* In case of the photodisintegration reactions the electromagnetic nuclear current is taken as a single nucleon current supplemented by two-nucleon contribution mimicked by the Siegert theorem. For the absorption processes the ~~dominant~~ two-nucleon currents are in included explicitly (leading order) on the top of the single nucleon operators.

CHAPTER 4

SUMMARY

of chiral expansion

the — the

In this thesis, I investigated (the) ^{2}H, ^{3}H and ^{3}He photodisintegration processes as well as (the) pion absorption by the same nuclei. To analyze these reactions and to calculate predictions for observables I used a chiral model of interaction ~~namely the most advanced~~ SMS nucleon-nucleon ~~chiral~~ potential up to N^{4}LO$^+$ order augmented by the consistently regularized three-nucleon force at N^{2}LO. Results prepared with the semi-phenomenological AV18 potential have been shown as a reference point.* ~~The current operator is restricted to the single-nucleon part only~~. Both processes are studied in ~~the~~ momentum space. The standard Lippmann-Schwinger equation is solved to get the t-operator and consequently 2N scattering state. For the three-nucleon processes, the formalism of Faddeev equations has been applied. I solved corresponding equations for Faddeev components both for the bound and 3N scattering states. In that way, I include all initial state as well as final state interactions. I am also able to test the importance of FSI by restricting ~~components~~ computations to only plane wave approximation. The used formalism allows me to study not only the total cross section or ~~capture~~ (total absorption) rates but also various differential cross sections and polarization observables. The latter ones are very important to test the model~~, and to compare with experimental data~~. That ~~also~~ in turn allows me to conclude on the sensitivity of various observables on studied effects and to pick up observables which after measurement could deliver the most valuable information.

The main goal of this work was to investigate the quality of currently available predictions based on the ~~semi-phenomenological~~ (chiral) SMS interactions if applied to the studied here processes. Such information is necessary due to expected two- and more- nucleon currents at higher orders of chiral expansion, consistent with the SMS potential. Various features of the model can be studied in that context. Firstly, I investigated if the predictions based on the SMS interaction are converged with respect to the chiral order. It would then be a hint whether the development of higher-order contributions to the potential is required. In most of the results, I observe very converged predictions ~~since there is a~~ (what I conclude from a) small difference between the last two investigated chiral orders: N^{4}LO and N^{4}LO$^+$. This difference in most of the regarded cases does not exceed a few percent. Another piece of evidence is the width of the truncation bands for N^{4}LO$^+$ predictions. For the deuteron photodisintegration process, observables have a maximum truncation error below 1 % for the two studied photon energies: $E_\gamma = 30\,\mathrm{MeV}$ and $E_\gamma = 100\,\mathrm{MeV}$. The same trend is present~~ed~~ also for other regarded reactions~~, as well~~. This ~~hints~~ ? us towards a conclusion that further chiral orders would not improve the predictions much and the current model

leads

check in whole thesis presented vs present

?

the potential's   of its predictions

shows satisfactory convergence. This is also confirmed by the AV18 predictions which are always very close to N^{4}LO$^+$ (see e.g. Fig. 3.8, Fig. 3.26 etc.).

The other interesting point in the investigation of chiral potential is ~~its~~ dependence on the value of ~~its~~ intrinsic cut-off parameter Λ, the four values of which (400, 450, 500 and 550 MeV) were investigated. I have shown that the relative spread of predictions concerning the cutoff value is higher for the higher energies. For example, the spread of the differential cross section for ^{3}He photodisintegration at $E_\gamma = 30$ MeV at the characteristic point (maximum) is around 3 %, while at $E_\gamma = 100$ MeV it is three times larger - around 3 % (see Fig. 3.28, Fig. 3.29 and discussions). Nevertheless, usually for higher energies the difference between the predictions obtained with different values of Λ is smaller than the difference with experimental data (when it is available) which is visible in Fig. 3.5(b).

something is wrong   e.g.

