

\section*{Abstract.} The application of the hyperspherical harmonic approach to the case of the \( N - d \) scattering problem is described. The nuclear Hamiltonian includes local and non-local two- and three-nucleon interactions. Also, Coulomb repulsion is included in the \( p - d \) case. Accurate calculation for \( p - d \) and \( n - d \) cross section and polarization observables at two center-of-mass energies are performed and the theoretical results are compared with the available experimental data. A satisfactory agreement between theory and experiment is found, except for the vector polarization observables. A quantitative estimate of the agreement or disagreement between theory and experiment is obtained performing a \( \chi^2 \) analysis.

\section{1. Introduction}

One of the main inputs for any study on nuclear systems within a non-relativistic framework is the model used to describe the nuclear interaction, i.e. the nuclear Hamiltonian. Nowadays, it is common practice to use, at least for the few-nucleon systems, Hamiltonian models composed of a two-nucleon (\( NN \)) plus, for \( A \geq 3 \), a three-nucleon interaction (TNI). The modern \( NN \) interaction models have a large number of parameters and can reproduce the deuteron properties and the nucleon-nucleon scattering data up to the pion threshold with a \( \chi^2/\text{datum} \approx 1 \). The available models for the TNI contain, instead, a small number of parameters, usually fixed to reproduce the \( ^3\text{H} \) binding energy and, in some cases, the nuclear matter equilibrium density. A crucial point for this type of studies is to test the model for the nuclear Hamiltonian studying \( A \geq 4 \) bound states and \( A \geq 3 \) scattering states. In the present work, we focus our attention to the \( A = 3 \) scattering problem.

To study the \( A = 3 \) scattering problem with a realistic Hamiltonian, we have chosen to use the hyperspherical harmonics (HH) method (for a recent review, see Ref. \[1\]). One of the main advantages of the HH method is the possibility of including the Coulomb interaction in \( p - d \) scattering without any additional difficulty compared to the \( n - d \) case. On the other hand, the HH method, being first developed in coordinate-space, was limited in the choice of the Hamiltonian models only to the local ones. A first step to implement the method to work in momentum-space has been done in Ref. \[2\], where the \( A = 3, 4 \) bound states have been studied using modern non-local interactions. In the present work, we apply the HH method to the \( N - d \) scattering problem again using non-local interactions. We limit this first analysis to the case of \( N - d \) elastic scattering at center-of-mass energy \( E_{\text{cm}} = 0, 1.33, 2 \text{ MeV} \) \( (0, 1.66, 2 \text{ MeV}) \) for
n − d (p − d). A more complete calculation at several center-of-mass energies will be given elsewhere [3].

The paper is organized as follows: in section 2, the HH method for the bound and the low-energy scattering problem is briefly outlined. In section 3, the results for the zero-energy scattering lengths and some low-energy elastic scattering observables will be presented and discussed. Some concluding remarks are given in section 4.

2. Formalism

In this section we present the HH method for scattering states. The method for bound states has been most recently reviewed in Ref. [1], and we briefly summarize its main characteristics.

The nuclear wave function for the three-body bound state can be written as

\[ |\Psi\rangle = \sum_{\mu} c_{\mu} |\Psi_{\mu}\rangle, \]  

where $|\Psi_{\mu}\rangle$ is a suitable complete set of states, and $\mu$ is an index denoting the set of quantum numbers necessary to completely specify the basis elements. The coefficients of the expansion are determined using the Rayleigh-Ritz variational principle, i.e. $\langle \delta c_{\mu} | H - E | \Psi \rangle = 0$, where $\delta c_{\mu}$ indicates the variation of $\Psi$ for arbitrary infinitesimal changes of the linear coefficients $c_{\mu}$. Then, the problem of determining $c_{\mu}$ and the energy $E$ is reduced to a generalized eigenvalue-eigenstate problem. The main difficulty of the method is to compute the matrix elements of the Hamiltonian $H$ with respect to the basis states $|\Psi_{\mu}\rangle$. Usually $H$ is given as a sum of terms (kinetic energy, $NN$ potential, etc.). The calculation of the matrix elements of some parts of $H$ can be more conveniently performed in coordinate-space, while for other parts it could be easier to work in momentum-space. Therefore, it is important that the basis states $|\Psi_{\mu}\rangle$ have simple expressions in both spaces. The HH functions indeed have such a property.

