$a_0^+(980)$-Resonance Production in $pp \to dK^+\bar{K}^0$ Reactions Close to Threshold

V. Kleber,[1,*] M. Büscher,[1] V. Chernyshev,[2] S. Dymov,[1,3] P. Fedorets,[2] V. Grishina,[4] C. Hanhart,[1] M. Hartmann,[1] V. Hejny,[1] A. Khoukaz,[5] H. R. Koch,[1] V. Komarov,[3] L. Kondratyuk,[2] V. Koptev,[6] N. Lang,[5] S. Merzliakov,[3] S. Mikirtychiants,[6] M. Nekipelov,[1,6] H. Ohm,[1] A. Petrus,[3,†] D. Prasuhn,[1] R. Schleichert,[1] A. Sibirtsev,[1] H. J. Stein,[1] H. Ströher,[1] K.–H. Watzlawik,[1] P. Wüstner,[7] S. Yaschenko,[3] B. Zalikhanov,[3] and I. Zychor[8]

[1]*Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[2]*Institute for Theoretical and Experimental Physics, Cheremushkinskaya 25, 117259 Moscow, Russia*
[3]*Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[4]*Institute for Nuclear Research, 60th October Anniversary Prospect 7A, 117312 Moscow, Russia*
[5]*Institut für Kernphysik, Universität Münster, W.-Klemm-Straße 9, 48149 Münster, Germany*
[6]*High Energy Physics Department, Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia*
[7]*Zentralinstitut für Elektronik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[8]*The Andrzej Soltan Institute for Nuclear Studies, 05400 Swierk, Poland*
(Received 6 May 2003; published 24 October 2003)

The reaction $pp \to dK^+\bar{K}^0$ has been investigated at an excess energy of $Q = 46$ MeV above the $K^+\bar{K}^0$ threshold with ANKE at the cooler synchrotron COSY-Jülich. From the detected coincident dK^+ pairs, about 1000 events with a missing $\bar{K}^0$ were identified, corresponding to a total cross section of $\sigma(pp \to dK^+\bar{K}^0) = [38 \pm 2(\text{stat}) \pm 14(\text{syst})]$ nb. Invariant-mass and angular distributions have been jointly analyzed and reveal s-wave dominance between the two kaons, accompanied by a p wave between the deuteron and the kaon system. This is interpreted in terms of $a_0^+(980)$-resonance production.

DOI: 10.1103/PhysRevLett.91.172304 PACS numbers: 13.75.Cs, 25.40.Ve

One of the primary goals of hadronic physics is the description of the internal structure of mesons and baryons, their production and decays, in terms of quarks and gluons. However, the severe complications, related to nonperturbative contributions and confinement effects in QCD, mean that progress in understanding the structure of light hadrons has mainly been within models which use effective degrees of freedom. The constituent quark model is one of the most successful in this respect (see, e.g., [1]). This approach treats the lightest scalar resonances $a_0/f_0(980)$ as conventional $\bar{q}q$ states. However, the structure of these states seems to be more complicated and they have also been identified with $K\bar{K}$ molecules [2] or compact qq-$\bar{q}\,\bar{q}$ states [3]. It has even been suggested that at masses below 1.0 GeV a complete nonet of four-quark states might exist [4]. Possible deviations from the minimal quark model are also generating much interest in the baryon sector, where the recently discovered low-lying θ^+ state in the K^+n system [5] requires at least five quarks.

At the cooler synchrotron COSY-Jülich [6], an experimental program has been started, using the ANKE spectrometer [7], which aims at exclusive data on a_0/f_0 production from pp, pn, pd, and dd interactions close to the $K\bar{K}$ threshold [8]. The final goal will be the extraction of the a_0/f_0 mixing amplitude to shed light on the nature of the light scalar resonances. Here, we report about the first exclusive study of the reaction $pp \to dK^+\bar{K}^0$, where some fraction of the kaon pairs is expected to stem from the decay of the a_0^+ resonance. The measurements were performed at a beam energy of $T_p =$ 2.65 GeV ($p_p = 3.46$ GeV/c), corresponding to an excess energy of 46 MeV above the $K\bar{K}$ threshold.

