Evidence for a New Resonance from Polarized Neutron-Proton Scattering

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Abstract: Evidence for a new resonance has been found in polarized neutron-proton elastic scattering in the energy region of the narrow resonance structure...
\[ I(J^P) = 0(3^+) \], \( M \approx 2380 \text{ MeV}/c^2 \) and \( \Gamma \approx 70 \text{ MeV} \) observed recently in the double-pionic fusion channels \( pn \rightarrow d\pi^0\pi^0 \) and \( pn \rightarrow d\pi^+\pi^- \). The experiment was carried out with the WASA detector setup at COSY having a polarized deuteron beam impinging on the hydrogen pellet target and utilizing the quasifree process \( dp \rightarrow np + p_{\text{spectator}} \). That way the \( np \) analyzing power \( A_y \) was measured over a large angular range. The obtained \( A_y \) angular distributions deviate systematically from the current SAID SP07 NN partial-wave solution. Incorporating the new \( A_y \) data into the SAID analysis produces a pole in the \( ^3D_3 - ^3G_3 \) waves as expected from the \( d^* \) resonance hypothesis.

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INTRODUCTION

Recent exclusive and kinematically complete measurements of the basic double-pionic fusion reactions \( pn \rightarrow d\pi^0\pi^0 \) and \( pn \rightarrow d\pi^+\pi^- \) revealed a narrow resonance-like structure in the total cross section \([1,2]\) at a mass \( M \approx 2380 \text{ MeV}/c^2 \) with a width of \( \Gamma \approx 70 \text{ MeV} \), which is consistent with a \( I(J^P) = 0(3^+) \) assignment \([2]\). Additional evidence for it has been traced recently also in the \( pn \rightarrow pp\pi^0\pi^- \) reaction \([3]\), where it was denoted by \( d^* \) following its first notation in context with the so-called "inevitable dibaryon" \([5]\).

If true that the observed resonance structure constitutes a \( s \)-channel resonance in the neutron-proton system, then it must be also sensed in the observables of elastic \( np \) scattering. In Ref. \([6]\) the resonance effect in \( np \) scattering has been estimated and it has been shown that it should be most noticeable in the analyzing power \( A_y \), since this observable is composed only of interference terms between partial waves being thus most sensitive to small changes in the partial waves.

For the analyzing power there exist data only below and above the resonance region. The data sets closest to this energy region, that at \( T_n = 1.095 \text{ GeV} \) \((\sqrt{s} = 2.36 \text{ GeV})\) \([7,8]\) and that at \( T_n = 1.27 \text{ GeV} \) \((\sqrt{s} = 2.43 \text{ GeV})\) \([9,10]\) exhibit very similar angular distributions. In between, in the conjectured resonance region, there are no \( A_y \) data.

EXPERIMENT

In order to investigate this issue about \( d^* \) in a comprehensive manner we measured the energy dependence of \( np \) elastic scattering in the quasifree mode with the WASA detector including a hydrogen pellet target \([11,12]\) at COSY (FZ Jülich) and by using a polarized deuteron beam with an energy of \( T_d = 2.27 \text{ GeV} \). That way the full energy range of the conjectured resonance was covered. Note that we observe here the quasi-free scattering process \( dp \rightarrow np + p_{\text{spectator}} \) in inverse kinematics, which allows to detect also the fast spectator proton in the forward detector of WASA in this case.

Since we deal here with events originating from channels with large cross section, the trigger was set to just at least one hit in the first layer of the forward range hodoscope. This hit could originate from either a charged particle or a neutron. For the case of quasifree \( np \) scattering this defines three event classes with each of them having the spectator proton detected in the forward detector:

- scattered proton and scattered neutron both detected in the central detector covering the neutron angle region \( 31^\circ < \Theta_n^cm < 129^\circ \)
- scattered proton detected in the forward detector with the scattered neutron being unmeasured covering thus \( 132^\circ < \Theta_n^cm < 178^\circ \) and
- scattered proton detected in the central detector with the neutron being unmeasured covering the angular range \( 30^\circ < \Theta_n^cm < 41^\circ \).

That way nearly the full range of neutron scattering angles could be covered.

Since by use of the inverse kinematics the spectator proton is in the beam particle, the deuteron, the spectator is very fast. This allows its detection in the forward detector and by reconstruction of its kinetic energy and its direction the full four-momentum of the spectator proton has been determined.

Similarly the four-momentum of the actively scattered proton has been obtained from its track information in either forward or central detector (in the latter case the energy information was not retrieved).

Therefore we can reconstruct the full event including the four-momentum of the unmeasured neutron and even have one overconstraint in the subsequent kinematic fit, when the neutron has not been measured explicitly.

In the case, where the neutron has been detected by a hit in the calorimeter (composed of 1012 CsI(Na) crystals) of the central detector – associated with no hit in the preceding plastic scintillator barrel –, also the directional information of the scattered neutron has been obtained. Therefore these events have undergone a kinematic fit with two overconstraints.

