$N\Delta$ and $\Delta\Delta$ dibaryons

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Abstract. Experimental evidence for $I(J^P)$=0(3^+) $\Delta\Delta$ dibaryon $\mathcal{D}_{03}(2370)$ has been presented recently by the WASA-at-COSY Collaboration. Here I review new hadronic-basis calculations of $L = 0$ nonstrange $N\Delta$ and $\Delta\Delta$ dibaryon candidates. In particular, $\mathcal{D}_{03}(2370)$ is generated dynamically in terms of long-range physics dominated by pions, nucleons and Δ's. These calculations are so far the only ones to reproduce the relatively small $\mathcal{D}_{03}(2370)$ width of 70-80 MeV. Predictions are also given for the location and width of $\mathcal{D}_{30}$, the $I(J^P)$=3(0^+) exotic partner of $\mathcal{D}_{03}(2370)$.

1. Introduction

The WASA-at-COSY Collaboration has presented recently striking evidence for a $I(J^P) = 0(3^+)$ $\Delta\Delta$ dibaryon some 80-90 MeV below the $\Delta\Delta$ threshold, with a relatively small width of $\Gamma \approx 70 - 80$ MeV, by observing a distinct resonance in the energy spectrum of $pn \to d\pi\pi$ reactions [1, 2] as shown in Fig. 1–left. Isospin $I = 0$ is uniquely fixed in this particular $\pi^0\pi^0$ production reaction and the spin-parity 3^+ assignment follows from the measured deuteron and pions angular distributions, assuming s-wave decaying $\Delta\Delta$ pair. The peak of the $M^2_{d\pi}$ distribution on the right panel at $\sqrt{s}$ ≈2.13 GeV, almost at the $\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon location (see below), suggests that $\mathcal{D}_{12}$ plays a role in forming the $\Delta\Delta$ dibaryon $\mathcal{D}_{03}$.

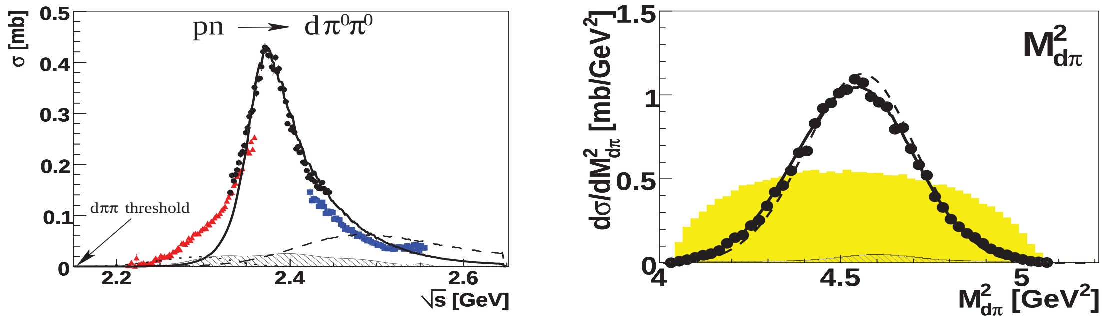

Figure 1. $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ dibaryon resonance signal on the left panel, and its $M^2_{d\pi^0}$ Dalitz-plot projection on the right panel, from $pn \to d\pi^0\pi^0$ measurements by WASA-at-COSY [1]. This resonance was also observed consistently in $pn \to d\pi^+\pi^-$ measurements [2]. Figures courtesy of Heinz Clement.

Further evidence supporting the $\mathcal{D}_{03}(2370)$ dibaryon assignment comes from very recent measurements of pn elastic scattering as a function of energy, taking sufficiently small steps around $\sqrt{s} = 2370$ MeV [3]. This is shown in Fig. 2–left for the Argand diagram of the $^3D_3$ partial wave, and in the right panel for the speed plot of the $^3D_3$ partial wave, within a new SAID partial wave analysis incorporating these measurements.