Let us first consider the expression of the HH functions in coordinate space. The internal dynamics of a system of three nucleons of identical mass $m$ is conveniently described in terms of the standard Jacobi vectors $x_1, x_2$. It is convenient to replace the moduli of $x_2$ and $x_1$ with the so-called hyperradius $\rho = \sqrt{x_1^2 + x_2^2}$ and hyperangle $\phi = \frac{x_1}{x_2}$ [4]. The complete set of hyperspherical coordinates is then given by \{\rho, \Omega^{(\rho)}\}, with $\Omega^{(\rho)} = \{x_2, x_1; \phi\}$ and the suffix $(\rho)$ recalls the use of the coordinate space.

The expansion states $|\Psi_{\mu}\rangle$ of Eq. (1) are then given by

\[ |\Psi_{\mu}^{(\rho)}\rangle = f_l(\rho) Y_{l G}^{(\Omega^{(\rho)})}, \]  

where $f_l(\rho)$ for $l = 1, \ldots$ is a complete set of hyperradial functions, here chosen to be Laguerre polynomials multiplied by a decreasing exponential function of $\rho$. The functions $Y_{l G}^{(\Omega^{(\rho)})}$ contain all the dependence on the angular, spin and isospin quantum numbers of the three nucleons, schematically included in \{G\}, and on the angular-hyperangular variables $\Omega^{(\rho)}$. They are known as the spin-isospin HH functions of grand-angular momentum $G$. More details can be found in Ref. [1].

The expansion states of Eq. (1) in momentum space can be obtained as follows. Let $\hbar k_1, \hbar k_2$ be the standard conjugate Jacobi momenta of the Jacobi vectors. We then define a hypermomentum $Q$ and a set of angular-hyperangular variables as

\[ Q = \sqrt{k_1^2 + k_2^2}, \quad \Omega^{(Q)} = [\hat{k}_2, \hat{k}_1; \varphi], \]  

where $\tan \varphi = \frac{k_1}{k_2}$. Then, the momentum-space version of the wave function given in Eq. (2) is

\[ |\Psi_{\mu}^{(Q)}\rangle = g_{G l}(Q) Y_{l G}^{(\Omega^{(Q)})}, \]
Table 1. $^3$H, $^3$He and $^4$He binding energies in MeV calculated with the HH method using different two- and three-nucleon Hamiltonian models.

| Interaction                  | $^3$H | $^3$He | $^4$He |
|------------------------------|-------|--------|--------|
| AV18/UIX                    | 8.479 | 7.750  | 28.46  |
| CDBonn/TM                   | 8.474 | 7.720  | 29.00  |
| N3LO-Idaho/UIXp             | 8.481 | 7.730  | 28.53  |
| N3LO-Idaho/N2LO             | 8.474 | 7.733  | 28.36  |
| Experimental                | 8.482 | 7.718  | 28.30  |

where $\mathcal{Y}_{(G)}(\Omega^{(Q)})$ is the same as $\mathcal{Y}_{(G)}(\Omega^{(\rho)})$ with $x_i \to k_i$, and

$g_{G,l}(Q) = (-i)^G \int_0^\infty d\rho \frac{\rho^3}{Q^2} J_{G+2}(Q\rho) f_l(\rho). \quad (5)$

Here $J_{G+2}(Q\rho)$ is a Bessel function. With the adopted form of $f_l(\rho)$, the corresponding functions $g_{G,l}(Q)$ can be easily calculated, and they are explicitly given in Ref. [2].

