K^-pp search with FINUDA

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A deeply-bound kaonic state, K^-pp, has been searched for with the FINUDA spectrometer. Almost monochromatic K^-'s produced through the decay of $\phi(1020)$ mesons are used to observe K^- absorption reactions stopped on very thin nuclear targets. In the absorption process, the K^-pp bound state is eventually formed as a fragment, and is identified through its two-body decay into a Λ hyperon and a proton. The binding energy and the decay width are determined from the invariant-mass distribution as $115\,^{+6}_{-5}\,(\text{stat.})\,^{+3}_{-4}\,(\text{sys.})$ MeV and $67\,^{+14}_{-11}\,(\text{stat.})\,^{+2}_{-3}\,(\text{sys.})$ MeV, respectively.

1 Introduction

The kaon properties in the nuclear medium have been investigated in various theoretical approaches. One of the interesting subjects is the possible existence of kaon condensation [1] in dense nuclear matter, which might be realized inside a neutron star. Stimulated by the enhanced production of K^- in subthreshold and near-threshold heavy ion collisions by the KaoS collaboration at GSI [2], the modification of the K^- mass in the nuclear medium has been also discussed intensively.

As for the K^-p interaction in free space, there exist low-energy elastic and inelastic K^-p scattering data [3] of not so good quality and rather precise K^-p threshold branching ratios [4]. The K^-p scattering length was determined convincingly by a kaonic-hydrogen atomic X-ray measurement [5, 6]. However, there are no K^--deuteron scattering data available at low energies. Therefore, the scattering amplitude is constrained not so well, which leaves much rooms for different theoretical extrapolations. Nevertheless, by applying the relativistic chiral $SU(3)$ Lagrangian in order to control the uncertainties, the

*M. Agnello, G. Beer, L. Benussi, M. Bertani, S. Bianco, E. Botta, T. Bressani, L. Busso, D. Calvo, P. Camerini, P. Cerello, B. Dalena, F. De Mori, G. D'Erasmo, D. Di Santo, F.L. Fabbri, D. Faso, A. Feliciello, A. Filippi, V. Filippini , E.M. Fiore, H. Fujioka, P. Gianotti, N. Grion, V. Lucherini, S. Marcello, T. Maruta, N. Mirfakhrai, O. Morra, H. Outa, A. Olin, E. Pace, M. Palomba, A. Pantaleo, A. Panzarasa, V. Paticchio, S. Piano, F. Pompili, R. Rui, G. Simonetti, H. So, S. Tomassini, A. Toyoda, R. Wheadon, A. Zenoni kaon-nucleon and antikaon-nucleon scattering were excellently described up to the laboratory momentum of $p_{lab.} \simeq 500$ MeV/c [7].

The information on K^- nucleus interaction has been obtained with the kaonic atomic data [8]. Unfortunately, we have qualitatively two different predictions for the depth of the K^- nucleus potential at nuclear matter density: very deep attractive potentials (-Re $V_{opt}(\rho_0) \approx$ 150–200 MeV) [9, 10] and much shallower potentials (-Re $V_{opt}(\rho_0) \approx$ 50–75 MeV) [11, 12, 13, 14, 15]. Both types of potentials reasonably describe the shifts and widths of the X-ray data. The main difference is coming from the different treatments of the existence of the $\Lambda(1405)$ hyperon resonance, which is considered to be an unstable $\bar{K}N$ bound state just 27 MeV below the K^-p threshold.

Recently, an interesting idea has been proposed suggesting the possible existence of deeply bound nuclear $\bar{K}$ states in light nuclei [16, 17], where the potential is categorized as a very deep potential. Since the potential is strongly attractive in the I=0 $\bar{K}N$ interaction, proton-rich $\bar{K}$-nuclei such as K^-pp and K^-ppn are predicted to have large binding energies of 50–100 MeV. A further interesting suggestion is that the nucleus might be contracted because of the large binding energy and form the high-density state, which is also confirmed with the method of anti-symmetrized molecular dynamics for the cases of K^-ppn and K^- ^{8}Be [18].

If such a $\bar{K}$-nucleus is observed, it would give us direct information of the K^- nucleus potential at nuclear matter density. Another idea to get the information of the K^- nucleus potential is proposed to study the (K^-_{stop}, π^-) reaction into specific Λ-hypernuclear states [11].