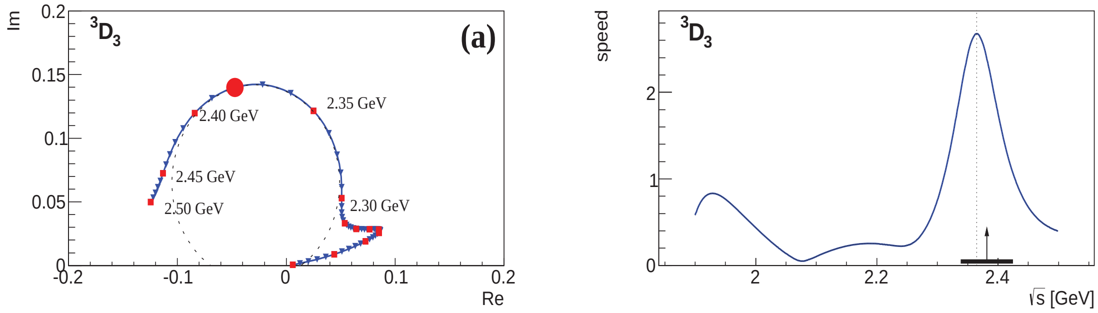

Figure 2. $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ dibaryon resonance signals in the Argand diagram on the left panel, and in the speed plot on the right panel, both for the np $^3D_3$ partial wave, from recent np scattering measurements by WASA-at-COSY [3]. Figures courtesy of Heinz Clement.

$N\Delta$ and $\Delta\Delta$ s-wave dibaryon resonances $\mathcal{D}_{IS}$ with isospin I and spin S were proposed as early as 1964, when quarks were still perceived as merely mathematical entities, by Dyson and Xuong [4] who focused on the lowest-dimension SU(6) multiplet in the $\mathbf{56} \times \mathbf{56}$ product that contains the SU(3) $\overline{\mathbf{10}}$ and $\mathbf{27}$ multiplets in which the deuteron $\mathcal{D}_{01}$ and NN virtual state $\mathcal{D}_{10}$ are classified. This yields two dibaryon candidates, $\mathcal{D}_{12}$ ($N\Delta$) and $\mathcal{D}_{03}$ ($\Delta\Delta$) as listed in Table 1. Identifying the constant A in the resulting mass formula $M = A+B[I(I+1)+S(S+1)-2]$ with the NN threshold mass 1878 MeV, a value $B \approx 47$ MeV was determined by assigning $\mathcal{D}_{12}$ to the $pp \leftrightarrow \pi^+d$ resonance at $\sqrt{s} = 2160$ MeV (near the $N\Delta$ threshold) which was observed already during the 1950's. This led to the prediction $M(\mathcal{D}_{03})$=2350 MeV. The $\mathcal{D}_{03}$ dibaryon was the subject of many quark-based model calculations since 1980, see Refs. [5–13] for a representative although incomplete listing. Dibaryons were reviewed recently in Ref. [14].

Table 1. Nonstrange s-wave dibaryon SU(6) predictions [4].

dibaryon	I	S	SU(3)	legend	mass
$\mathcal{D}_{01}$	0	1	$\overline{\mathbf{10}}$	deuteron	A
$\mathcal{D}_{10}$	1	0	$\mathbf{27}$	nn	A
$\mathcal{D}_{12}$	1	2	$\mathbf{27}$	$N\Delta$	$A+6B$
$\mathcal{D}_{21}$	2	1	$\mathbf{35}$	$N\Delta$	$A+6B$
$\mathcal{D}_{03}$	0	3	$\overline{\mathbf{10}}$	$\Delta\Delta$	$A+10B$
$\mathcal{D}_{30}$	3	0	$\mathbf{28}$	$\Delta\Delta$	$A+10B$

It is shown below that the pion-assisted methodology applied recently by Gal and Garcilazo [15, 16] couples $\mathcal{D}_{12}$ and $\mathcal{D}_{03}$ dynamically in a perfectly natural way, the analogue of which has not emerged in quark-based models. Our hadronic-based calculations emphasize the long-range physics aspects of nonstrange dibaryons.

2. Pion-assisted nonstrange dibaryons

The discussion in this section is divided into two subsections, the first one specializing to $N\Delta$ dibaryons and the second one highlighting the $\mathcal{D}_{03}$ $\Delta\Delta$ dibaryon.

2.1. $N\Delta$ dibaryons

The $\mathcal{D}_{12}$ dibaryon shows up experimentally as $NN(^1D_2) \leftrightarrow \pi d(^3P_2)$ coupled-channel resonance corresponding to a quasibound $N\Delta$ with mass $M \approx 2.15$ GeV, near the $N\Delta$ threshold, and width $\Gamma \approx 0.12$ GeV [17, 18] as shown in Fig. 3 for the Argand diagram of the $^1D_2$ partial wave in *pp* elastic scattering.