In table 1 we list the binding energies in MeV of $^3$H, $^3$He and $^4$He calculated using different two- and three-nucleon Hamiltonian models. In particular, we have considered the local AV18 [6] $NN$ potential in conjunction with the Urbana IX [7] (UIX) TNI, the non-local CDBonn 2000 (CDBonn) [8] $NN$ potential in conjunction with the Tucson-Merlbourne (TM) [9] TNI, and the non-local N3LO-Idaho [10] $NN$ potential in conjunction with the UIX or the N2LO [11] TNIs. To be noticed that in the case of the N3LO-Idaho plus UIX Hamiltonian model, the parameter in front of the spin-isospin independent part of the UIX TNI has been rescaled by a factor of 0.384 to fit the triton binding energy [14] (UIXp). From inspection of the table, we can conclude that the theoretical predictions are in good agreement with the experimental data, although some discrepancies of the order of 10 keV can be found for the $A = 3$ binding energies, whereas for $A = 4$ the discrepancies can be even of few hundreds of keV, as for the CDBonn/TM potential.

We consider now the extension of the HH technique to describe $N-d$ scattering states below deuteron breakup threshold. Both local and non-local interaction models are considered.

The wave function $\Psi_{N-d}^{LSJJ_z}$ describing the $N-d$ scattering state with incoming orbital angular momentum $L$ and channel spin $S$, parity $\pi = (-)^L$, and total angular momentum $J, J_z$, can be written as

$\Psi_{N-d}^{LSJJ_z} = \Psi_{C}^{LSJJ_z} + \Psi_{A}^{LSJJ_z}. \quad (6)$

Here $\Psi_{C}^{LSJJ_z}$ must describe the system in the region where the particles are close to each other and their mutual interactions are strong, while $\Psi_{A}^{LSJJ_z}$ must describe the relative motion between the nucleon $N$ and the deuteron $d$ in the asymptotic region, where the $N-d$ nuclear interaction is negligible. The function $\Psi_{C}^{LSJJ_z}$, which has to vanish in the limit of large $N-d$ separation, can be expanded on the HH basis as it has been done in the case of bound states (see Eq. (1)), and the expansion basis $|\Psi_{\mu}\rangle$ is given in Eqs. (2) and (4) in coordinate- and momentum-space, respectively. The function $\Psi_{A}^{LSJJ_z}$ is the appropriate solution of the Schrödinger equation in the case of a two-body scattering problem, and can be casted in the form [1]

$\Psi_{A}^{LSJJ_z} \propto F_{LS}(pr_Nd) + \sum_{L'S'} R_{LS,L'S'}^J G_{L'S'}(pr_Nd), \quad (7)$
where $p$ ($r_{N,d}$) is the $N - d$ relative momentum (distance), and $F_{LS}(pr_{N,d})$ and $G_{LS'}(pr_{N,d})$ are the regular and irregular Coulomb (Bessel) functions for the $p - d$ $(n - d)$ scattering problem. The parameters $R^{J}_{LS,LS'}(q)$ give the relative weight between the regular and irregular components, and are closely related to the reactance matrix ($\mathcal{K}$-matrix) elements. By definition, the $\mathcal{K}$-matrix eigenvalues are proportional to the phase shifts of the scattering problem.

The matrix elements $R^{J}_{LS,LS'}(q)$ and the linear coefficients $c_{\mu}$ occurring in the expansion of $\Psi_{C}^{LSJJ_{z}}$ are determined applying the Kohn variational principle [12], which states that the functional

$$
[\mathcal{R}^{J}_{LS,LS'}(q)] = \mathcal{R}^{J}_{LS,LS'}(q) - \langle \Psi_{N-d}^{LSJJ_{z}} | H - E | \Psi_{N-d}^{LSJJ_{z}} \rangle,
$$

has to be stationary with respect to variations of the trial parameters in $\Psi_{N-d}^{LSJJ_{z}}$. Here $E$ is the total energy of the system. Performing these variations, the problem reduces to find the solution of a system of linear inhomogeneous equations for $c_{\mu}$ and a set of algebraic equations for $R^{J}_{LS,LS'}(q)$. This can be done with standard numerical techniques. A second order estimate of $R^{J}_{LS,LS'}(q)$ is given by the quantities $[\mathcal{R}^{J}_{LS,LS'}(q)]$, obtained by substituting in Eq. (8) the first order results. Such second-order calculation provides a symmetric reactance matrix. This condition is not a priori imposed, and therefore it is a useful test of the numerical accuracy.