2 FINUDA experiment

The experiment is carried out at an intersection region of the e^+e^- collider DAΦNE in Laboratori Nazionali di Frascati (LNF), which produces copious $\phi(1020)$ mesons. A key characteristic of the FINUDA spectrometer is the achievement of high resolution through the use of very thin nuclear targets of $\approx 200\,\mathrm{mg/cm^2}$ and low mass chambers in a He atmosphere [19]. The nearly monochromatic K^- from the ϕ decays are fully stopped in these targets. The spectrometer covers a solid angle larger than 2π sr. This good performance enables us to carry out the spectroscopy of Λ-hypernuclei with a good energy resolution better than 1 MeV FWHM.

Figure 1 (TOP) shows an overview of the FINUDA spectrometer. It consists of three regions: the interaction/target region, the tracking system and the external time-of-flight system. The K^+K^- pair from the ϕ decay is detected by a barrel of 12 thin scintillator slabs (TOFINO) and an octagonal array of silicon microstrip detectors (ISIM). The kaon loses its energy in the beam pipe, TOFINO and ISIM, and finally stops in one of the thin targets. After K^- absorption in the target, the emitted particles are detected by the external tracking system. Charged particles are detected with a second layer of silicon microstrip detectors (OSIM), two layers of low-mass drift chambers (LMDC), and six layers of aluminized mylar straw tubes, arranged in three groups, the first one beam-oriented, the others tilted by $\pm 12°$. The dE/dx information obtained in the OSIM detector is used for particle identification. 72 external scintillator slabs (TOFONE) are installed in the outermost part, which are used to measure the time-of-flight of a charged or neutral particle and for triggering purpose.

In the first data taking in 2003–2004, five kinds of targets (^{6}Li, ^{7}Li, ^{12}C, ^{27}Al and ^{51}V) were installed as shown in Fig. 1 (BOTTOM). The integrated luminosity during the run reached $\sim 250\,\mathrm{pb}^{-1}$, of which $\sim 190\,\mathrm{pb}^{-1}$ was effectively used in the present analyses.

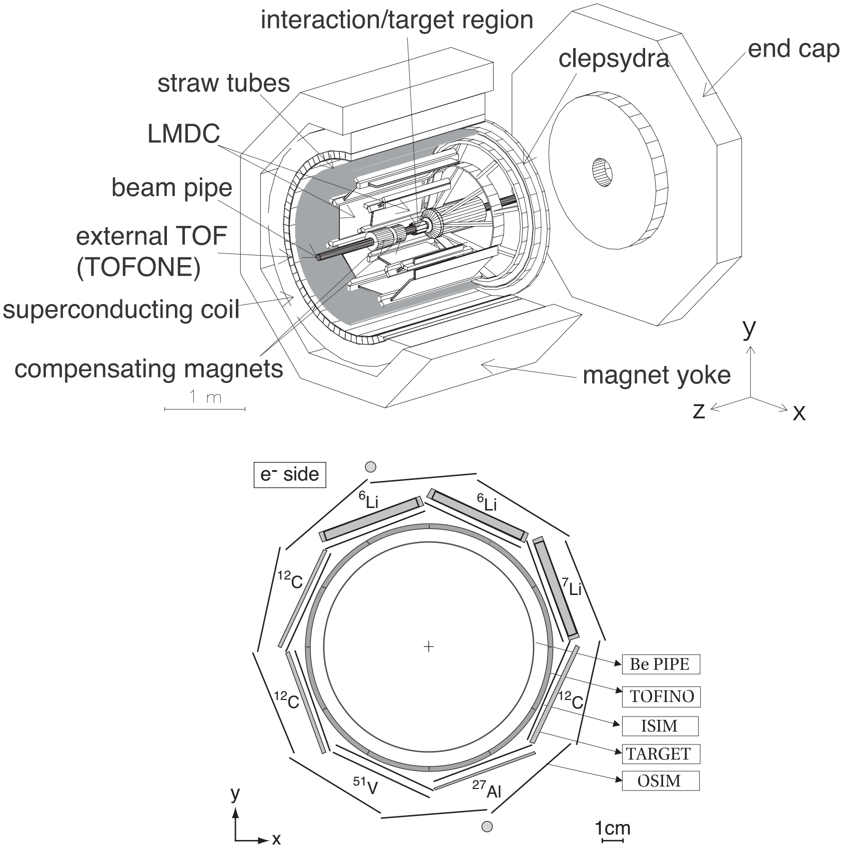

Figure 1: Global views (top: complete apparatus, bottom: interaction/target region) of the FINUDA apparatus.