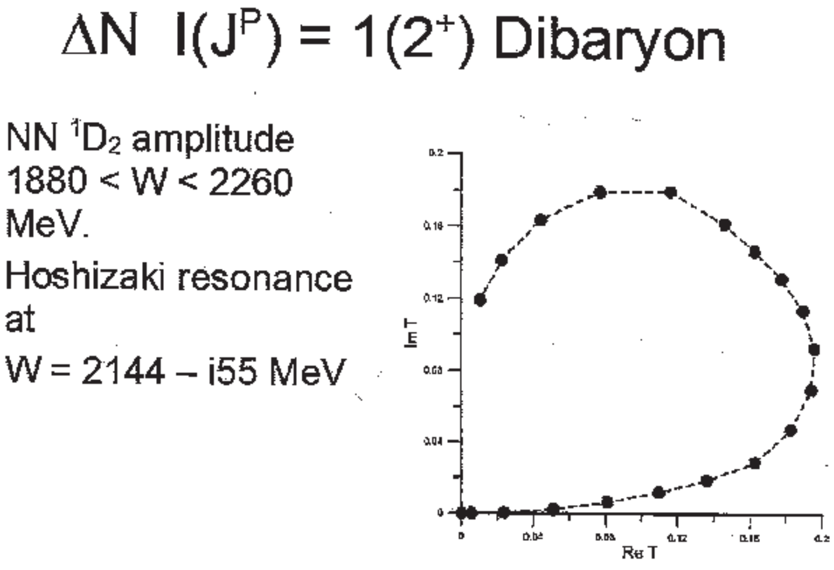

Figure 3. Argand diagram of the $^1D_2$ partial wave in *pp* elastic scattering from SAID, in agreement with past determinations of the $\mathcal{D}_{12}$ dibaryon resonance pole position, W=2148-i63 MeV [17] and W=2144-i55 MeV [18].

In our recent work [16] we have calculated this dibaryon and other $N\Delta$ dibaryon candidates such as $\mathcal{D}_{21}$ (see Table 1) by solving Faddeev equations with relativistic kinematics for the πNN three-body system, where the πN subsystem is dominated by the P_{33} $\Delta(1232)$ resonance channel and the NN subsystem is dominated by the $^3S_1$ and $^1S_0$ channels. The coupled Faddeev equations give rise then to an effective $N\Delta$ Lippmann-Schwinger (LS) equation for the three-body S-matrix pole, with energy-dependent kernels that incorporate spectator-hadron propagators, as shown diagrammatically in Fig. 4 where circles denote the $N\Delta$ T matrix.

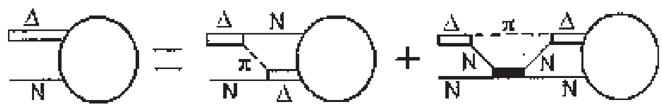

Figure 4. $N\Delta$ dibaryon's Lippmann-Schwinger equation [16].

Of the four possible $L = 0$ $N\Delta$ dibaryon candidates $\mathcal{D}_{IS}$ with $IS = 12, 21, 11, 22$, the latter two do not provide resonant solutions. For $\mathcal{D}_{12}$, only $^3S_1$ contributes out of the two NN interactions, while for $\mathcal{D}_{21}$ only $^1S_0$ contributes. Since the $^3S_1$ interaction is the more attractive one, $\mathcal{D}_{12}$ lies below $\mathcal{D}_{21}$ as borne out by the calculated masses listed in Table 2 for two choices of the P_{33} interaction form factor corresponding to spatial sizes of 1.35 fm and 0.9 fm of the Δ isobar. The two dibaryons are found to be degenerate to within less than 20 MeV. The mass values calculated for $\mathcal{D}_{12}$ are reasonably close to the value $W = 2148 - \mathrm{i}63$ MeV [17] and $W = 2144 - \mathrm{i}55$ MeV [18] derived in coupled-channel phenomenological analyses.

Table 2. $N\Delta$ dibaryon S-matrix poles (in MeV) for $\mathcal{D}_{12}$ and $\mathcal{D}_{21}$, obtained by solving πNN Faddeev equations for two choices of the πN P_{33} form factor, with large (small) spatial size denoted $>$ ($<$).