In the particular case of $q = 0$ (zero-energy scattering), the scattering occurs only in the channel $L = 0$ and the observables of interest are the scattering lengths. Within the present approach, they can be easily obtained as $(2J + 1)_{R_{N,d}} = -\lim_{q \to 0} \mathcal{R}^{J}_{LS,LS'}(q)$.

The approach presented so far for the $N - d$ scattering process does not have too many differences compared to the method presented for instance in Ref. [13], and known as pair-correlated hyperspherical harmonics (PHH) method. In the PHH method, a correlation factor is included in the HH expansion to take into account the strong short-range correlations induced by the realistic $NN$ potentials, like the AV18. The presence of correlation functions makes the convergence of the expansion much faster than in the uncorrelated case. However, the PHH method cannot be easily implemented when non-local $NN$ interactions are considered, as in this work. Here, instead, the calculation involving $\Psi_{C}^{LSJJ_{z}}$ can be performed in coordinate- or in momentum-space, depending on what is more convenient, as it has been previously explained for the bound state. Some difficulties, however, arise for the calculation of the potential energy matrix elements which involve $\Psi_{A}^{LSJJ_{z}}$, like $\langle \Psi_{\mu} | V | \Psi_{A}^{LSJJ_{z}} \rangle$ and $\langle \Psi_{A}^{LSJJ_{z}} | V | \Psi_{A}^{LSJJ_{z}} \rangle$, when non-local potentials expressed in momentum-space are used. On the contrary to $\Psi_{C}^{LSJJ_{z}}$, which can be alternatively expressed in coordinate- or in momentum-space, the asymptotic state $\Psi_{A}^{LSJJ_{z}}$ does not have an easy expression in momentum-space, and is more conveniently given and used in coordinate-space. This is especially true when the Coulomb interaction is considered, as for the $p - d$ case. Therefore, we have decided to perform the Fourier transform of the non-local potential $\psi(k, k')$ and to work only in coordinate-space. The integrations over $k$ and $k'$, which run from 0 to $\infty$, are easily performed when the potential model considered does not have a high-momentum tail, but goes rapidly to zero at rather low values of $k$ and $k'$. This is true for the N3LO-Idaho potential model, but not for the CDBonn 2000. Since the main goal of the present work is to perform a first test of the applicability of the HH method to the $A = 3$ scattering problem using non-local realistic interactions, only the N3LO-Idaho $NN$ potential has been considered.

3. Results
The $N - d$ elastic scattering observables have been studied using the following interaction models: the two-nucleon AV18 and N3LO-Idaho and the two- plus three-nucleon AV18/UIX, N3LO-Idaho/UIXp and N3LO-Idaho/N2LO models. In the case of $p - d$ elastic scattering, only the point Coulomb electromagnetic interaction has been considered, also when the AV18 potential is used.
Table 2. $n-d$ and $p-d$ doublet and quartet scattering lengths in fm calculated with the HH technique using different Hamiltonian models.

| Interaction | $a_{nd}^2$ | $a_{nd}^4$ | $a_{pd}^2$ | $a_{pd}^4$ |
|-------------|------------|------------|------------|------------|
| AV18        | 1.275      | 6.325      | 1.185      | 13.588     |
| AV18/UIX    | 0.610      | 6.323      | -0.035     | 13.588     |
| N3LO-Idaho  | 1.100      | 6.342      | 0.876      | 13.646     |
| N3LO-Idaho/UIXp | 0.623   | 6.343      | -0.007     | 13.647     |
| N3LO-Idaho/N2LO | 0.675   | 6.342      | 0.072      | 13.647     |

