EPJ Web of Conferences **303**, 01006 (2024)
MENU 2023
https://doi.org/10.1051/epjconf/202430301006

Partial Wave Amplitude Analysis in Pion-Induced Reactions at the HADES Experiment

Ahmed Marwan Foda[1,*] *for the HADES collaboration*

[1]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany.

Abstract. The High Acceptance Di-Electron Spectrometer (HADES) collaboration at GSI employs a pion beam to examine the characteristics of baryonic resonances and their decay channels. This pion-beam facility enables the generation of baryonic resonances at a fixed center of mass energy ($\sqrt{s}$), *i.e.* in the S-channel. In anticipation of conducting a more comprehensive exploration of the resonance regions in pion-proton collisions, a new implementation of the K-matrix & D-matrix frameworks is currently under development. This updated implementation aims to offer a refined mapping of these regions. Example fits are presented showing the current status and the potential of the new framework.

1 Introduction

The High Acceptance Di-Electron Spectrometer (HADES) experiment aims to study the structure of strongly interacting matter [1]. The heavy ion synchrotron SIS18 delivers proton or heavy ion beams to the experiment and to secondary production targets. At this facility, beams can be prepared with kinetic energies between 1-2 *A*GeV for nuclei, up to 4.5 GeV for protons and 0.5-2 GeV for secondary pions. The combination of a secondary pion beam with the universal HADES detector represents a worldwide unique facility [2].

In 2014, HADES conducted a pion-beam study, with a primary focus on two pion production in the second resonance region, where $\sqrt{s} \approx 1.49$ GeV. The gathered data was integrated into the Bonn-Gatchina Partial Wave Amplitude (PWA) analysis framework. This integration was crucial in isolating various final states such as $\Delta\pi$, $\rho\pi$, and Nσ, along with initial resonant and non-resonant states [3]. HADES data played an indispensable role in constraining ρ meson production and in determining the branching ratios of the N(1440), N(1520), and N(1535) resonances into the ρN channel. These significant findings contributed to eight new entries in the 2021 edition of the Review of Particle Physics (RPP) for the branching ratios of N(1520) and N(1535) decays into $\Delta\pi$, $\rho\pi$, and Nσ final states [4]. This contribution has been widely recognized within the hadronic physics community, markedly advancing our understanding of light baryon structures and resonances [5]. This eagerly anticipated result holds significance for comprehending the applicability of the Vector Dominance Model (VDM) to baryons and the observed broadening of the ρ meson in both proton-nucleus (HADES) and heavy-ion reactions [6–9].

*e-mail: a.foda@gsi.de

Another experiment using the pion beam is planned for 2025 in the third resonance region, *i.e.* $\sqrt{s}$ = 1.67 − 1.79 GeV. One of the main goals for this experiment is to map the excitation function in various hadronic channels (*e.g.* η n, ω n, Λ N, Σ N). Particularly the two-pion production around the N(1720) resonance pole. PWA analysis techniques will be employed to separate the various waves contributing coherently to the observed final states. This analysis will yield the production amplitude for ρ meson production in the third resonance region. Such information is crucial for quantitatively understanding the contribution of off-shell ρ meson decay into e^+e^- pairs to the total dilepton production, which will be also measured in this run [10, 11].

1.1 Baryon-Meson couplings

The successful application of PWA analysis to the HADES pion beam data for two-pion production channels is seen as a proof of concept, potentially extendable to other hadronic channels in the third resonance region. At a center-of-mass energy of approximately $\sqrt{s}$ = 1.73 GeV, numerous hadronic channels (e.g., $K^0\Lambda$, $\Sigma^0 K^0$, $\Sigma^+ K^-$, η n, ω n, *etc.*) become accessible in addition to two-pion production. These channels are expected to help in constraining the hadronic couplings of baryon states in this region, which are currently not well-understood [12]. The objective is to yield high-statistics differential data for these hadronic channels, particularly those involving neutral mesons [13]. These measurements, along with the existing precision data from photo- and electroproduction reactions, will be incorporated into the PWA analysis. Primarily, the two-pion channels will provide new insights into the 2πN channels, especially the ρN channel, which has significant implications for medium effects [14]. The exploration of resonant final states such as N(1440)π, N(1520)π, and others, is of keen interest due to their potential as dominant decay modes for missing resonances [15].

Table 1: Fit Results from CLAS collaboration for the N(1720)3/2$^+$ and N'(1720)3/2$^+$ reosnances [16].