$W^>(\mathcal{D}_{12})$	$W^>(\mathcal{D}_{21})$	$W^<(\mathcal{D}_{12})$	$W^<(\mathcal{D}_{21})$
2147−i60	2165−i64	2159−i70	2169−i69

2.2. $\Delta\Delta$ dibaryons

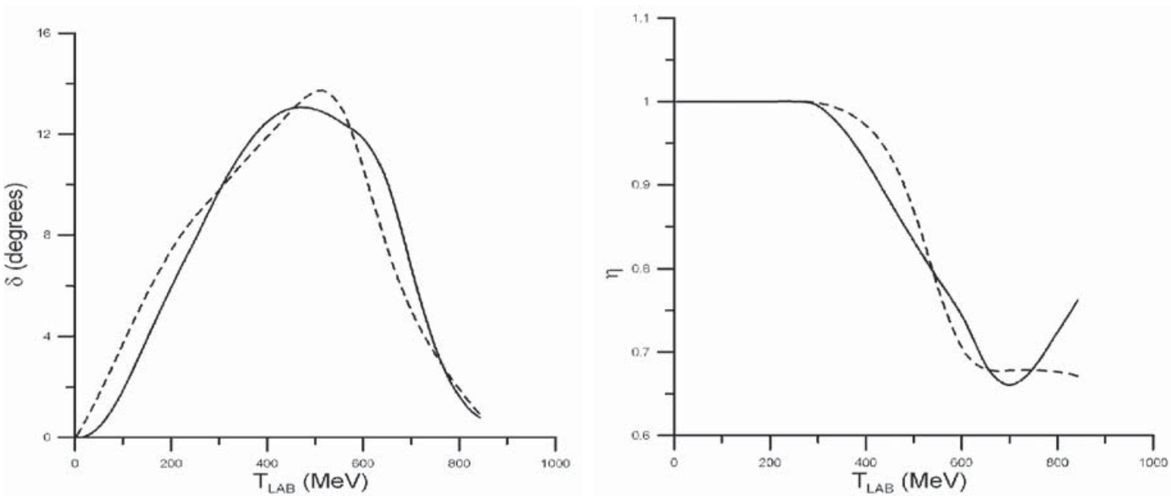

Figure 5. Coupled-channel fit (solid) to the SAID (dashed) NN $^1D_2$ phase shift δ (left panel) and inelasticity η (right panel), see text.

Four-body $\pi\pi NN$ calculations are required, strictly speaking, to discuss $\Delta\Delta$ dibaryons. In Ref. [15] we studied the $\mathcal{D}_{03}$ dibaryon by solving a $\pi N\Delta'$ three-body model, where Δ' is a stable $\Delta(1232)$ and the $N\Delta'$ interaction is dominated by the $\mathcal{D}_{12}$ dibaryon. The $I(J^P) = 1(2^+)$ $N\Delta'$ interaction was not assumed to resonate but, rather, it was fitted within a NN–πNN–$N\Delta'$ coupled-channel caricature model to the NN $^1D_2$ T-matrix, requiring that the resulting $N\Delta'$ separable-interaction form factor is representative of long-range physics, with momentum-space soft cutoff $\Lambda \lesssim 3$ fm^{-1}. A fit of this kind is shown in Fig. 5.

The Faddeev equations of the $\pi N\Delta'$ three-body model give rise, as before, to an effective LS equation for the $\Delta\Delta'$ S-matrix pole corresponding to $\mathcal{D}_{03}$. This LS equation is shown diagrammatically in Fig. 6, where D stands for the $\mathcal{D}_{12}$ dibaryon. The πN interaction was

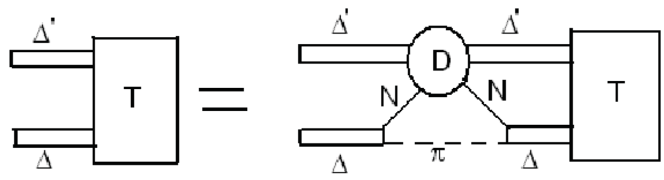

Figure 6. S-matrix pole equation for $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ dibaryon [15].

