Vol. 29 (1998) *ACTA PHYSICA POLONICA B* No 9

# HUNTING THE DIBARYON $d'(2065)$*

GERHARD J. WAGNER

Physikalisches Institut der Universität Tübingen, Tübingen, Germany

for the LEPS Collaboration

R. BILGER[a], H. CLEMENT[a], A. DENIG[b], K. FÖHL[c], J. GRÄTER[a], W. KLUGE[b] J. PÄTZOLD[a], R. MEIER[a], M. SCHEPKIN[d], G.J. WAGNER[a]

for the CHAOS Collaboration

P.A. AMAUDRUZ[e], A. AMBARDAR[f], R. BILGER[a], F. BONUTTI[g], P. CAMERINI[g] J. CLARK[h], H. CLEMENT[a], L. FELAWKA[e], E. FRIEDMAN[i], J. GRÄTER[a] N. GRION[g], G.J. HOFMAN[f], P. HONG[j], M. KERMANI[f], E.L. MATHIE[j] R. MEIER[a], D. OTTEWELL[e], O. PATARAKIN[k], R. RUI[g], M. SCHEPKIN[d] M.E. SEVIOR[h], G.R. SMITH[e], R. TACIK[j], G. TAGLIENTE[f], G.J. WAGNER[a]

for the WASA/PROMICE Collaboration

R. BILGER[a], W. BRODOWSKI[a], H. CALÉN[l], H. CLEMENT[a], C. EKSTRÖM[m] K. FÖHL[c], K. FRANSSON[l], L. GUSTAFSSON[l], S. HÄGGSTRÖM[l], B. HÖISTAD[l] A. JOHANSSON[l], T. JOHANSSON[l], K. KILIAN[n], S. KULLANDER[l], A. KUPŚĆ[o] G. KURZ[a], P. MARCINIEWSKI[o], B. MOROSOV[p], J. MOEHN[l], A. MÖRTSELL[l] W. OELERT[n], V. RENKEN[n], R. RUBER[l], M.G. SCHEPKIN[d], U. SIODLACZEK[a] J. STEPANIAK[o], A. SUKHANOV[p], A. TUROWIECKI[s], G.J. WAGNER[a] Z. WILHELMI[s], J. ZABIEROWSKI[r], A. ZERNOV[p], J. ZLOMANCZUK[s]

[a]Physikalisches Institut, Universität Tübingen, 72076 Tübingen, Germany
[b]Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany
[c]Department of Physics and Astronomy, University of Edinburgh, U.K.
[d]ITEP Moscow, 117218 Moscow, Russia
[e]TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6t 2A3, Canada
[f]Department of Physics and Astronomy, UBC, Vancouver, Canada
[g]University and INFT Trieste, 34127 Trieste, Italy
[h]School of Physics, University of Melbourne, Parkville, Vic., Australia
[i]Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
[j]University of Regina, Regina, Sak. Canada
[k]RRC Kurchatov Institute, 123182 Moscow, Russia
[l]Dept of Radiation Sciences, University of Uppsala, Sweden
[m]The Svedberg Laboratory, Uppsala, Sweden
[n]Institut für Kernphysik, KFA Jülich, Germany
[o]Institute for Nuclear Studies, Warsaw, Poland
[p]Joint Institute for Nuclear Research, Dubna, Russia
[r]Institute for Nuclear Studies, Łódź, Poland
[s]Institute for Experimental Physics, Warsaw, Poland

*(Received June 11, 1998)*

* Presented at the NATO Advanced Research Workshop, Cracow, Poland, May 26–30, 1998.

In order to explain the resonance-like excitation functions of pionic double-charge-exchange reactions near 50 MeV the existence of a narrow $\pi NN$-resonance $d'$ with a mass of about 2.06 GeV has been postulated. The status of the various experiments that have been performed to establish the existence of the $d'$ is reported.