3 Data analysis

3.1 Λ detection

The momentum resolution of the FINUDA spectrometer at this stage of the analysis was estimated from the two monochromatic peaks corresponding to $K_{\mu 2}(K^+ \to \mu^+\nu_\mu)$ and $K_{\pi 2}(K^+ \to \pi^+\pi^0)$ decays of K^+ stopping in the targets. It was found to be $\Delta p/p \sim 0.6\%$ FWHM. It is remarkable that the spectrometer delivered the right momenta of the monochromatic particles to a precision better than 200 keV$/c$, without the need of further correction. Efforts to further improve the momentum resolution are in progress.

Λ particles can be identified by reconstructing the invariant mass of a proton and a negative pion as shown in Fig. 2(left). The peak position agrees well with the known Λ mass, and the width of the peak is as narrow as 6 MeV$/c^2$ FWHM. In this analysis, we did not use the information of a Λ decay vertex.

Λ hyperons are produced with a sizable fraction in kaon absorption through various processes. The quasifree process ($K^-N \to \Lambda\pi$) emits a slow Λ with a momentum $\sim$ 300 MeV$/c$. Above $\sim$ 400 MeV$/c$, a main contribution comes from the Λ hyperons emitted from two-nucleon absorptions (K^- + "NN" $\to \Lambda N,\ \Sigma^0 N$). The acceptance of the FINUDA spectrometer cuts the Λ hyperons with a momentum lower than 300 MeV$/c$ which is restricted by the low momentum threshold for π^- from the $\Lambda \to p + \pi^-$ decay. Therefore, the Λ from the quasifree process is hardly observed in the FINUDA spectrometer as shown in Fig. 2(right). The low momentum threshold is determined with the present magnetic field of 1.0 T and the tracking detector configuration.

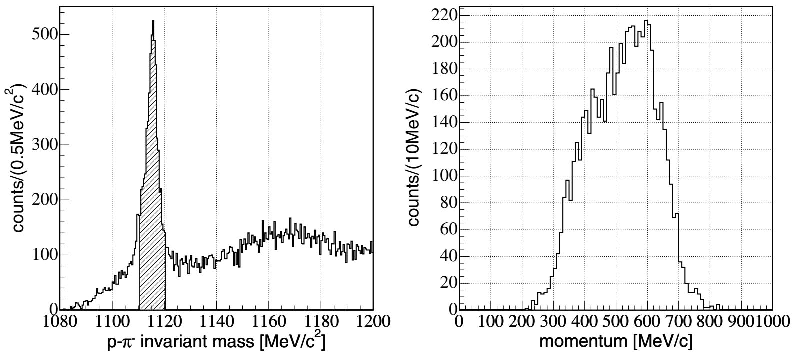

Figure 2: (left) Invariant mass distribution of a proton and a π^- for all the events in which these two particles are observed. The hatched region is selected for Λ's. (right) Momentum distribution of Λ's without acceptance corrections.

3.2 $p + \Lambda$ events

When a K^- interacts with two protons, one expects that a hyperon and a nucleon ($\Lambda + p$, $\Sigma^0 + p$ or $\Sigma^+ + n$) are emitted in opposite directions, ignoring final state interactions inside the nucleus. The angular correlation between a Λ and a proton from the same point in the target clearly indicates the existence of this kind of reaction as shown in Fig. 3. Even for heavy nuclei such as ^{27}Al and ^{51}V the similar correlations were observed, which might suggest the absorption would take place at the surface of a nucleus. If a Λ and a proton are emitted from the center of heavy nuclei, the back-to-back correlation would diminish due to final-state interactions.

In the following analysis, we use the Λ-p pairs emitted in the opposite direction ($\cos\theta^{\mathrm{Lab.}} < -0.8$) only from the light nuclear targets (^{6}Li, ^{7}Li and ^{12}C). In this way, the possible contaminations from other processes can be minimized, and the signal-to-noise ratio as well as the available statistics are kept to a good level.