I have also studied the role of the various dynamical components of the model by checking how they influence the predicted values. Namely, I compare(d) predictions obtained with plane wave part only (first term in the Eq. (2.31)), with those taking into account the final state interaction* ~~as well as predictions with and without 2N current contributions (introduced via the Siegert approach)~~. For example, in the Fig. 3.4b ~~we see~~ there are predictions for the deuteron photodisintegration cross section obtained without rescattering part, without 2N contributions to the current and full predictions. The contribution of rescattering processes is relatively small for the predictions at $E_\gamma = 30$ MeV, but ~~is increasing with larger~~ grows with increa[sing] energies. In some cases the analysis of the relative difference at the specific θ_p value does not show this trend (the differences are 10 %, 7 % and 4 % for $E_\gamma = 30$, 100 and 140 MeV respectively at $\theta_p = 80$ %), but we see that at the lower energy all predicted cross section values are qualitatively very similar and they differ mainly around the maximum point. In contrast, for the larger energies, predictions differ qualitatively, and the analyzed point depicts the region where the difference is relatively small. The ~~difference~~ discrep[ancy] between the full predictions and the ones, where only 1NC was used is much bigger: even for the lowest energy inclusion of two-body currents changes the cross section by around 50 % and for the larger two it grows up to ~ 78 %. Clearly, both rescattering part and 2NC contributions are very important and bring significant contributions. Similar trend is visible also for other observables(see e.g. Fig. 3.10) and processes (see Figs.3.52, 3.54, 3.56 to compare contributions for the pion absorption on ^{3}He).

That complex pattern reveals the interplay between For interaction and the current operator, and is one more recommendation after derivation fully consistent model, i.e. with consistent 2N forces, 3N forces, and one-, two- and three-body currents. Such a model must be applied only within the ~~readable~~ reliable ~~readable~~ unambiguously scheme to compute observables. My work culminated in the preparation of such a scheme, both analytical and numerical sides, and now we are ready to study more sophisticated Hamiltonians.

Giving mentioned above results, ~~we can also~~ I conclude that changing the current version of the chiral SMS potential is of very high quality: it rather does not require any additional development in the sense of adding higher chiral orders or regularization. Contrary, the 2NC should be completely derived as it is expected to bring a significant contribution and thus improvements in our understanding of ~~electromagnetic~~ processes with photons or pions. for both types of processes

Among ~~the studied processes and observables~~, I would like to ~~point out~~ highlight the following ~~main~~ conclusions: results my results important Part

I propose to change order and give the most important electromagnetic → 1. is on separate page

1. *The most sensitive to FSI are for (observables, energies)*

2 ~~1~~ 2. 2NC is very important for the regarded strong processes and observables. Even including it via the Siegert theorem allows seeing significant improvements (e.g. Figs. 3.2,

* I also investigated the role of two-body ~~currents (introduced via the~~ contributions to nuclear current or absorption operator, by performing computations ~~which takes~~ or that take or do not take two-body operators into account

at leading order

predictions shown in

New point 3

The same is

3.6 and 3.8 for the deuteron photodisintegration process). For the pion absorption process, I took into account ~~full~~ 2NC and the difference between Fig. 3.52 and Fig. 3.56 (1NC only) ~~is a~~ proofs of its importance. *

4 ~~3~~. The importance of 3NF is less obvious looking at my results. For example, for ^{3}He photodisintegration in Fig. 3.30 3NF makes cutoff dependence weaker, but the difference between predictions with and without 3NF is not very big. **

7 ~~4~~. Investigation of the differential cross section is beneficial compared to the total cross sections as it allows us to see smaller details of the reaction mechanisms and the model in a sense of convergence and cutoff dependence. One may observe the reason for particular discrepancies (e.g. some singularity point which causes computational problems). It is also less computationally expensive as the total cross section is obtained via integration of the differential cross section through the whole region. ***

2?

8 ~~5~~. It would be interesting to check experimentally if theoretical uncertainties appearing at some configurations would be also reflected in the data. For example, we see that the kinematical configuration presented in Fig. 3.28 is less sensitive to the model parameters than the one in Fig. 3.30. So measuring the data for ^{3}He gives more possibilities to test the model as lots of configurations for the differential cross section are possible. OK but we need to discuss

5 ~~6~~. *For $\pi+{}^3H$ there are 3 neuterons in the final state. It is a very unusual but interesting situation*

9 ~~7~~. *For pion absorption write if I suggest measurements in FSI configuration, QFS configuration or other.*

maybe 10 should be 2 added to 2?