Resonance	Mass (GeV)	Total Width (MeV)	Branching fractions $\Delta\pi$	Nρ
N(1720)3/2$^+$	1.743-1.753	114 ± 6	38-53%	31-46%
N′(1720)3/2$^+$	1.715-1.735	120 ± 6	47-62%	4-10%

Recent studies in photo and electro-production have also indicated a potential new N'(1720) $J^P = 3/2^+$ resonance, distinguished by its unique ρ and electromagnetic couplings compared to the known N(1720) $J^P = 3/2^+$ resonance [16]. The resonance mass, width and branching fractions, as reported by the CLAS collaboration, are presented in Table. 1. A study has been performed to investigate the sensitivity of the HADES experiment to disentangle the N(1720) double resonance. The study examined the effects of varying branching fractions for the decay of N(1720) and N'(1720) resonances into $\Delta\pi$ and Nρ final states, along with the yield ratio between these resonances and the impact of the number of events. The analysis was conducted within both 4π and estimated HADES acceptance, comparing the polar angle distribution of the N(1720) resonance along with that of the combined N(1720)

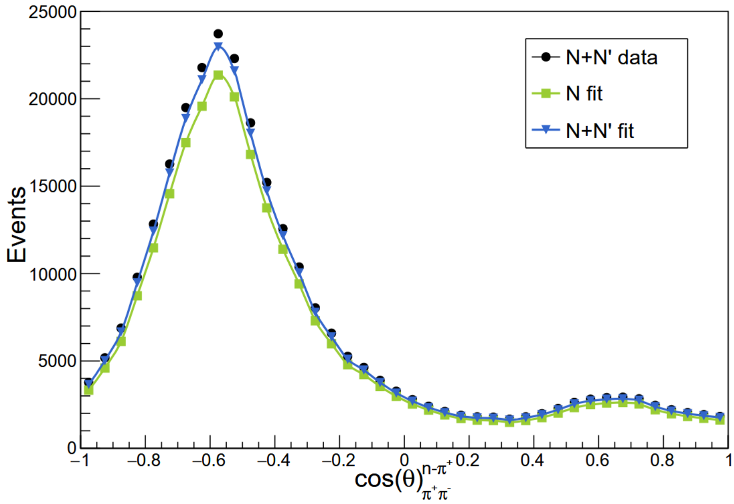

Figure 1: An example fit of a single baryon resonance (green squares) and a fit accounting for two states (blue triangles) of $\pi^+\pi^-$ angular distribution for N(1720) double resonance generated in π^-p reaction at $\sqrt{s}$=1.76 GeV within 4π acceptance [17]. The simulation is generated with M = 1.750 GeV, $\Gamma(\Delta\pi)$ = 51.9 MeV & $\Gamma(N\rho)$ = 43.9 MeV, M = 1.725 GeV, $\Gamma(\Delta\pi)$ = 65.4 MeV & $\Gamma(N\rho)$ = 8.4 MeV for the N(1720) and N'(1720) respectively.

and N'(1720) resonances, quantifying differences through a χ^2 value. An example result of the partial-wave fit of 10^5 N(1720) double resonance simulated events within 4π acceptance is presented in Fig. 1. The fit with a two-state model results in a $\chi^2/NDF = 14$, whereas the fit with a one-state model shows a significantly larger $\chi^2/NDF = 144$ and can thereby be excluded. These χ^2/NDF values while far from optimum, they demonstrate the ability of the framework and the experiment to disinguish a two-state data set from a one-state data set. A Breit-Wigner description was used for the two resonances, with a decay into $\Delta\pi$ and $N\rho$ as a 3/2 P-wave. The 3/2 F-wave is expected to be suppressed so it was ignored for this study. Similarly, the branching fraction of the $N\rho$ S=1/2 P-wave is small and is therefore neglected in this study. The required number of events for a significant observation within the HADES acceptance varies based on branching fraction but still orders of magnitude lower than the expected yield for two pion events in the upcoming pion-beam experiment. The comparison indicates that the HADES experiment is capable of identifying the N'(1720) resonance. In the future, a more detailed study could include the N(1720) resonance decay into the Nσ final state, background contributions from other N resonances, and exploring the decay of N(1720) and N'(1720) resonances into $\Delta\pi$ and Nρ as a spin-3/2 F-wave. Different PWA analysis models might be considered. A more detailed simulation of the HADES detector could provide an improved estimate of the acceptances and account for reconstruction effects [17].