PACS numbers: 14.20.Pt, 25.80.Gn, 13.75.Cs

## 1. The $d'$ hypothesis

QCD is compatible with the existence of colour neutral objects including exotic objects such as glueballs and dibaryons. However, the difficulties of solving QCD equations on the 1-GeV scale prevent an understanding of the confinement properties. Therefore present calculations of dibaryon states lack predictive power which leaves the burden of proof to the experimentalists. By the same token the discovery of a dibaryon state would help to approach the confinement problem.

During the 1980s this goal motivated a hectic search for dibaryons of all sorts, mostly in the $NN$-channel. Indeed, numerous claims of observed dibaryons were made, none of which survived a later scrutiny of the data, in most cases due to a lack of statistical accuracy. For our purpose it is interesting to note that almost all searches in the non-strange sector were insensitive to states with spin and parity $J^P = 0^-, 2^-$ and isospin even. In the early 1990s when we started our investigations the persistent failure to observe a dibaryon led to an anticlimax of the expectations.

Indeed, we started the pionic double charge exchange (DCX) experiments that led to the so-called $d'$ hypothesis rather with the aim of studying nucleon-nucleon correlations in nuclei, a topic which we still pursue to date with electromagnetically induced two-nucleon emission reactions. The sensitivity of DCX reactions at low energies to short-range correlations had been demonstrated by systematic studies at LAMPF. In the conventional model of the reaction mechanism the DCX proceeds via two sequential single-charge exchange processes with an intermediate off-shell $\pi^0$ propagating through nuclear matter. It is intuitively clear that the amplitude for such a process will depend on spatial correlations of nucleons.

The sequential model of the reaction mechanism, however, was unable and still is today to describe the resonance-like behaviour of the forward-angle DCX cross sections leading to discrete final states, which has been observed at pion energies near 50 MeV in all nuclei with $A > 4$ investigated so far. (Note, that this failure of the model has prevented the originally intended exploitation of this reaction for a quantitative study of $NN$-correlations).

When our DCX experiments at PSI using the ideally suited low-energy pion spectrometer LEPS confirmed the resonance behaviour of the excitation functions, we suggested [1], in the absence of a conventional explanation, the participation of a hypothetical dibaryon $d'$ as the origin of this behaviour. This assumption was not entirely *ad hoc*, but rather based on QCD-inspired quark models [2,3] which predicted $q^4 - q^2$ type non-strange, isospin-zero dibaryons slightly above the $\pi NN$-threshold. The $l = 1$ multiplet would contain members with $J^P = 0^-, 2^-$ which cannot decay into the $NN$-channel and are expected to have a narrow width. Bilger, Clement and Schepkin [4] using a Breit–Wigner ansatz for the $\pi NN$-resonance $d'$ were able to describe all available excitation functions and angular distributions assuming a $J^P = 0^-, I$ even $\pi NN$-resonance with a mass of 2.06 GeV/$c^2$, a vacuum width for decay into the $\pi NN$-channel of about 0.5 MeV, and an additional spreading width of about 5 MeV. The Fermi motion of the $NN$-pairs in the initial and final states was taken into account explicitly by using shell-model wave functions.

The signal of this suspected dibaryon undoubtedly is statistically significant, despite its tiny cross sections of the order of $1\mu$/sr. Indeed, the signal could only be observed because the competing conventional amplitude is even smaller. Also the experimental efforts required to suppress the non-physical background were considerable. In the ensuing discussions we also convinced ourselves that there was no other available experiment where the $d'$ with the given properties could have been seen previously. In our quest for the existence of the $d'$ we pursued three major lines which shall be discussed in the following.