assumed again to be dominated by the P_{33} Δ resonance, using two different parametrizations of its form factor that span a reasonable range of the Δ hadronic size. In Ref. [16] we have extended the calculation of $\mathcal{D}_{03}$ to other $\mathcal{D}_{IS}$ $\Delta\Delta$ dibaryon candidates, with D now standing for both $N\Delta$ dibaryons $\mathcal{D}_{12}$ and $\mathcal{D}_{21}$. Since $\mathcal{D}_{21}$ is almost degenerate with $\mathcal{D}_{12}$, and with no NN observables to constrain the input (I,S)=(2,1) $N\Delta'$ interaction, the latter was taken the same as for (I,S)=(1,2). The model dependence of this assumption is under study at present. The lowest and also narrowest $\Delta\Delta$ dibaryons found are $\mathcal{D}_{03}$ and $\mathcal{D}_{30}$.

Table 3. $\Delta\Delta$ dibaryon S-matrix poles (in MeV) obtained in Refs. [15, 16] by using a spectator-Δ' complex mass $W(\Delta')$ (first column) in the propagator of the LS equation depicted in Fig. 6. The last two columns give calculated mass and width values averaged over those from the $>$ and $<$ columns, where $>$ and $<$ are defined in the caption of Table 2.

$W(\Delta')$	$W^{>}(\mathcal{D}_{03})$	$W^{>}(\mathcal{D}_{30})$	$W^{<}(\mathcal{D}_{03})$	$W^{<}(\mathcal{D}_{30})$	$W_{\rm av}(\mathcal{D}_{03})$	$W_{\rm av}(\mathcal{D}_{30})$
1211−i49.5	2383−i47	2412−i49	2342−i31	2370−i30	2363−i39	2391−i39
1211−i(2/3)49.5	2383−i41	2411−i41	2343−i24	2370−i22	2363−i33	2390−i32

Representative results for $\mathcal{D}_{03}$ and $\mathcal{D}_{30}$ are assembled in Table 3, where the calculated mass and width values listed in each row correspond to the value listed there of the spectator-Δ' complex mass $W(\Delta')$ used in the propagator of the LS equation shown in Fig. 6. The value of $W(\Delta')$ in the first row is that of the $\Delta(1232)$ S-matrix pole. It is implicitly assumed thereby that the decay $\Delta' \to N\pi$ proceeds independently of the $\Delta \to N\pi$ isobar decay. However, as pointed out in Ref. [15], care must be exercised to ensure that the decay nucleons and pions satisfy Fermi-Dirac and Bose-Einstein statistics requirements, respectively. Assuming $L = 0$ for the decay-nucleon pair, this leads to the suppression factor 2/3 depicted in the value of $W(\Delta')$ listed in the second row. It is seen that the widths obtained upon applying this width-suppression are only moderately smaller, by less than 15 MeV, than those calculated disregarding this quantum-statistics correlation.

The mass and width values calculated for $\mathcal{D}_{03}$ [15] agree very well with those determined by the WASA-at-COSY Collaboration [1–3], reproducing in particular the reported width value $\Gamma(\mathcal{D}_{03}) \approx 70$ MeV which is considerably below the phase-space estimate $\Gamma_\Delta \leq \Gamma(\mathcal{D}_{03}) \leq 2\Gamma_\Delta$, with $\Gamma_\Delta \approx 118$ MeV. No other calculation so far has succeeded to do that. Similarly small widths according to Table 3 hold for $\mathcal{D}_{30}$ which is located about 30 MeV above $\mathcal{D}_{03}$. This is about half of the spacing found very recently in the quark-based calculations of Ref. [13]. Note, however, that the widths calculated there are considerably larger than ours. A more complete discussion of these and of other $\mathcal{D}_{IS}$ $\Delta\Delta$ dibaryon candidates is found in Ref. [16].