1.2 Time-like Electromagnetic Baryon Transitions (π^-p→ne^+e^-)

The upcoming pion-beam experiment at HADES will offer insights into time-like baryon transitions in the third resonance region. Simulations of the $\pi^- p \rightarrow n\gamma$ reaction around $\sqrt{s}$ = 1.76 GeV indicated the N(1675) and Δ(1700) as major contributors due to their large γN couplings. The ρ meson's contribution was observed across a broad invariant mass range below the pole. The new data will test the validity of VDM over an extended range [15].

A center-of-mass energy of 40 MeV above the ω production threshold enables a detailed study of the ω meson spectral function [18]. Effects of interference between isoscalar and isovector e^+e^- production in the region below the ω peak are also anticipated [10, 19]. Analysis of electron angular distributions and the extraction of spin density matrix elements (SDMEs) will provide detailed information on the nature of the transitions [11].

The upcoming pion-beam experiment will pave the way to test and extend theoretical models for electromagnetic baryon transitions to the third resonance region. The new data will facilitate comparisons to predictions based on VDM and baryon-meson couplings from baryon decays and quark models.

2 Towards A Modular Approach

Most of the PWA analysis studies for the HADES experiment have been conducted using the BnGa framework which is a FORTRAN based software package to perform unbinned maximum likelihood fit using K-matrix and D-matrix techniques [20]. The current effort is focused on presenting the analysis framework in a modular setup and user friendly interface. To achieve this, we are collaborating with the BnGa group to implement the K-matrix and D-matrix analysis models into AmpTools [21]. AmpTools is a collection of C++ libraries with modular design for unbinned maximum likelihood fitting and a GUI interface for visualization. The first milestone will be to establish a PWA analysis framework for final states from pion induced reactions studied with HADES. This will serve as a proof of concept by comparing our results with previous fit results obtained using BnGa and it will prepare us for PWA analysis efforts for the upcoming pion-beam data. Afterwards, we will expand the framework to include more reactions of interest (*e.g.* proton-beam reactions). The software will be available on GitLab (GSI) where users can add amplitudes or report problems. In this section, we will briefly present the two formalisms and their relative advantages.

2.1 Formalism

2.1.1 K-matrix

In the K-matrix formalism, the amplitude A_{ab} between channels a and b is written as a sum over the off-shell interaction K_{aj} between a and all relevant intermediate channels j. It has the form:

$$A_{ab} = \sum_j K_{aj}(I - i\rho K)^{-1}_{jb},$$

where ρ_j represents the phase volume of channel j. The matrix K_{aj} is constructed from the couplings g^α_a between the included state α and the channel j.

$$K_{aj} = \sum_\alpha \frac{g^\alpha_a g^\alpha_j}{(M_\alpha - s)^2} + NR,$$

where M_α is the mass of the state α, s the center-of-mass energy and NR refers to non-resonant background.

The K-matrix approach is used to fit hadronic spectra in various PWA analyses. This technique facilitates simultaneous fitting of several reactions, ensuring correct analytical properties and unitarity of all investigated amplitudes. The K-matrix amplitude is the minimal amplitude satisfying unitarity of the S-Matrix and therefore, includes only the effects of the right hand (threshold opening) cuts. Left-hand cuts, however, result from crossing channels and need to be introduced into the amplitude. There are many ways to include the contributions of the left hand cuts in the K-matrix. This leads to ambiguity in determining these contributions due to the dependence of the t and u channel exchanges on the coupling and form factors, which are not well known. The K-matrix method typically effectively accounts for the real part of loop diagrams as renormalization of resonance masses [22]. While lacking precise contributions of left-hand cuts, A K-matrix analysis performed at a distance from the left-hand cut allows for the determination of masses and full widths of resonances (*i.e.* position of poles) as well as the residues of poles, namely, factorized couplings of resonances to different channels.

2.1.2 D-matrix

In the D-matrix formalism, the amplitude A_{ab} between channels a and b is summed over states α, β. It is formed as a convolution of the matrix $D_{\alpha\beta}$ of the transition between states, the diagonal matrix $d_{\alpha\alpha}$ of the propagators (resonant and non-resonant) and the couplings g_a^α between state α and channel a. It has the form:

$$A_{ab} = \sum_{\alpha,\beta} g_a^\alpha d_{\alpha\alpha} D_{\alpha\beta} g_b^\beta.$$

The D-matrix approach uses the analytic properties following from causality and the use Cauchy's theorem to obtain the real part of an amplitude from the imaginary part which is often better accessible and is, therefore, considered theoretically more robust than the K-matrix approach [23]. It involves the direct calculation of the real parts of loop diagrams, thereby ensuring that the amplitude is free from false kinematical singularities in the region of left-side singularities. The D-matrix amplitudes describe transitions of bare states, taking into account the cloud of virtual mesons [22].