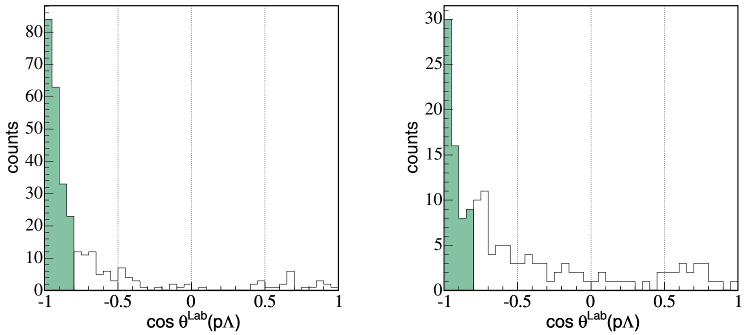

Figure 3: Opening angle distribution between a Λ and a proton. (Left : ^{6}Li, ^{7}Li and ^{12}C, Right : ^{27}Al and ^{51}V). The shaded area ($\cos\theta^{\mathrm{Lab.}} < -0.8$) is selected as the back-to-back events.

3.3 Invariant mass of a proton and a Λ

Since the back-to-back angular correlation between a Λ and a proton is so clear, it is naturally expected that the two particles are emitted from a "K^-pp" intermediate system. The angular correlation is smeared out due to the Fermi motions of the two protons at the surface of a nucleus by which the K^- is absorbed after cascading down the atomic orbits by emitting X-rays. If the reaction process were simply two-nucleon absorption process, the mass of the system should be close to the sum of a kaon and two proton mass, namely $2.370\,\mathrm{GeV}/c^2$.

The invariant-mass distribution of the Λ-p pairs is shown in Fig. 4 (left). A significant mass decrease of the K^-pp system with respect to its expected mass is observed. It can be interpreted as a bound state composed of a kaon and two protons; hereafter abbreviated as K^-pp.

In Fig. 4 (right), the acceptance corrected invariant mass distribution for events with two well-defined long-track protons is shown. Since the trigger and detection acceptance are monotonically increasing functions of the invariant mass in this mass region, the peak further shifts to a lower mass side. The binding energy $B_{K^-pp} = 115\,^{+6}_{-5}\,(\text{stat.})\,^{+3}_{-4}\,(\text{sys.})$ MeV and the width $\Gamma = 67\,^{+14}_{-11}\,(\text{stat.})\,^{+2}_{-3}\,(\text{sys.})$ MeV are obtained from the fitting with a Lorentzian function (folded with a Gaussian with $\sigma = 4\,\text{MeV}/c^2$, corresponding to the detector resolution, estimated with a Monte Carlo simulation) in the region of 2.22–2.33 GeV/c^2. Although we still have ambiguities on absolute normalization, a rough estimate on the yield of $K^-pp \to \Lambda + p$ is of the order of 0.1% per stopped K^-.

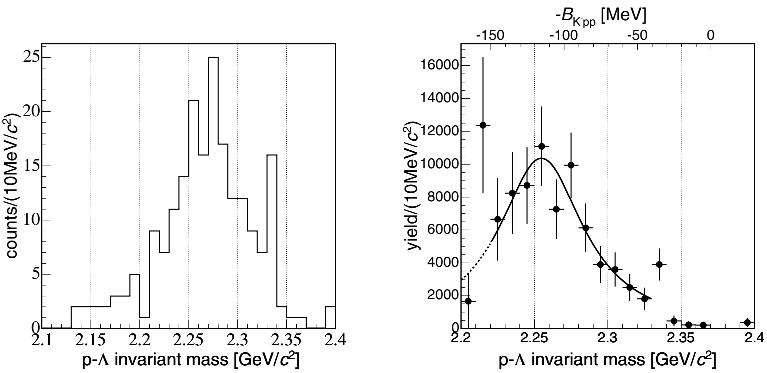

Figure 4: Invariant mass of a Λ and a proton in back-to-back correlation ($\cos\theta^{\text{Lab.}} < -0.8$) from light targets before the acceptance correction (left). The figure on the right shows the result after the acceptance correction for the events which have two protons with well-defined good tracks. Only the bins between 2.22–2.33 GeV/c^2 are used for the fitting. The curve shows the best fit (see text).

Consistency of the Monte Carlo simulation used for estimations of the acceptance and the resolutions was examined by producing the K^-pp events according to the obtained mass and width. The same simulation conditions were applied to these events; the momentum distributions of Λ's and protons (see Fig. 5), the $\Lambda - p$ opening angle distribution, the momentum distribution of the K^-pp system, etc. were in good agreement with the observed ones.