Experimental [15]: 0.65±0.04 6.35±0.02
Experimental [16]: 0.645±0.003±0.007

The results for the $n-d$ and $p-d$ doublet and quartet scattering lengths are given in table 2 and are compared with the available experimental data [15, 16]. The calculation has been performed including also the $T = 3/2$ components of the wave function. To make the calculation faster, the PHH expansion has been used in the AV18 and AV18/UIX cases. The dimension of the basis and the number of the integration points have been increased in order to reach an accuracy of 0.002 fm in the calculation of the scattering lengths. Comparing the theoretical and experimental results for $^2a_{nd}$ and $^4a_{nd}$, we can conclude that $^4a_{nd}$ is very little model-dependent (as well as $^4a_{pd}$), and there is a satisfactory agreement between theory and experiment. On the contrary, $^2a_{nd}$ is strongly model-dependent. Only the inclusion of the TNI brings the theoretical value close to the experimental one, but some disagreement is still observed, in particular for the AV18/UIX model. Note that the results presented have been calculated without including the neutron-proton mass difference contribution, which is expected to further decrease the value of $^2a_{nd}$. Finally, the recent measurement of Ref. [16] is not well described by any of the potential models considered. However, the N3LO-Idaho with the UIXp and N2LO gives better results. Further analysis of this aspect can be found in Ref. [17].

The $n-d$ elastic scattering observables, including differential cross section, neutron vector analyzing power $A_Y$, deuteron vector and tensor analyzing powers $iT_{11}$, $T_{20}$, $T_{21}$ and $T_{22}$, at $E_{cm} = 1.33$ MeV and 2 MeV are given in figure 1. In figure 2 the same observables are presented but for $p-d$ at $E_{cm} = 1.66$ MeV and 2 MeV. The experimental data are from Refs. [18, 19, 20, 21, 22] and Ref. [23] for the $n-d$ and $p-d$ case, respectively. From inspection of the figures, we can observe that there is an overall agreement between experimental data and theoretical prediction except for few remarkable cases: (i) the $n-d$ differential cross section at $E_{cm} = 1.33$ MeV for large values of the center-of-mass angle $\theta_{cm}$. Such a discrepancy disappears at $E_{cm} = 2$ MeV and is not present in the $p-d$ case. Its origin has still to be clarified [24]. (ii) The $p-d$ tensor analyzing power $T_{21}$ is poorly described in the first minimum region by the Hamiltonian models which include both two- and three-nucleon interactions. However, the non-local potential models seem to do a slightly better job than the local ones. (iii) The $n-d$ and $p-d$ vector analyzing powers $A_Y$ and $iT_{11}$ are poorly described by the theory, in particular in the maximum region. Such a discrepancy, since long time known as the “$A_Y$-puzzle”, is more remarked with two-nucleon only Hamiltonian models. The inclusion of the TNI slightly improves the situation, but not significantly. In particular, it should be noticed that the differences between the AV18 and N3LO-Idaho results could be explained by the fact that the N3LO-Idaho potential model, on the contrary to the AV18 one, includes the effects of the magnetic moment interaction. On the other hand, the better description of the experimental data given by the N3LO-Idaho/N2LO with respect to the N3LO-Idaho/UIXp Hamiltonian model, could be an
Figure 1. (Color on-line) The theoretical values of the differential cross section, $A_y$, $iT_{11}$, $T_{20}$, $T_{21}$ and $T_{22}$, at $E_{cm} = 1.33$ MeV and $E_{cm} = 2$ MeV are compared to the experimental data of Refs. [18, 19, 20] for $E_{cm} = 1.33$ MeV and Refs. [21, 22] for $E_{cm} = 2$ MeV. The calculation are done with the AV18 (dashed blue line), the AV18/UIX (solid blue line), the N3LO-Idaho (dashed green line), the N3LO-Idaho/UIXp (solid green line), and the N3LO-Idaho/N2LO (solid red line) potential models. The incident neutron (deuteron) is $E_n = 2$ MeV ($E_d = 4$ MeV) on the left panel and $E_n = 3$ MeV ($E_d = 6$ MeV) on the right panel.

indication that the N2LO TNI model is somehow “better” than the UIX one. Further studies on this aspect are currently underway [3].