The isovector $a_0(980)$ has been studied in $p\bar{p}$ annihilations [9], in π^-p collisions [10], and $\gamma\gamma$ interactions [11]. Data on radiative ϕ decays [12,13] are interpreted in terms of a_0/f_0 production in the channels $\phi \to \gamma a_0/f_0 \to \gamma\pi^0\eta/\pi^0\pi^0$. In pp reactions, the $a_0(980)$ has been seen at $T_p = 450$ GeV [14], and a resonant structure around 980 MeV/c^2 has been observed in inclusive $pp \to dX^+$ data at $p_p = 3.8$, 4.5, and 6.3 GeV/c [15].

ANKE is located at an internal target position of COSY, which supplies stored proton beams with intensities up to $\sim 4 \times 10^{10}$. A H_2 cluster-jet target [16] has been used, providing areal densities of $\sim 5 \times 10^{14}$ cm^{-2}. The luminosity has been measured with the help of pp elastic scattering events by detecting one fast proton concurrently recorded with the dK^+ data [17]. Protons in the angular range $\vartheta = 5.5°$–$9°$ have been selected, since the ANKE acceptance changes smoothly for these angles and the elastic peak in the momentum distribution is easily distinguished from the background. The average luminosity during the measurements has been determined to $L = [2.7 \pm 0.1(\text{stat}) \pm 0.7(\text{syst})] \times 10^{31}$ s^{-1} cm^{-2} corresponding to $L_{\text{int}} = 3.3$ pb^{-1}.

ANKE comprises three dipole magnets (D1-3), which guide the circulating COSY beam. The central C-shaped spectrometer dipole D2 downstream of the target separates the reaction products from the beam. The angular acceptance of D2 for kaons from a_0^+ decay is $|\vartheta_H| \leq 12°$ horizontally and $|\vartheta_V| \leq 3.5°$ vertically [18]. The angular acceptance for the fast deuterons ($p_d \sim 2100$ MeV/c) is roughly $|\vartheta_{\rm H}| \leq 10°$ and $|\vartheta_{\rm V}| \leq 3.0°$ and depends on the momentum in the horizontal direction [19].

K^+ mesons are detected in range telescopes, located at the side of D2 along the focal surface, providing excellent kaon-versus-background discrimination, and were identified by means of time-of-flight (TOF) and energy-loss (ΔE) measurements. Details of the procedure can be found in Ref. [18]. For our measurements, only some of the telescopes were used, covering the lower momentum range [$p_{K^+} = (390\text{–}625)$ MeV/c] of the a_0^+ decay K^+ mesons. Two multiwire proportional chambers (MWPCs) positioned in front of the telescopes allow one to deduce the ejectile momenta and to suppress scattered background [7,18]. Coincident fast particles and elastically scattered protons are detected in the ANKE forward-detection (FD) system consisting of two layers of scintillation counters for TOF and ΔE measurements as well as three MWPCs, each with two sensitive planes, for momentum reconstruction and background suppression [7,19].

Two bands from protons and deuterons are clearly seen in the time difference between the detection of a K^+ meson in one of the telescopes and a particle in the FD as a function of the FD particle momentum [see Fig. 1(a)]. The deuterons are selected with the criterion indicated by the dashed lines. In Fig. 1(b), the missing-mass distribution $m(pp, dK^+)$ for the selected $pp \to dK^+X$ events is presented. At $T_p = 2.65$ GeV, the missing particle X must be a $\bar{K}^0$ due to charge and strangeness conservation. The measured dK^+ missing-mass distribution peaks at $m_{\bar{K}^0} = 498$ MeV/c^2, reflecting the clean particle identification. Approximately 1000 events within the gate indicated by the dashed arrows are accepted as $dK^+\bar{K}^0$ events for further analysis. The remaining background from misidentified particles is $(9 \pm 2)\%$.