3. Conclusion

It was shown how the 1964 Dyson-Xuong SU(6)-based classification and predictions of nonstrange dibaryons [4] are confirmed in our hadronic model of pion-assisted $N\Delta$ and $\Delta\Delta$ dibaryons [15, 16]. The input for dibaryon calculations in this model consists of nucleons, pions and Δ's, interacting via long-range pairwise interactions. These calculations reproduce the two nonstrange dibaryons established experimentally and phenomenologically so far, the $N\Delta$ dibaryon $\mathcal{D}_{12}$ [17, 18] and the $\Delta\Delta$ dibaryon $\mathcal{D}_{03}$ reported by WASA-at-COSY [1–3], predicting also an exotic $I = 2$ $N\Delta$ dibaryon $\mathcal{D}_{21}$ nearly degenerate with $\mathcal{D}_{12}$. We note that $\mathcal{D}_{12}$ provides in our $\pi N\Delta$ three-body model of $\mathcal{D}_{03}$ a two-body decay channel $\pi\mathcal{D}_{12}$ with threshold lower than $\Delta\Delta$. Our calculations are capable of dealing with other $\Delta\Delta$ dibaryon candidates [16], in particular the $I = 3$ exotic $\mathcal{D}_{30}$ highlighted recently by Bashkanov, Brodsky and Clement [19]. These authors emphasized the dominant role that six-quark hidden-color configurations might play in binding $\mathcal{D}_{03}$ and $\mathcal{D}_{30}$, but recent explicit quark-based calculations [13] find these configurations to play a marginal role, enhancing dibaryon binding by merely 15±5 MeV and reducing the dibaryon width from 175 to 150 MeV for $\mathcal{D}_{03}$, still twice as big as the reported width, and from 216 to 200 MeV for $\mathcal{D}_{30}$. Hidden-color considerations are naturally outside the scope of hadronic models and it is gratifying that the results presented here in the hadronic basis are independent of such poorly understood configurations.

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References

[1] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Rev. Lett. **106** (2011) 242302. See also the preceding reports: H. Clement et al. (CELSIUS-WASA Collaboration), Prog. Part. Nucl. Phys. **61** (2008) 276; M. Bashkanov et al. (CELSIUS/WASA Collaboration), Phys. Rev. Lett. **102** (2009) 052301.
[2] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Lett. **721** (2013) 229.
[3] P. Adlarson et al. (WASA-at-COSY Collaboration, SAID Data Analysis Center), Phys. Rev. C **90** (2014) 035204. See also P. Adlarson et al. (WASA-at-COSY Collaboration, SAID Data Analysis Center), Phys. Rev. Lett. **112** (2014) 202301.
[4] F.J. Dyson, N.-H. Xuong, Phys. Rev. Lett. **13** (1964) 815.
[5] P.J. Mulders, A.T. Aerts, J.J. de Swart, Phys. Rev. D **21** (1980) 2653.
[6] M. Oka, K. Yazaki, Phys. Lett. B **90** (1980) 41.
[7] P.J. Mulders, A.W. Thomas, J. Phys. G **9** (1983) 1159.
[8] K. Maltman, Nucl. Phys. A **438** (1985) 669.
[9] T. Goldman, K. Maltman, G.J. Stephenson, K.E. Schmidt, F. Wang, Phys. Rev. C **39** (1989) 1889.
[10] X.Q. Yuan, Z.Y. Zhang, Y.W. Yu, P.N. Shen, Phys. Rev. C **60** (1999) 045203.
[11] R.D. Mota, A. Valcarce, F. Fernández, D.R. Entem, H. Garcilazo, Phys. Rev. C **65** (2002) 034006.
[12] J.L. Ping, H.X. Huang, H.R. Pang, F. Wang, C.W. Wong, Phys. Rev. C **79** (2009) 024001.
[13] H. Huang, J. Ping, F. Wang, Phys. Rev. C **89** (2014) 034001.
[14] A. Gal, in *From Nuclei to Stars, Festschrift in Honor of Gerald E Browm*, Ed. Sabine Lee (WS, 2011) pp. 157-170 (arXiv:1011.6322). See also M. Oka, Phys. Rev. D **38** (1988) 298.
[15] A. Gal, H. Garcilazo, Phys. Rev. Lett. **111** (2013) 172301.
[16] A. Gal, H. Garcilazo, Nucl. Phys. A **928** (2014) 73.
[17] R.A. Arndt, J.S. Hyslop III, L.D. Roper, Phys. Rev. D **35** (1987) 128.
[18] N. Hoshizaki, Phys. Rev. C **45** (1992) R1424, Prog. Theor. Phys. **89** (1993) 563.
[19] M. Bashkanov, S.J. Brodsky, H. Clement, Phys. Lett. B **727** (2013) 438. See also F. Huang, Z.Y. Zhang, P.N. Shen, W.L. Wang, arXiv:1408.0458 [nucl-th].