## 2. DCX reactions on nuclei

Over the years we have considerably supplemented the systematics of low-energy DCX reactions by measuring excitation functions and angular distributions on $^7$Li, $^{12}$C, $^{16}$O, $^{40}$Ca, $^{56}$Fe and $^{93}$Nb from threshold to about to about 90 MeV. A review of the results will be given by H. Clement in the ensuing workshop MESON 98. Therefore I will only show, by way of example, the forward-angle excitation functions for the ground state transitions on $^{16}$O and $^{40}$Ca [5] in Fig. 1. At $T_\pi \approx 160$ MeV one notices the contribution from the $\Delta$-resonance thoroughly investigated at LAMPF. But the most conspicuous structure is the low-energy resonance attributed to the possible $d'$. It is truly remarkable that this striking phenomenon is still not understood in conventional models. For the closed shell target nuclei displayed here the most successful model so far [6] would even predict vanishing cross sections, or at most tiny ones if ground state correlations were included. In contrast, the $d'$ model calculations (solid curves) reproduce the data quite well, including the rough mass independence of the peak cross sections. To that aim, the spreading width of the $d'$ in nuclear matter was adjusted to $9\pm4$ MeV and $19\pm5$ MeV for $^{16}$O and $^{40}$Ca, respectively, values that are compatible with estimates [5] of the collision damping.

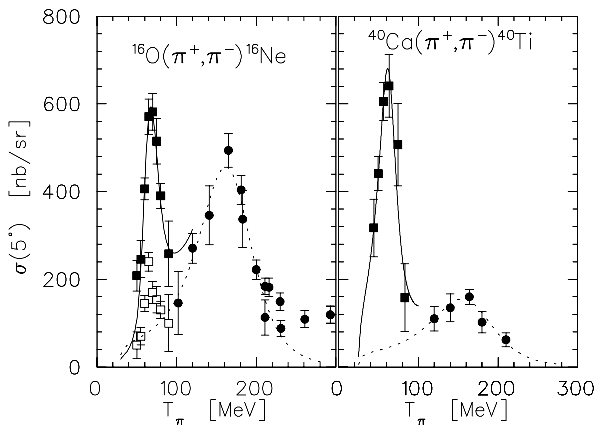


Fig. 1. Forward-angle cross sections for ground state transitions. The open symbols show our results for the $0_2^+$ state in $^{16}$Ne. Data for $T_\pi \geq 100$ MeV are from LAMPF. Dotted lines give the parametrization of the $\Delta\Delta$-process, solid lines are $d'$ calculations. From Ref. [5].

These recent DCX data corroborate the original $d'$ picture. Being more accurate and detailed than previous measurements, they could serve as a source of information on the dibaryon properties once its existence will have been established. But given the possible influence of the medium, these data by themselves are not presented as a proof of its existence.

## 3. DCX reactions on few-nucleon systems

To minimize the influence of the nuclear medium the CHAOS collaboration at TRIUMF studied DCX reactions on $^3$He and $^4$He which are the lightest nuclei where DCX is possible. In these cases the final states are in the continuum with three and four identical nucleons, respectively. In Ref. [7] we have shown that as a result of Pauli blocking the cross section for the conventional process rises slowly above the DCX threshold (about 30 MeV for $^4$He). In the case of additional $d'$ production the cross section, now being much less subject to Pauli blocking, was predicted to rise steeply at the $d'$ threshold of about 80 MeV (depending on the precise $d'$ mass). Based on that prediction we performed [8] an inclusive $^4$He$(\pi^+,\pi^-)$ experiment (E 725 ) using a liquid $^4$He target in the CHAOS detector. The results (Fig. 2) show the predicted fast rise of the cross section at the $d'$ threshold and they match well with recent measurements at higher energies. The most sophisticated conventional model calculation was performed by Friedman using a code by Gibbs and Rebka; his results are shown by the dashed-and-dotted curve. It clearly shows a much slower energy dependence than the data. To be able to study the effects of Pauli blocking and final state interactions we developed our own semi-classical Monte-Carlo simulation of the sequential single-charge-exchange cross sections. This model (dashed curve) yields only relative cross sections and was adjusted to the data at higher energies where the predicted contribution from $d'$ production (solid curve) is negligible. Near 90 MeV the measured cross sections still exceed the calculated ones by at least a factor of three and agree well with the predicted (incoherent) sum of conventional plus $d'$ cross sections. But the model dependence for the conventional process is such that again we do not present these findings as a proof of the $d'$ existence.