In order not to distort the beam polarization, the magnetic field of the solenoid in the central detector was switched off. The measurements have been carried out with cycles of the beam polarization "up", "down" and unpolarized (originating from the same polarized source),
where "up" and "down" refers to a horizontal scattering plane. Runs with the conventional unpolarized source verified that the beam originating from the polarized source indeed was unpolarized when using it in its "unpolarized" mode.

The magnitude of the beam polarization has been determined and monitored by dp elastic scattering, which was measured in parallel by detecting the scattered deuteron in the forward detector as well as the associated scattered proton in the central detector. The vector and tensor components of the deuteron beam have been obtained by fitting our results for the vector and tensor analyzing power to those obtained previously at ANL [13] for \( T_d = 2.0 \) and more recently at COSY-ANKE [14] at \( T_d = 2.27 \) GeV. As a result we obtain beam polarizations of \( P_x = 0.67(2) \), \( P_{zz} = 0.65(2) \) for "up" and \( P_z = -0.45(2) \), \( P_{zz} = 0.17(2) \) for "down".

The vector polarization of the beam for quasifree scattering has been checked by quasifree pp scattering, which also was measured in parallel by detecting one of the protons in the forward detector and the other one in the central detector – and, in addition, checking their angular correlation for elastic events. Our results from the quasifree measurement for the pp analyzing power are in quantitative agreement both with the EDDA measurements [15] of the free pp scattering and with the current SAID phase shift solution SP07 [16].

Since we have measurements with spin "up", "down" and unpolarized, the vector analyzing power can be derived in three different ways by using each two of the three spin situations. All three methods should give identical results. Differences in the results may be taken as an estimate of systematic uncertainties, which are added quadratically to the statistical ones to give the total uncertainties plotted in Figs. 1, 2 and 4.

The momentum distribution of the observed spectator proton in the elastic np scattering process agrees with Monte Carlo simulations of the proton momentum distribution in the deuteron filtered by the acceptance of the WASA detector. Due to the beam-pipe ejectiles can only be detected in the forward detector for lab angles larger than three degrees. In order to assure a quasi-free process we omit events with spectator momenta larger than 0.16 GeV/c (in the deuteron rest system) as done in previous work [2, 3].

RESULTS AND DISCUSSION

Due to the Fermi motion of the nucleons bound in the beam deuteron, the measurement of the quasi-free np scattering process covers a range of energies in the np system. Meaningful statistics could be collected for the range of np center-of-mass energies \( 2.37 < \sqrt{s} < 2.40 \) GeV corresponding to \( T_n = 1.11 - 1.20 \) GeV. First, we show the data (solid circles) in Fig. 1 without selection according to the np center-of-mass energies, i.e. without accounting for the spectator momentum. Hence this data set corresponds to the weighted average over the measured interval representing effectively the range \( \sqrt{s} = 2.38 \pm 0.03 \) GeV \( (T_n = 1.135 \pm 0.06 \) GeV). The results from this work are shown by the solid circles with error bars including both statistical and systematic uncertainties. The solid line represents the SAID SP07 phase shift solution [16], whereas the dashed (dotted) line gives the result of the new weighted (unweighted) SAID partial-wave solution.

The new \( A_y \) data have been included in the SAID database and the phenomenological approach used in generating the NN partial-wave solution, SP07 [16], has been retained. Here we are simply considering whether the existing form is capable of describing the new \( A_y \) measurements. One advantage of this approach is that the employed Chew-Mandelstam K-matrix can produce a pole in the complex energy plane without the explicit inclusion of a K-matrix pole in the fit form. Neither the existence of a pole nor the effected partial waves are predetermined.

The energy-dependent fits use a product S-matrix approach as described in detail in Ref. [19] with \( S_x \) being an 'exchange' part, including the one-pion-exchange piece, plus smooth phenomenological terms, and \( S_p \), a 'production' part. The full S matrix is

\[
S = S_x^{1/2} S_p S_x^{1/2} = 1 + 2iT, \tag{1}
\]
where

\[ T = T_x + S_x^{1/2} T_p S_x^{1/2}. \]  

For spin-uncoupled waves, the production T-matrix is parameterized using a Chew-Mandelstam K-matrix, as is also used in the GW πN [17] and KN [18] analyses, with

\[ T_p = \rho^{1/2} K_p (1 - C K_p)^{-1} \rho^{1/2}; \]  

where \( \rho \) is a phase space factor, \( K_p \) is a real symmetric matrix coupling the \( NN \) and an \( N\Delta \) channel, and \( C \) is a Chew-Mandelstam matrix. For spin-uncoupled waves, the matrices are \( 2 \times 2 \); for coupled waves, the matrices are \( 3 \times 3 \), as described in Ref. [19]. The global energy-dependent fit includes \( pp \) data from threshold up to a lab kinetic energy of 3 GeV, and \( np \) data from threshold up to 2 GeV. Since above 1.3 GeV the amount of \( np \) data is sparse, the fit is considered to be valid only up to 1.3 GeV for the \( np \) case. Single-energy (narrow energy bin) fits are also carried out, with constraints on the energy-dependence over a particular energy bin fixed to the underlying global analysis.