4 Discussion

From old bubble chamber and emulsion data [20] it is known that kaon two-nucleon absorption processes take place in 15–20% per stopped K^- in the broad range of the periodic table. However, the experimental information was statistically too limited to further

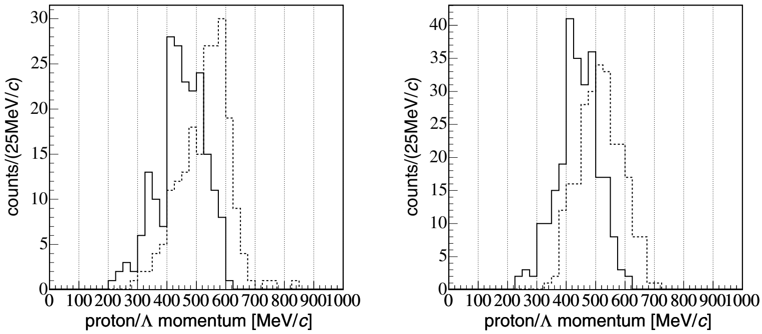

Figure 5: Momentum distributions of a proton(dashed) and a Λ(solid) from the $K^- pp$ decay for the experimental data (left) and a Monte Carlo simulation (right).

investigate the reaction mechanism, and nobody has identified the kaon two-nucleon absorption process experimentally. Several theoretical analyses were performed in 1960s to understand the reaction mechanism. A more recent theoretical analysis [21] roughly explained it with two-nucleon absorption process including meson-rescattering diagrams. Here, it should be noted that the main mode for the kaon two-nucleon absorption is on a pn pair with S=1 and I=0 and not on a pp pair, which only contributes by $\sim$10% according to the calculation. Thus, there is no a priori reason that the two-nucleon absorption processes are to be observed in the Λ-p coincidence events.

On the other hand, the detector system is very sensitive to the existence of the two-nucleon absorption mode $K^- +$ "pp" $\rightarrow \Lambda p$ since its invariant mass resolution is 10 MeV/c^2 FWHM. The effect of the nuclear binding of two protons is only to move the peak position to the lower mass side of the order of separation energies of two protons ($\sim$ 30 MeV), and not to broaden the peak. A sharp spike around 2.34 GeV/c^2 may be attributed to this process. There could be, in addition, the two-nucleon absorption mode $K^- +$ "pp" $\rightarrow \Sigma^0 p$. In this case, the Λ-p invariant-mass distribution is shifted to the lower mass region by about 74 MeV and broadened because a γ from the $\Sigma^0 \rightarrow \Lambda + \gamma$ decay is missing. However, the observed invariant-mass distribution is too broad to be attributed to this process only. Also, according to the old data in helium bubble chamber [22], the branching ratios of $K^- NN \rightarrow \Lambda N$ and $\Sigma^0 N$ are estimated to be $9.3 \pm 2.6\%$ and $2.3 \pm 1.0\%$ per stopped K^- in ^{4}He, respectively. The theoretical calculation [21] also suggests the ΛN mode has a larger branching ratio than the $\Sigma^0 N$ mode. Therefore, we can assume that the kaon two-nucleon absorption mode is not dominant in this channel, nor in the $\Sigma^0 + p$ one which has even a lower branching ratio.

Thus, we attribute the observed events in the bound region to the formation of the deeply-bound $K^- pp$ state. Since the $K^- pp$ mass that we have obtained is so far above the $\Lambda + p$ threshold, the $\Lambda + p + \pi$ decay would be possible. However, it would contribute to the non back-to-back events in the opening angular distribution of Λ-p pairs. With the present invariant mass precision, it is not clear that the state is below the $\Sigma\pi$ thresholds.

4.1 Other modes to be studied in FINUDA

Recently, the neutron analysis with the TOFONE counters has been implemented in the offline analysis. It enables us to identify $\Sigma^{\pm}$ through $\Sigma^{\pm} \rightarrow$ "n" $+ \pi^{\pm}$. Further, the two-nucleon K^- absorption on a pn pair can be identified through the decay modes $K^-pn \rightarrow \Lambda + n$ and $K^-pn \rightarrow \Sigma^- + p$. Since a pn pair has both $I = 1$ and $I = 0$ components, it would be interesting to compare it with the K^- absorption on the pp pair. Because of the low detection efficiency for neutrons (about 10%), the statistics are limited at this moment.