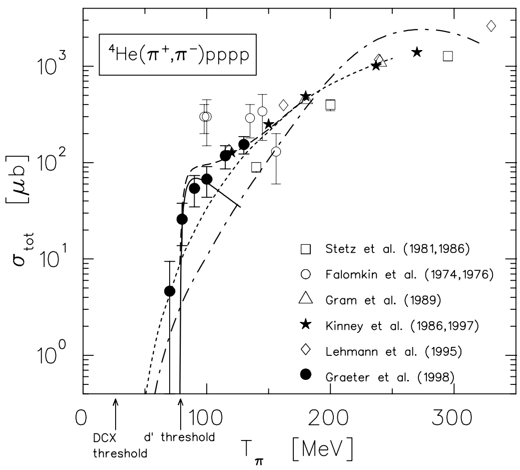


Fig. 2. Total $^4$He $(\pi^+, \pi^-)$ cross sections. The dot-dashed curve shows results from the Gibbs-Rebka model, the dotted curve represents the MC model, the full curve the $d'$ mechanism and the dashed curve the incoherent sum of the MC model and the $d'$ mechanism. From Ref. [8].

We had hoped that this proof would come from an ambitious exclusive $^4$He$(\pi^+, \pi^-)4p$ experiment (E 719), where the invariant mass of two protons and the $\pi^-$ was measured at energies of 105 and 115 MeV. The observation of the proton tracks in the CHAOS detector necessitated the use of a gas target which entailed a low statistical accuracy. Together with the combinatorial background from the spectator protons the results are barely conclusive.

But a signal of a size as expected from the inclusive experiment was not observed.

Finally, using a liquid $^3$He target, we measured (E 785) the $^3\mathrm{He}(\pi^-,\pi^+)3\mathrm{n}$ reaction. One of the neutrons coincident with the positive pion was measured with a time-of-flight wall. Obviously in the case of intermediate $d'$ formation the TOF spectrum should show a narrow signal from the two-body reaction $\pi^- + {}^3\mathrm{He} \to d' + n$. The data taken last summer are presently being analyzed.

## 4. Production of the free $d'$

Based on estimates of the $d'$ production by photoabsorption on deuterium an attempt was made at MAMI to study the $\gamma + d \to d' \to np\pi^0$ reaction using the TAPS detector. As only one third of the requested run time was made available I consider this experiment as a feasibility study only. Once the existence of the $d'$ will have been established by other means, the use of electromagnetic probes to study its properties of course will become indispensable.

In contrast, our attempts to produce the free $d'$ hadronically look very promising. Based on estimates of the $d'$-production in $pp$-collisions [9] the WASA/PROMICE collaboration at the CELSIUS ring in Uppsala has investigated the $pp \to pp\pi^-\pi^+$ reaction at 750 MeV [10]. Using the scintillator hodoscope positive pions were identified by their afterpulses from weak decays. The trigger was set to at least 3-prong events, this way excluding single pion production.

For events of the two-body reaction $pp \to d'\pi^+$ the $\pi^+$ spectra alone should carry the information on the $d'$ invariant mass. The spectrum of $\pi^+$ kinetic energies integrated for polar angles $4 \leq \Theta \leq 21^\circ$ spanned by the detector (Fig. 3) shows a structure in excess of the phase space distribution expected for conventional charged $2\pi$ production. Using in addition the information on the measured $\pi^+$ angles the $\pi^-pp$-invariant mass spectrum of Fig. 4 is obtained. One sees that the broad excess structure of Fig. 3 collapses into a narrow peak with $4\sigma$-statistical significance at the expected $d'$ mass. The width of this peak is very sensitive to the kinematical assumptions; by changing the assumed interaction vertex by 5 mm in height, which corresponds to a change in angle of about $0.5^\circ$, this peak essentially disappears. Let me stress that this is not likely to happen for an artifact.