The tracking efficiency for kaons in the side MWPCs has been determined by requiring TOF and ΔE of a kaon (and any particle in FD) and calculating the ratio of identified kaons (as peak in the TOF distribution) with and without demanding a reconstructed track. The efficiency depends on the telescope number, i.e., K^+ momentum, and varies between 71% and 93%. The efficiency of the ΔE criterion for the K^+ mesons has been deduced with the help of simultaneously recorded $pp \to pK^+\Lambda$ events which, due to the significantly larger cross section, can be selected by TOF alone. This efficiency is independent of the telescope number and amounts to 52%. The FD MWPC efficiencies have been determined for each of the six sensitive planes individually from events with hits in all other five planes. The information from two horizontal (vertical) planes has been used to reconstruct the intersection point in the remaining plane and, subsequently, to determine the efficiency distribution across the chamber areas, i.e., the angular and momentum dependences. The average FD track efficiency for deuterons is 73%. The efficiency of the FD scintillators and all TOF criteria is larger than 99% [18]. The data have been corrected for all efficiencies on an event-by-event basis.

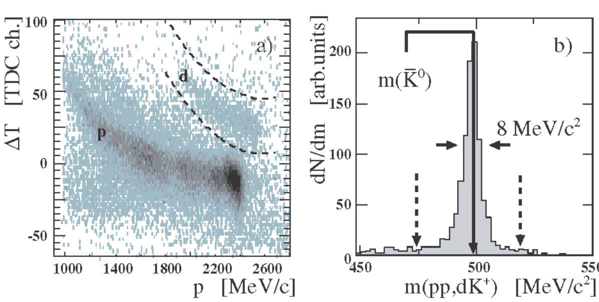

FIG. 1 (color online). (a) Time difference between the fast forward going particles in layer 1 of the FD scintillators and the K^+ mesons versus the momentum of the forward particle. The dashed lines indicate the selection for deuteron identification. (b) Missing mass $m(pp, dK^+)$ distribution of the $pp \to dK^+X$ events.

The differential acceptance of ANKE has been obtained with the Monte Carlo method described in Ref. [20], which allows one to determine the acceptance independently of the ejectile distributions at the production point. The acceptance is defined as a discrete function of the five relevant degrees of freedom in the three-body final state. For an unpolarized measurement, the acceptance can be expressed by a four-dimensional matrix with four independent kinematical variables. Two different matrices, each composed of 500 elements (see Table I) were used for the reconstruction of the invariant masses $m(K^+\bar{K}^0)$, $m(d\bar{K}^0)$, and the center-of-mass (cms) angular distributions $|\cos(pk)|$, $|\cos(pq)|$, and $\cos(kq)$ (for a definition see Fig. 2). Ninety million events following a phase-space distribution were simulated and tracked through ANKE, taking into account small angle scattering, decay in flight, and the MWPC resolutions. Subsequently, the mass and angular distributions have been corrected with the weights from the corresponding acceptance matrices on an event-by-event basis. The impact of the few acceptance holes has been investigated using distributions with different shapes in the masses and angles and is included in the systematic error of the differential distributions and the total cross section. The efficiency and acceptance corrected data are shown in Fig. 3 with statistical and systematic uncertainties.

TABLE I. Variables (all in the overall cms) of acceptance matrices I (upper) and II (lower) and their number of bins. Matrices I and II are used for the correction of the mass and angular spectra, respectively. $\psi(K\bar{K})$ is the rotation angle of the decay plane around the direction of the deuteron momentum $\vec{k}$. The symmetry of the angular distributions around 90° with respect to the proton beam has been utilized.

$m^2(K^+\bar{K}^0)$	$m^2(d\bar{K}^0)$	$\lvert\cos(pk)\rvert$	$\psi(K\bar{K})$
5	5	5	4
$\lvert\cos(pk)\rvert$	$\lvert\cos(pq)\rvert$	$\cos(kq)$	$E(d)$
5	5	5	4

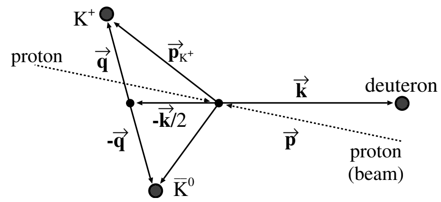

FIG. 2. Definition of the vectors $\vec{p}$, $\vec{k}$, and $\vec{q}$ in the cms of the reaction $pp \to dK^+\bar{K}^0$. Angular distributions with respect to the beam direction $\vec{p}$ have to be symmetric around 90° since the two protons in the entrance channel are indistinguishable.

The integrated acceptance of ANKE for the $dK^+\bar{K}^0$ events is 2.2%. Taking into account all correction factors, a total cross section of $\sigma(pp \to dK^+\bar{K}^0) = [38 \pm 2(\text{stat}) \pm 14(\text{syst})]$ nb has been derived.