10 ~~8~~. *Our Full model nicely describes data up to $E_\gamma = 70$ MeV.* Write for 1, 6

* However discrepancy with the ~~dat~~ existing data for the total capture rates calls for more advanced model of two- ~~[illegible]~~ and three-body absorption operator.

** Thus the investigated here processes are not best field to study ~~pr~~ details of the three-nucleon interaction. The only exception is pion absorption on 3H, see below.

*** Thus, while the exclusive or semi-exclusive experiments are much harder to do than the measurement of the total cross sections or ~~rates~~ absorption rates, ~~I would like to~~ the experimental efforts should focus on such types of measurements in future

1. The chiral SMS nucleon - nucleon interaction at ~~N3LO~~ higher orders of chiral expansion (above N^2LO) ~~shows~~ leads to very stable behavior of predictions ~~one applied to~~ for the photodisintegration and pion absorption processes. That confirms previous findings for ~~pure~~ processes in pure nucleonic systems.

I ~~don't~~ ~~[illegible]~~ haven't observed any strange or worrying pattern for observables which could be related with ~~[illegible]~~ deficiencies in the nucleon-nucleon interaction. In consequence I conclude, that NN force is known with sufficient accuracy to be used in studies nuclear processes ~~beyond that~~ with external sonds

6. Write what ~~is more important~~ gives more uncertainty - cutoff or order
One - three examples

CHECK ALSO OLDER LIST FOR CONCLUSIONS
(I SCAN ~~TH~~ It in next page)

(in points)

In summary you ~~are~~ should give few detailed conclusions like

Among the studied processes and observables:

1) The most sensitive to FSI are for ... (observables, energies)

2) ______ " ______ 2NC

3) ______ " ______ 3NF

4) ~~cross~~ total cross section vs differential cross sections

5) cross sections vs polarization observables

6) Is it better do measurement on ^2H, ^3He or ^3H ?

7) stress that for $\pi + {}^3H$ there are three neutrons in final state which is very unusual but extremely interesting situation

8) For pion absorption write if you suggest measurements in FSI configuration, QFS or others ?

⋮

BIBLIOGRAPHY

[1] D. M. Skopik, Y. M. Shin, M. C. Phenneger, and J. J. Murphy. Photodisintegration of deuterium determined from the electrodisintegration process. *Phys. Rev. C*, 9:531–536, Feb 1974.

[2] F. F. Liu, D. E. Lundquist, and B. H. Wiik. Measurements of the polarization of protons from deuteron photodisintegration. *Phys. Rev.*, 165:1478–1482, Jan 1968.

[3] Reinhold Kose, Bjoern Martin, Rainer Runkel, Helmut Wahlen, and Karl Heinz Kissler. Measurements of the polarization of protons from deuteron photodisintegration for photon energies between 282 and 405 MeV. *Zeitschrift für Physik A Hadrons and nuclei*, 220:305–320, 1969.

[4] T. Kamae, I. Arai, T. Fujii, H. Ikeda, N. Kajiura, S. Kawabata, K. Nakamura, K. Ogawa, H. Takeda, and Y. Watase. Observation of an anomalous structure in proton polarization from deuteron photodisintegration. *Phys. Rev. Lett.*, 38:468–471, Feb 1977.

[5] Andrew L. Cooper, K. J. Kelly, E. Machado, I. Pogrebnyak, J. Surbrook, C. Tysor, P. Thompson, M. Emamian, B. Walsh, B. Carlin, J. R. Dermigny, A. E. Champagne, and T. B. Clegg. Development of a variable-energy, high-intensity, pulsed-mode ion source for low-energy nuclear astrophysics studies. *Review of Scientific Instruments*, 89(8):083301, 2018.

HIγS

[6] A.P. Tonchev, M. Boswell, C.R. Howell, H.J. Karwowski, J.H. Kelley, W. Tornow, and Y.K. Wu. The high intensity γ-ray source (hiγs) and recent results. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 241(1):170–175, 2005. The Application of Accelerators in Research and Industry.