While the D-matrix method is theoretically more founded, the majority of PWA analyses are performed using the K-matrix approach. The K-matrix amplitude is built on the imaginary part of the amplitude, whereas the D-matrix method calculates these real part. The K-matrix analysis is effective in determining particle properties, including their quark content, in the $q\bar{q}$ states, identifying nonets and extra states. The D-matrix method, with its direct calculation of loop diagrams, provides a more precise and theoretically sound analysis, especially when the K-matrix method faces ambiguity.

3 Summary

The upcoming pion-beam experiment at HADES will investigate baryonic resonances and their decay processes in the third resonance region. Utilizing PWA analysis, this experiment will extract the couplings of these resonances to various final states, primarily focusing on collecting high-statistics differential data for channels that involve neutral mesons. Recent investigations hint at a possible new N'(1720) resonance, which will be conclusively identified with the forthcoming pion-beam data. Additionally, the imminent pion-beam experiment aims to shed light on time-like baryon transitions through an in-depth analysis of the e^+e^- production. This research is anticipated to broaden the application of theoretical models for electromagnetic baryon transitions into the third resonance region.

Our objective is to develop a modular and user-friendly analysis framework, incorporating the K-matrix and D-matrix methodologies. This new framework will initially demonstrate its usefulness with the upcoming pion-beam data and subsequently be adapted to encompass additional reactions of interest.

References

[1] HADES Collaboration, Eur. Phys. J. A 41, 243 (2009).
[2] HADES Collaboration, Eur. Phys. J. A 53, 188 (2017).
[3] HADES Collaboration, Phys. Rev. C **102**, 024001 (2020).
[4] P.A. Zyla *et al*. (Particle Data Group), Prog. Theor. Exp. Phys. 083C01 (2020).
[5] A. Thiel, F. Afzal, Y. Wunderlich, Prog. Part. Nucl. Phys. **125**, 103949 (2022).
[6] HADES Collaboration, arXiv:2205.15914 (2022).
[7] HADES Collaboration, arXiv:2309.13357 (2023).
[8] K. Gallmeister *et al*., Phys. Rev. C **106**, 6, 064910 (2022).
[9] G. Ramalho, & M. T. Pena, Phys. Rev. D **101** (2020)
[10] A. Titov & B. Kampfer, Eur. Phys. J. A **12**, 217-229 (2001).
[11] M. Zetenyi, D. Nitt, M. Buballa & T. Galatyuk, Phys. Rev. C **104**, 015201 (2021).
[12] W. J. Briscoe *et al*., Phys. Rev. C **94**, 3, 035202 (2016).
[13] V. Shklyar, H. Lenske, & U. Mosel, Phys. Rev. C **87**, 015201 (2013).
[14] HADES Collaboration, Nat. Phys. **15**, 1040–1045 (2019).
[15] HADES Collaboration, Baryon couplings to Mesons and Virtual Photons in the Third Resonance Region: Vacuum and Cold Matter Studies, Experimental Proposal (2022).
[16] V. I. Mokeev *et al*., Phys. Lett. B **805**, 135457 (2020).
[17] J. Gollub, Sensitivity study for baryon resonances searches in pion-proton collisions with HADES, M.Sc. Thesis, Ruhr University Bochum, Germany (2023).
[18] H. Karami *et al*., Nucl. Phys. B **154**, 503-518 (1979).
[19] M. F. M. Lutz, B. Friman, M. Soyeur, Nucl. Phys. A **713**, 97-118 (2003).
[20] ‘Bonn-Gatchina’ Webpage https://pwa.hiskp.uni-bonn.de
[21] M. Shepherd *et al*., ‘AmpTools’ https://doi.org/10.5281/zenodo.7336113
[22] A. V. Anisovich *et al*., Phys. Rev. D **84**, 076001 (2011).
[23] R, Zwicky. Proceedings Of The Helmholtz International Summer School, 93-120, (2016), doi:10.3204/DESY-PROC-2016-04/Zwicky