The mass and angular resolutions for the spectra in Fig. 3 have been obtained from simulations and amount to $\delta m_{K^+\bar{K}^0} = (8\text{–}1)\ \text{MeV}/c^2$ in the range $(0.991\text{–}1.038)\ \text{GeV}/c^2$, $\delta m_{d\bar{K}^0} \sim 3\ \text{MeV}/c^2$ in the full mass range, and $\delta[\cos(\vartheta)] \sim 0.2$ for all angular spectra (FWHM values). The effect of these resolutions on the shape of the differential spectra is included in the systematic errors shown in Fig. 3. Because of the finite values of δm, some events lie outside the kinematical limits at $m(K^+\bar{K}^0) = 0.991$ and $m(d\bar{K}^0) = 2.420\ \text{GeV}/c^2$ and have been excluded from the fit described below.

In the close-to-threshold regime, only a limited number of final states can contribute. If we restrict ourselves to the lowest partial waves, we need to consider either a p wave in the $K\bar{K}$ system accompanied by an s wave of the deuteron with respect to the meson pair or an s wave $K\bar{K}$ with a p-wave deuteron. Selection rules do not allow for s waves in both subsystems simultaneously. Under these assumptions, one may write for the square of the transition matrix element

$$|\bar{\mathcal{M}}|^2 = C_0^q q^2 + C_0^k k^2 + C_1(\hat{p}\cdot\vec{k})^2 + C_2(\hat{p}\cdot\vec{q})^2 + C_3(\vec{k}\cdot\vec{q}) + C_4(\hat{p}\cdot\vec{k})(\hat{p}\cdot\vec{q}), \quad (1)$$

with $\hat{p} = \vec{p}/|\vec{p}|$. The parameters C_i can be directly related to the eight allowed partial wave amplitudes, as was done, e.g., in Refs. [21–23]. Only $K\bar{K}$ p waves contribute to C_0^q and C_2, only $K\bar{K}$ s waves to C_0^k and C_1, and only s-p interference terms to C_3 and C_4. Thus, a fit to the data supplies direct information on the relative strength of the different partial waves. The result of the fit is shown as the solid line in Fig. 3 and the corresponding parameters C_i are displayed in Table II {note that from our spectra C_3 and C_4 cannot be extracted individually but only $[C_3 + (1/3)C_4]$}. The overall agreement between fit and data confirms the assumption that only the lowest partial waves contribute. The dashed lines in Fig. 3 depict the contributions from $K\bar{K}$ s waves only ($C_0^q = C_2 = C_3 = C_4 = 0$) and the dotted line those from pure $K\bar{K}$ p waves ($C_0^k = C_1 = C_3 = C_4 = 0$). Thus, we find that the reaction is dominated by the $K\bar{K}$ s wave. The contribution from $K\bar{K}$ p waves is less than 20%.

Since the $K\bar{K}$ p waves prefer large masses, it is the slope at higher $K\bar{K}$ masses that sets an upper bound for the p-wave contribution. On the other hand, the slope of the $|\cos(pq)|$ distribution determines the minimum p-wave strength. Therefore, the contribution of $K\bar{K}$ p waves is strongly constrained by the data. The deviation in $|\cos(pk)|$ might indicate a small contribution from a d wave of the deuteron with respect to the s-wave meson pair. This d-wave contribution would have little influence on the shapes of the other measured distributions.

Since the excess energy is small and the nominal mass of the a_0^+ is very close to the $K\bar{K}$ threshold, the resonance cannot be seen as a clear structure in the invariant-mass spectra, but, in any case, the propagation of low energy s-wave $K\bar{K}$ pairs should be governed by the a_0^+ resonance due to the proximity of its pole to the $K\bar{K}$ threshold. This, together with the result of the fit, leads us to the conclusion that the reaction $pp \to dK^+\bar{K}^0$ at $T_p = 2.65$ GeV proceeds mainly via the a_0^+ resonance.