The new \( A_y \) data are angular distributions at \( T_{\text{lab}} \) values of 1.108, 1.125, 1.135, 1.139, 1.156, 1.171, and 1.197 GeV. Starting from the functional form of the current SP07 fit, and only varying the associated free parameters, a \( \chi^2/\text{datum} \) of 1.8 was found for all angular distributions apart from the one at 1135 MeV. This is fairly consistent with the overall \( \chi^2/\text{datum} \) given by the global fit of \( np \) to 2 GeV. However, the set at 1135 MeV contributes a \( \chi^2/\text{datum} \) of about 25, has better statistics and a wider angular coverage.

The fit form was scanned to find partial waves for which an added term in the K-matrix expansion produced the most efficient reduction in \( \chi^2 \). Adding parameters and re-fitting resulted in a rapid variation of the coupled \( ^3D_3 \) and \( ^3G_3 \) waves in the vicinity of the problematic 1135 MeV data set.

Some weighting seemed necessary in this fit, as only a few angular points from the full set were determining the altered energy dependence. The fit was repeated with different weightings (with a factor of 2 or 4) for the new \( A_y \) data. Initially, the full set of energies was weighted equally. However, it was found that just weighting the 1135 MeV angular distribution improved the fit to the new analyzing power data at all energies. The results reported here thus considered only the weighting at this single energy. As we have seen in fits to other reactions, heavily weighting new and precise polarization observables inevitably degrades the fit to older data. Therefore, as a test, the parameterization producing a pole was re-fitted to the full database with no weighting. This gave, as expected, a worse fit to the 1135 MeV angular distribution but did not change the shape qualitatively.

In Fig. 1 we plot the fit to the 1135 MeV angular distribution from the SP07 prediction (not including the new data), a weighted fit (errors decreased by a factor of 4), and an unweighted fit including the new data and using the fit form having added parameters.

Resulting changes in the \( ^3D_3-^3G_3 \) coupled waves are displayed in Fig. 3. Here the \( ^3D_3 \) wave obtained a typical resonance shape, whereas the \( ^3G_3 \) wave changed less dramatically. A search of the complex energy plane revealed a pole in the coupled \( ^3D_3-^3G_3 \) wave. Other partial waves did not change significantly over the energy range spanned by the new data. Note that single-energy solutions obtained previously [12] for energies up 1.1 GeV fit better to the new partial-wave solution than to SP07.

The fit repeated with different weightings for the new \( A_y \) data resulted in a variation of the pole position and could be considered a minimal ‘error’ on its value within the present fit form. In the weighted fits, a pole was located at \( (2392 \pm 137) \) MeV. The re-fit without weighting produced a pole with \( (2385 \pm 139) \) MeV. Together with a speed-plot determination we arrive at \( (2380 \pm 10 - i40 \pm 5) \) MeV as our best estimate for the pole position.

From the decomposition of the \( np \) observables into partial-wave amplitudes [20] it follows that the reso-
nance contribution in $A_y$ is proportional to the associated Legendre polynomial $P^3_1(\cos \Theta_c^m)$. $P^3_1$ is maximal at $\Theta_c^m = 31.1^\circ$ and minimal at $90^\circ$. Since at the latter angle the differential cross section is at minimum and much lower than at the former angle, the resonance effect in $A_y$ gets maximal at $\Theta_c^m = 90^\circ$. In order to check this behavior, we plot in Fig. 4 the energy dependence of $A_y$ for this angle. In order to include a reasonable amount of previous measurements we have chosen $\Theta_c^m = 83^\circ \pm 2^\circ$. The data exhibit a pronounced resonance behavior in accordance with the new partial-wave solution – in tendency even somewhat narrower.

**SUMMARY AND CONCLUSIONS**

In conclusion our exclusive and kinematically complete measurement of quasi-free polarized $np$ scattering provides detailed high-statistics data for the analyzing power in the energy range, where previously a narrow resonance structure with $I(J^P) = 0(3^+)$ has been observed in the double-pionic fusion to deuterium. A partial-wave analysis including the new $np$ scattering data exhibits a resonance pole in the coupled $^3D_3 - ^3G_3$ partial waves in accordance with the expectation from the $d^*$ resonance structure. This has been associated with a bound $\Delta\Delta$ resonance, which could contain a mixture of asymptotic $\Delta\Delta$ [26] and 6-quark, hidden color, configurations [27]. Though less exotic explanations cannot be excluded at the present stage, dibaryon systems matching the mass and width of this dibaryon candidate have been recently successfully generated within 3-body [28] and quark model [29] calculations. It should be noted that earlier dibaryon candidates [19] were widely discounted due to their appearance near the $N\Delta$ cut and the possibility of a pseudo-resonance mimicking their behavior. Such complications do not arise here – though we would like to mention the nearby $NN^*$(1440) threshold. However, we are not aware of any mechanism, how the very broad Roper resonance could induce the narrow resonance structure considered here.

Finally we note that the new partial-wave solution im-
proves also the description of total cross section data as well as of polarization observables obtained at ANKE in the resonance region. A full account of the new results will be given in an extended forthcoming paper.

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