[7] J Bermuth, P Merle, C Carasco, D Baumann, R Böhm, D Bosnar, M Ding, M.O Distler, J Friedrich, J.M Friedrich, J Golak, W Glöckle, M Hauger, W Heil, P Jennewein, J Jourdan, H Kamada, A Klein, M Kohl, B Krusche, K.W Krygier, H Merkel, U Müller, R Neuhausen, A Nogga, Ch Normand, E Otten, Th Pospischil, M Potokar, D Rohe, H Schmieden, J Schmiedeskamp, M Seimetz, I Sick, S Širca, R Skibiński, G Testa, Th Walcher, G Warren, M Weis, H Witała, H Wöhrle, and M Zeier. The

[80] I.E. Vnukov, I.V. Glavanakov, Y.F. Krechetov, A.P. Potylitsyn, G.A. Saruev, V.N. Stibunov, and A.N. Tabachenko. Photodisintegration of the deuteron by linearly polarized photons below the pion-production threshold. *Sov. J. Nucl. Phys. (Engl. Transl.); (United States)*, 47:4, 4 1988.

[81] W. Del Bianco, L. Federici, G. Giordano, G. Matone, G. Pasquariello, P. Picozza, R. Caloi, L. Casano, M. P. De Pascale, L. Ingrosso, M. Mattioli, E. Poldi, C. Schaerf, P. Pelfer, D. Prosperi, S. Frullani, B. Girolami, and H. Jeremie. Neutron Asymmetry Measurements in the Deuteron Photodisintegration between 10 and 70 MeV. *Phys. Rev. Lett.*, 47:1118–1120, Oct 1981.

[82] R. W. Jewell, W. John, J. E. Sherwood, and D. H. White. Polarization of Photoneutrons Produced from Deuterium by 2.75-MeV Gamma Rays. *Phys. Rev.*, 139:B71–B79, Jul 1965.

[83] J.M. Cameron, C.A. Davis, H. Fielding, P. Kitching, J. Pasos, J. Soukup, J. Uegaki, J. Wesick, H.S. Wilson, R. Abegg, D.A. Hutcheon, C.A. Miller, A.W. Stetz, and I.J. van Heerden. Radiative capture of polarized neutrons by hydrogen below the pion production threshold. *Nuclear Physics A*, 458(4):637–651, 1986.

[84] Th. Strauch, F. D. Amaro, D. F. Anagnostopoulos, P. Bühler, D. S. Covita, H. Gorke, D. Gotta, A. Gruber, A. Hirtl, P. Indelicato, E.-O. Le Bigot, M. Nekipelov, J. M. F. dos Santos, S. Schlesser, Ph. Schmid, L. M. Simons, M. Trassinelli, J. F. C. A. Veloso, and J. Zmeskal. Precision determination of the $d\pi \leftrightarrow$NN transition strength at threshold. *Phys. Rev. Lett.*, 104:142503, Apr 2010.

[85] Th. Strauch, F. D. Amaro, D. F. Anagnostopoulos, P. Bühler, D. S. Covita, H. Gorke, D. Gotta, A. Gruber, A. Hirtl, P. Indelicato, E. O. Le Bigot, M. Nekipelov, J. M. F. dos Santos, Ph. Schmid, S. Schlesser, L. M. Simons, M. Trassinelli, J. F. C. A. Veloso, and J. Zmeskal. Pionic deuterium. *The European Physical Journal A*, 47(7), July 2011.

[86] J. Golak, V. Urbanevych, R. Skibiński, H. Witała, K. Topolnicki, V. Baru, A. A. Filin, E. Epelbaum, H. Kamada, and A. Nogga. Pion absorption from the lowest atomic orbital in ^{2}H,^{3}H, and ^{3}He. *Phys. Rev. C*, 106:064003, Dec 2022.

[87] I. Schwanner, G. Backenstoss, W. Kowald, L. Tauscher, H.-J. Weyer, D. Gotta, and H. Ullrich. Pionic and muonic x-ray measurements on light isotopes. *Nuclear Physics A*, 412(2):253–272, 1984.

[88] J. McCarthy, T. Meyer, R. C. Minehart, E. A. Wadlinger, K. O. H. Ziock, and J. Vincent. Negative pion capture in ^{3}He. *Phys. Rev. C*, 11:266–268, Jan 1975.

[89] P. Truöl, H.W. Baer, J.A. Bistirlich, K.M. Crowe, N. de Botton, and J.A. Helland. Measurement of the panofsky ratio in ^{3}He. *Phys. Rev. Lett.*, 32:1268–1271, Jun 1974.

Panofsky ?