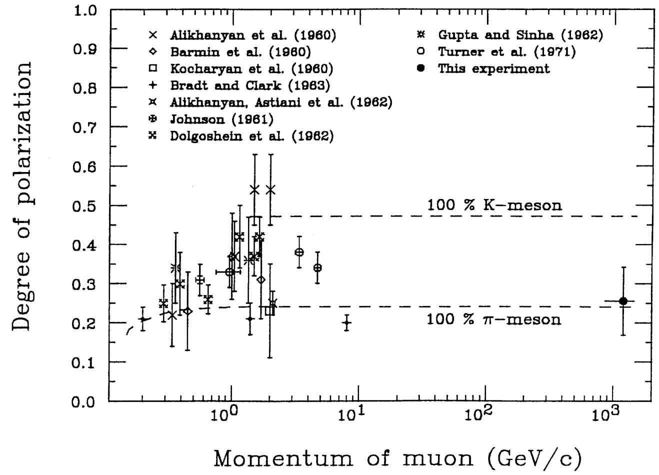

FIG. 4. The polarization of the cosmic-ray muons. Data obtained in previous experiments are also shown. The horizontal axis is the sea-level momentum of the muons. The two dashed lines indicate the predicted values of the polarization of muons using Eq. (6), assuming the parent mesons are all K or all π. For the case of all K mesons, all decay modes of the charged and neutral K mesons are taken into account.

According to Ref. 1, the polarization of the cosmic-ray muons produced in the two-body decay of mesons is represented as

$$P_0=1+\left[\frac{E_\mu E^*_\mu}{p_\mu p^*_\mu}-1\right]\left[1-\left[\frac{\alpha-1}{\alpha-2}\right]\left[\frac{1-(\varepsilon_-/\varepsilon_+)^{\alpha-2}}{1-(\varepsilon_-/\varepsilon_+)^{\alpha-1}}\right]\right]\ ,\quad \alpha>2 \tag{6}$$

in the laboratory system. Here E_μ and E^*_μ (p_μ and p^*_μ) are the muon total energy (momentum) in the laboratory system and in the rest system of the parent meson, respectively. The energy spectrum of the parent meson is assumed to be proportional to $\varepsilon^{-\alpha}$, where ε represents the energy of the meson between the limits ε_- and ε_+ producing a muon of energy E_μ. By a kinematical calculation, ε_- and ε_+ are E_μ and $1.74\times E_\mu$ for pion two-body decay, E_μ and $21.82\times E_\mu$ for kaon two-body decay. Using Eq. (6), the polarization, P_0 is predicted to be 0.24 for pion decay and 0.88 for kaon two-body decay with the reasonable value of $\alpha=2.65$. The polarization reflects the rest mass of the parent meson, and therefore yields information on the K/π ratio in the initial interaction at high altitude. If the secondary hadronic interactions of π, K mesons produced in the interactions of primaries with atmospheric nuclei are neglected for simplification, the K/π ratio is represented as

$$\left[\frac{K}{\pi}\right]=1.479\left[\frac{P_0-P_\pi}{P_K-P_0}\right] \tag{7}$$

using the method of Ref. [3] where P_π (=0.24) and P_K (=0.47) are the predicted polarizations for pion and kaon decay (for kaon decay, all decay modes were taken into account), respectively, and calculated to be $0.11^{+0.65}_{-0.11}$.

It has been suggested theoretically that strangeness will be created abundantly when the transition from the hadronic phase to the quark-gluon-plasma phase occurs [22–28] and some experimental groups have reported a signal of the enhanced strangeness in various energy regions [29–33]. However, our result on the K/π ratio shows no significant indication of enhanced strangeness production in the TeV region and is consistent with results from other accelerator experiments [34–36].

In conclusion, the charge ratio of cosmic-ray muons, $R(\mu^+/\mu^-)=1.37\pm0.06$(stat)$\pm0.01$(syst), was obtained by a new and entirely different method from previous measurements, i.e., through analysis of the decay curve of stopped muons in the Kamiokande II detector. The polarization of high-energy cosmic-ray muons, $P_0=0.26\pm0.04$(stat)±0.05(syst) was also obtained. This is the first measurement of the polarization of cosmic-ray muons at a laboratory energy of 1.2 TeV.

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*Present address: National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan.

†Present address: University of Michigan, Ann Arbor, MI 48109.

‡Present address: Los Alamos National Laboratory, Los Alamos, NM 87545.

[1] S. Hayakawa, Phys. Rev. **108**, 1533 (1957).

[2] G. W. Clark and J. Hersil, Phys. Rev. **108**, 1538 (1957).

[3] J. L. Osborne, Nuovo Cimento **32**, 816 (1964).

[4] R. Turner, C. M. Ankenbrandt, and R. C. Larsen, Phys. Rev. D **4**, 17 (1971).

[5] K. S. Hirata, T. Kajita, M. Koshiba, M. Nakahata, Y. Oyama, N. Sato, A. Suzuki, M. Takita, Y. Totsuka, T. Kifune, T. Suda, K. Takahashi, T. Tanimori, K. Miyano, M. Yamada, E. W. Beier, L. R. Feldsher, W. Frati, S. B. Kim, A. K. Mann, F. M. Newcommer, R. Van Berg, W. Zhang, and B. G. Cortez, Phys. Rev. D **38**, 448 (1988).