Yet, the possibility of an artifact produced by the segmented calorimeter has been our main worry since publishing the results of the 1995 run [10]. A higher-statistics run at 750 and 775 MeV was made 1996. As the detector had been partly dismantled between the two run series a new set of calibration constants are presently being determined. To this aim the detector response is being tested both for protons and pions by measuring

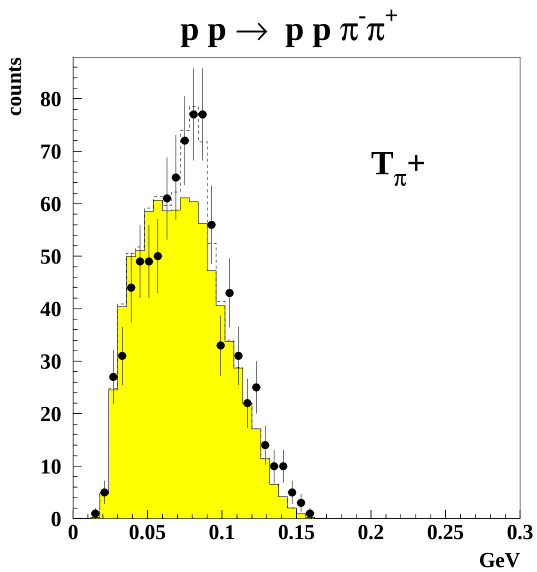


Fig. 3. Spectrum of the kinetic energy of identified $\pi^+$ events resulting from the reaction $pp \to pp\pi^+\pi^-$ at $T_p = 750$ MeV. The solid histogram shows a MC-simulation of the conventional $2\pi$-production process, the dashed one shows the MC-result with inclusion of the $d'$ production process. From Ref. [10].

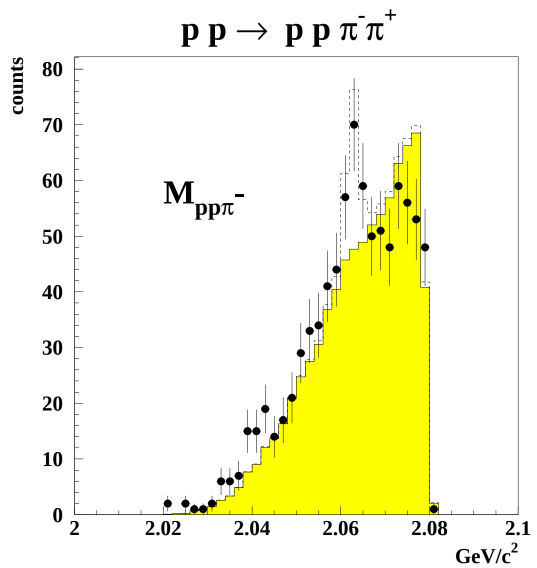


Fig. 4. Invariant-mass spectrum $M_{pp\pi^-}$ of the reaction $pp \to pp\pi^-\pi^+$ at $T_p = 750$ MeV. For definition of histograms see Fig. 3. From Ref. [10].

and analyzing the $pn\pi^+$ and $d\pi^+$ channels at properly chosen collision energies. Simultaneously the detector response to all these reactions is studied by Monte-Carlo simulations with constantly increasing degree of sophistication. Despite these efforts my predictions are that a residual doubt will remain in view of the segmentation of the WASA/PROMICE detector. Therefore we plan to repeat the measurement with an entirely different type of detector, namely with the TOF detector at COSY.