In Ref. [24], a model has been presented which describes both resonant, dominated by the direct a_0 production off a single nucleon, as well as nonresonant $K\bar{K}$

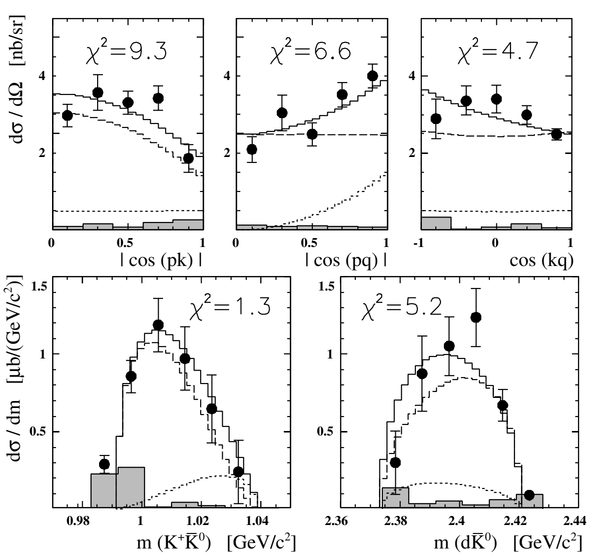

FIG. 3. Angular and invariant mass distributions. The shaded areas correspond to the systematic uncertainties of the acceptance correction. The dashed (dotted) line corresponds to $K^+\bar{K}^0$ production in a relative s (p) wave, and the solid line is the sum of both contributions. The overall errors from the luminosity determination are not included in the statistical and systematic uncertainties. The common fit with Eq. (1) to all spectra yields $\chi^2_{\text{ndf}} = 1.1$. The individual χ^2 values are displayed in the corresponding panels.

TABLE II. Result for the various coefficients of Eq. (1). All coefficients are given in units of GeV^{-2}.

C_0^q	C_0^k	C_1	C_2	$C_3 + \frac{1}{3}C_4$
0 ± 0.1	0.89 ± 0.03	-0.5 ± 0.1	1.12 ± 0.07	-0.32 ± 0.15

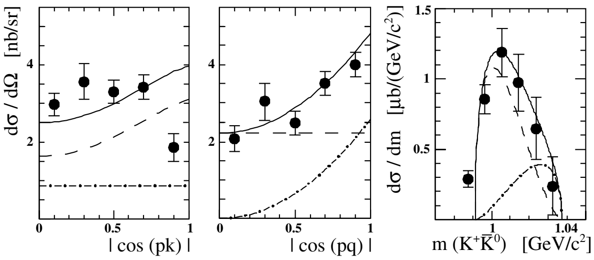

FIG. 4. Predictions of the model of Ref. [24] in comparison to the experimental data. An overall scaling factor is included as described in the text.

production, driven by a π-K^*-π exchange current. This current, due to G-parity conservation, generates the $K\bar{K}$ pair in a relative p wave. The only free parameter of the model, an overall factor, was adjusted to higher energy data [15]. The predictions of this model for some of the spectra measured in this experiment are shown in Fig. 4. A scaling factor of 0.75 has been included in order to adjust the model results to the integrated cross section.

As can be seen from the figure, the model calculations agree with the data for $m(K^+\bar{K}^0)$ and $|\cos(pq)|$, the spectra which are most sensitive to the relative s- and p-wave contributions. The discrepancy in Fig. 4, left side, indicates that there might be another possible reaction mechanism involved. Here it is important to note that within the model from Ref. [24] the ratio of integrated resonant to nonresonant production cross section has very little sensitivity on the details of the $\cos(pk)$ distribution.

In summary, first, data on the reaction $pp \to dK^+\bar{K}^0$ close to the production threshold are presented. The total cross section for this reaction as well as differential distributions have been determined. Dominance of the $K\bar{K}$ s wave ($>80\%$ of the total cross section) has been deduced based on a joint analysis of angular and invariant-mass spectra. This is clear evidence for a predominant resonant production via the $a_0^+(980)$. A comparison of the experimental data to model calculations [24] shows that the background ($K\bar{K}$ p waves) can be understood in terms of a simple meson exchange current. Further theoretical investigations are necessary to identify the possible role of a strong $d\bar{K}$ interaction as proposed in Ref. [25]. Here both a measurement at higher energies and polarization experiments would be of great use. Our results demonstrate the feasibility of studying light scalar resonances in exclusive measurements close to the $K\bar{K}$ threshold with high mass resolution and low background using ANKE at COSY-Jülich.