[6] Particle Data Group, J. J. Hernández *et al.*, Phys. Lett. B **239**, 1 (1990).

[7] T. Suzuki, D. F. Measday, and J. P. Roalsvig, Phys. Rev. C **35**, 2212 (1987).

[8] G.K. Ashley II, J. W. Keuffel, and M. O. Larson, Phys. Rev. D **12**, 20 (1975).

[9] S. Matsuno, F. Kajino, Y. Kawashima, T. Kitamura, K. Mitsui, Y. Muraki, Y. Ohashi, A. Okada, T. Suda, Y. Minorikawa, K. Kobayakawa, Y. Kamiya, I. Nakamura, and T. Takahashi, Phys. Rev. D **29**, 1 (1984).

[10] P. W. Percival, H. Fischer, M. Camani, F. N. Gygax, W. Ruegg, A. Schenk, H. Schilling, and H. Graf, Chem. Phys. Lett. **39**, 333 (1976).

[11] P. W. Percival, E. Roduner, and H. Fischer, Chem. Phys. **32**, 3 (1978).

[12] D. C. Buckle, J. R. Kane, R. T. Siegel, and R. J. Wetmore, Phys. Rev. Lett. **20**, 705 (1968).

[13] V. L. Lyuboshits, Yad. Fiz. **32**, 702 (1980) [Sov. J. Nucl. Phys. **32**, 362 (1980)].

[14] A. I. Alikhanyan, Proc. Moscow Cosmic Ray Conf. **1**, 317 (1959).

[15] V. V. Barmin, V. P. Kanavets, and B. V. Morozov, Zh. Eksp. Teor. Fiz. **39**, 986 (1961) [Sov. Phys. JETP **12**, 683 (1961)].

[16] N. M. Kocharyan, Z. A. Kirakosyan, E. G. Sharoyan, and A. P. Pikalov, Zh. Eksp. Teor. Fiz. **38**, 18 (1960) [Sov. Phys. JETP **11**, 12 (1960)].

[17] H. V. Bradt and G. N. Clark, Phys. Rev. **132**, 1306 (1963).

[18] A. I. Alikhanyan, T. L. Astiani, and E. M. Matevosyan, Zh. Eksp. Teor. Fiz. **42**, 126 (1962) [Sov. Phys. JETP **15**, 90 (1962)].

[19] C. S. Johnson, Phys. Rev. **122**, 1883 (1961).

[20] B. Dolgoshein, B. Luchkov, and V. Ushakov, Zh. Eksp. Teor. Fiz. **42**, 949 (1962) [Sov. Phys. JETP **15**, 654 (1962)].

[21] S. N. Sen Gupta and M. S. Sinha, Proc. Phys. Soc. **79**, 1183 (1962).

[22] A. K. Mann and H. Primakoff, Phys. Rev. D **22**, 1115 (1980).

[23] J. Rafelski and B. Müller, Phys. Rev. Lett. **48**, 1066 (1982).

[24] P. Koch, J. Rafelski, and W. Greiner, Phys. Lett. **123B**, 151 (1983).

[25] J. Rafelski, Nucl. Phys. **A418**, 215 (1984).

[26] P. Koch, B. Müller, and J. Rafelski, Phys. Rep. **142**, 167 (1986).

[27] M. Jacob and J. Rafelski, Phys. Lett. B **190**, 173 (1987).

[28] C. P. Singh and S. Uddin, Phys. Rev. D **41**, 870 (1990).

[29] V. V. Abramov *et al.*, Yad. Fiz. **31**, 660 (1980) [Sov. J. Nucl. Phys. **31**, 343 (1980)].

[30] V. V. Abramov *et al.*, Yad. Fiz. **31**, 937 (1980) [Sov. J. Nucl. Phys. **31**, 484 (1980)].

[31] UA2 Collaboration, M. Banner *et al.*, Phys. Lett. **122B**, 322 (1983).

[32] K. Miyano, Y. Noguchi, Y. Yoshimura, M. Fukawa, F. Ochiai, T. Sato, R. Sugahara, A. Suzuki, K. Takahashi, N. Fujiwara, S. Noguchi, S. Yamashita, A. Ono, M. Chikawa, O. Kusumoto, and T. Okusawa, Phys. Rev. C **38**, 2788 (1988).

[33] E-802 Collaboration, T. Abbott *et al.*, Phys. Rev. Lett. **64**, 847 (1990).

[34] A. Bertin, P. Capiluppi, M. D'Agostino-Bruno, R. J. Ellis, G. Giacomelli, A. M. Rossi, G. Vannini, A. Bussière, and R. T. Poe, Phys. Lett. **41B**, 201 (1972).

[35] UA5 Collaboration, K. Alpgård *et al.*, Phys. Lett. **115B**, 65 (1982).

[36] Axial Field Spectrometer Collaboration, T. Åkesson *et al.*, Phys. Rev. Lett. **55**, 2535 (1985).