In addition, Auger neutrons directly emitted in the formation process of kaonic nuclei could be identified as a peak structure in the neutron energy spectrum.

Another interesting mode to be investigated is the invariant-mass spectroscopy with a Λ and a deuteron, which is sensitive for the formation of a K^-ppn bound state.

5 Summary

We have successfully observed evidence of the kaon bound state K^-pp through its decay into a Λ and a proton. The invariant mass distribution of the Λ-p pair shows a significant mass decrease with respect to the mass of the system expected in the case of a simple kaon two-nucleon absorption. The state K^-pp has a binding energy of $115\,^{+6}_{-5}\,(\mathrm{stat.})\,^{+3}_{-4}\,(\mathrm{sys.})$ MeV and a decay width of $67\,^{+14}_{-11}\,(\mathrm{stat.})\,^{+2}_{-3}\,(\mathrm{sys.})$ MeV.

The obtained binding energy suggests the K^- nucleus potential is deeply attractive, and deeper than expected in Ref. [17].

References

[1] D.B. Kaplan and A.E. Nelson, Phys. Lett. B **175**, 57 (1986); A.E. Nelson and D.B. Kaplan, Phys. Lett. B **192**, 193 (1987).

[2] R. Barth *et al.*, Phys. Rev. Lett. **78**, 4007 (1997); F. Laue *et al.*, Phys. Rev. Lett. **82**, 1640 (1999).

[3] A. D. Martin, Nucl. Phys. B **179**, 33 (1981); J. Ciborowski *et al.*, J. Phys. G **8**, 13 (1982); D. Evans *et al.*, *ibid.* **9**, 885 (1983).

[4] D.N. Tovee *et al.*, Nucl. Phys. B **33**, 493 (1971); R.J. Nowak *et al.*, Nucl. Phys. B **139**, 61 (1978); W.E. Humphrey and R.R. Ross, Phys. Rev. **127**, 1305 (1962).

[5] M. Iwasaki *et al.*, Phys. Rev. Lett. **78**, 3067 (1997); T.M. Itoh *et al.*, Phys. Rev. C**58**, 2366 (1998).

[6] G. Beer *et al.*, Phys. Rev. Lett. (2005) (accepted for publication).

[7] M.F.M. Lutz, E.E. Kolomeitsev, Nucl. Phys. A **700**, 193 (2002).

[8] C.J. Batty, E. Friedman, and A. Gal, Phys. Rep. **287**, 385 (1997).

[9] E. Friedman, A. Gal, J. Mareš, A. Cieplý, Phys. Rev. C **60**, 024314 (1999).

[10] E. Friedman, A. Gal, C.J. Batty, Nucl. Phys. A **579**, 518 (1994).
[11] A. Cieplý, E. Friedman, A. Gal, J. Mareš, Nucl. Phys. A **696**, 173 (2001).
[12] N. Kaizer, P.B. Siegel, W. Weise, Nucl. Phys. A **594**, 325 (1995).
[13] T. Waas, N. Kaiser, W. Weise, Phys. Lett. B **365**, 12 (1996); **379**, 34 (1996).
[14] A. Ramos and E. Oset, Nucl. Phys. A **671**, 481 (2000).
[15] A. Baca, C. García-Recio, and J. Nieves, Nucl. Phys. A **673**, 335 (2000).
[16] Y. Akaishi and T. Yamazaki, Phys. Rev. C **65**, 044005 (2002).
[17] T. Yamazaki and Y. Akaishi, Phys. Lett. B **535**, 70 (2002).
[18] A. Doté, H. Horiuchi, Y. Akaishi, and T. Yamazaki, Phys. Lett. B **590**, 51 (2004).
[19] T. Bressani in *Proceedings of Workshop on Physics and Detectors for DAΦNE, Frascati, April 9-12, 1991*, edited by G. Pancheri (Laboratori Nazionali di Frascati), p. 475.
[20] V. Vander Velde-Wilquet *et al.*, Nuovo Cimento **39A**, 538 (1977).
[21] T. Onaga, H. Narumi, and T. Kohmura, Prog. Theor. Phys. **82**, 222 (1989).
[22] P. A. Katz *et al.*, Phys. Rev. D **1**, 1267 (1970).