We are grateful to W. Borgs, C. Schneider, and the IKP technicians for the support during the beam time and to J. Ritman and C. Wilkin for stimulating discussions and careful reading of the manuscript. The work at ANKE has partially been supported by BMBF (Grants No. WTZ-RUS-684-99, No. 686-99, No. 211-00, No. 691-01, No. GEO-001-99, No. POL-007-99, and No. 015-01); DFG (436 RUS 113/444, 561, 630); Polish State Committee for Scientific Research (2 P03B 101 19); Russian Academy of Science (RFBR99-02-04034, 18179a, 06518, 02-02-16349); and ISTC (1861, 1966).

*Present address: Institut für Kernphysik, Universität zu Köln, 50937 Köln, Germany.
Electronic address: v.kleber@fz-juelich.de
†Deceased.

[1] D. Morgan and M. R. Pennington, Phys. Rev. D **48**, 1185 (1993); A.V. Anisovich *et al.*, Eur. Phys. J. A **12**, 103 (2001); S. Narison, hep-ph/0012235.
[2] J. Weinstein and N. Isgur, Phys. Rev. D **41**, 2236 (1990); G. Janssen *et al.*, Phys. Rev. D **52**, 2690 (1995); J. A. Oller and E. Oset, Nucl. Phys. **A620**, 438 (1997); **652**, 407(E) (1999).
[3] N. N. Achasov, hep-ph/0201299; R. J. Jaffe, Phys. Rev. D **15**, 267 (1977); J. Vijande *et al.*, in *Proceedings of the International Workshop MESON 2002, Cracow, Poland* (World Scientific, Singapore, 2002); hep-ph/0206263.
[4] F. E. Close and N. A. Törnqvist, J. Phys. G **28**, R249 (2002).
[5] T. Nakano *et al.*, Phys. Rev. Lett. **91**, 012002 (2003).
[6] R. Maier, Nucl. Instrum. Methods Phys. Res., Sect. A **390**, 1 (1997).
[7] S. Barsov *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 364 (2001).
[8] M. Büscher *et al.*, Proceedings of the International Workshop Physics at COSY, Jülich, 2002 (hep-ph/0301126).
[9] A. Abele *et al.*, Phys. Lett. B **327**, 425 (1994); A. Abele *et al.*, Phys. Rev. D **57**, 3860 (1998); A. Bertin *et al.*, Phys. Lett. B **434**, 180 (1998).
[10] S. Teige *et al.*, Phys. Rev. D **59**, 012001 (1999).
[11] P. Achard *et al.*, Phys. Lett. B **526**, 269 (2002).
[12] N. N. Achasov *et al.*, Phys. Lett. B **485**, 349 (2000); Phys. Lett. B **479**, 53 (2000).
[13] A. Aloisio *et al.*, Phys. Lett. B **536**, 209 (2002); Phys. Lett. B **537**, 21 (2002).
[14] D. Baberis *et al.*, Phys. Lett. B **440**, 225 (1998); Phys. Lett. B **488**, 225 (2000).
[15] M. A. Abolins *et al.*, Phys. Rev. Lett. **25**, 469 (1970).
[16] A. Khoukaz *et al.*, Eur. Phys. J. D **5**, 275 (1999).
[17] P. Fedorets and V. Kleber, Proceedings of the International Conference on Quarks and Nuclear Physics 2002, Jülich, Germany [Eur. Phys. J. (to be published)].
[18] M. Büscher *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **481**, 378 (2002).
[19] V. Komarov *et al.*, Phys. Lett. B **553**, 179 (2003).
[20] F. Balestra *et al.*, Phys. Rev. C **63**, 024004 (2001).
[21] V. Yu. Grishina *et al.*, Phys. Lett. B **521**, 217 (2001).
[22] V. Chernyshev *et al.*, nucl-th/0110069.
[23] A. E. Kudryavtsev *et al.*, Phys. Rev. C **66**, 015207 (2002).
[24] V. Yu. Grishina *et al.*, in *Proceedings of the International Workshop MESON 2002, Cracow, Poland* (Ref. [3], p. 465).
[25] E. Oset *et al.*, Eur. Phys. J. A **12**, 435 (2001).