Our attempts to use the WASA/PROMICE detector with unprecedented precision has led to a (preliminary) spin-off result with interesting consequences. The cross section for charged two-pion production in $pp$-collisions at 750 MeV was found to be about 1.5 $\mu$b instead of the previously measured 7$\mu$b [11]. As the signal attributed to the $d'$ is only 7% of this cross section it corresponds to about 100 nb only. At this level a recent inclusive $pp$-experiment [12] which claims to rule out the $d'$ hypothesis is completely insensitive. But it is also true that this value is much lower than predicted by Schepkin *et al.* [9]. Their prediction can be made to agree with the experiment by increasing the $\omega NN$ coupling constant from its SU(3) value to that of the Bonn potential. As simultaneously the $d'$ decay width $\Gamma_{\pi NN}$ can be kept fixed the achieved fits to the DCX cross sections will not be affected.

## 5. Conclusions

I have presented a fairly large body of data obtained from experiments devoted to the search for the dibaryon candidate $d'$. Despite these efforts I can not answer the question if the $d'$ does exist or not. The inclusive DCX reactions on $A \geq 4$ nuclei consistently show a statistically significant signal which is described by the $d'$ hypothesis. However, this interpretation suffers from the uncertain influence of medium effects. There clearly remains the challenge for reaction theory to describe the excitation functions without exotic assumptions. The ambitious attempt to observe the $d'$ as a peak in the invariant $pp\pi^-$ mass spectrum of the exclusive $^4\mathrm{He}(\pi^+,\pi^-)4p$ reaction unfortunately was not met with success, possibly due to the low statistical accuracy. While this outcome is hardly encouraging, a promising result was obtained in the $2\pi$-production in $pp$-collisions. Admittedly the signal is weaker than predicted (if our preliminary normalization is confirmed). However, the theoretical estimate probably may be lowered without sacrificing the successful fits to the DCX cross sections. This then justifies our ongoing efforts to clarify the nature of this signal.

Once the existence of the $d'$ will have been proven it will be another challenge to determine its properties such as size, form factors and its structure. Should the search be unsuccessful, if only for the reason that the $d'$ does not exist, then all observed phenomena will have to be explained in a non-exotic way, and the hunt will have served as an incentive for an ambitious program on which we would never have embarked otherwise and which led to precision measurements which are of interest in their own right. Finally, a successful description of the low-energy DCX data by conventional means would allow to exploit this reaction for the study of $NN$-correlations in nuclei as originally intended.

Gerhard J. Wagner acknowledges the support of this work by the German Federal Minister of Education and Research (BMBF) under contract 06 TU 886 and by the Deutsche Forschungsgemeinschaft (Graduiertenkolleg Mu 705/3)

## REFERENCES

[1] R. Bilger *et al.*, *Z. Phys.* **A343**, 491 (1992).

[2] P.J.G. Mulders, A.T. Aerts, J.J. de Swart, *Phys. Rev.* **D 21**, 2653 (1980).

[3] L.A. Kondratyuk, B.V. Martemyanov, M.G. Schepkin, *Sov. J. Phys.* **45**, 776 (1987).

[4] R. Bilger, H. Clement, M.G. Schepkin, *Phys. Rev. Lett.* **71**, 42 (1993).

[5] K. Föhl *et al.*, *Phys. Rev. Lett.* **79**, 3849 (1997).

[6] N. Auerbach *et al.*, *Phys. Rev.* **C38**, 1277 (1988).

[7] H. Clement, M. Schepkin, G.J. Wagner, O. Zaboronsky, *Phys. Lett.* **B337**, 43 (1994).

[8] J. Gräter *et al.*, *Phys. Lett.* **B420**, 37 (1998) and submitted to *Phys. Rev.* **C**.

[9] M. Schepkin, O. Zaboronsky, H. Clement, *Z. Phys.* **A345**, 407 (1993).

[10] W. Brodowski *et al.*, *Z. Phys.* **A355**, 5 (1996).

[11] L.G. Dakhno *et al.*, *Sov. J. Nucl. Phys.* **37**, 540 (1983).

[12] B.M. Abramov *et al.*, *Eur. Phys. J.* **A1**, 115 (1998).