Since the comparison among the different potential models done by looking at figures 1 and 2 can be obtained only at a qualitative level, we have performed, in the example case of $p - d$ elastic scattering, a $\chi^2$ analysis. To this aim, following Ref. [25], $\chi^2$/datum = $\frac{1}{N} \sum_i \frac{(f_{exp}^i - f_{th}^i)^2}{(\Delta f_i)^2}$, where $f_{exp}^i$ is the $i$th datum at center-of-mass angle $\theta_i$ and $\Delta f_i$ is its experimental error, $f_{th}^i$ is the theoretical value at the same angle, and $N$ is the total number of data points included. The results for the $\chi^2$/datum obtained using the different Hamiltonian models considered in the present study for all the scattering observables are listed in table 3. Also listed are the results for the total $\chi^2$/datum. Note that the main goal of this analysis is to give a more quantitative argument to the statement that the N2LO TNI is somewhat “better” than the UIX. In fact, the $\chi^2$/datum calculated with the N3LO-Idaho/UIXp is comparable with the one calculated with the N3LO-Idaho/N2LO, except for $A_y$ at $E_{cm} = 1.66$ and 2 MeV, where the N3LO-Idaho/UIXp $\chi^2$/datum is higher than the N3LO-Idaho/N2LO one. Therefore, a slight improvement in the
description of the experimental observables is present for the N3LO-Idaho/N2LO calculation, compared with the N3LO-Idaho/UIXp one. Finally, we can notice that the total $\chi^2$ values at both center-of-mass energies are very similar, whatever two- plus three-nucleon Hamiltonian model is used.

4. Conclusions
We have presented a first study of $N - d$ elastic scattering problem below the deuteron breakup threshold using either local or non-local realistic Hamiltonian models. In particular, we have presented results for the zero-energy scattering lengths, and $n - d E_{cm} = 1.33$ MeV and 2 MeV ($p - d E_{cm} = 1.66$ MeV and 2 MeV) differential cross section, vector and tensor analyzing powers. Among the considered potential models, the N3LO-Idaho/N2LO seems to describe the experimental data slightly better than the previously widely used Hamiltonian models, like the AV18/UIX. A thorough study of $n - d$ and $p - d$ elastic scattering observables at several $E_{cm}$ values, below the deuteron breakup threshold, with different local and non-local Hamiltonian models is required and currently underway [3].
Table 3. $\chi^2$/datum of the $p-d$ elastic scattering observables at $E_{cm} = 1.66$ MeV and $E_{cm} = 2$ MeV calculated with the different Hamiltonian models considered in the present work. The different number $N$ of experimental data of Ref. [23] for each observable is also indicated.

| $E_{cm} = 1.66$ MeV | $d\sigma/d\Omega$ | $A_y$ | $iT_{11}$ | $T_{20}$ | $T_{21}$ | $T_{22}$ | total |
|---------------------|-----------------|------|---------|---------|---------|---------|-------|
|                     | $N$             |      |         |         |         |         |       |
| AV18                | 29.1            | 44   | 50      | 50      | 50      | 50      | 69.4  |
| N3LO-Idaho          | 21.5            | 267.1| 121.5   | 2.1     | 3.4     | 6.7     | 69.4  |
| AV18/UIX            | 3.1             | 198.2| 68.7    | 3.9     | 6.7     | 2.2     | 43.9  |
| N3LO-Idaho/UIXp     | 4.3             | 185.9| 67.0    | 2.0     | 3.1     | 3.2     | 43.1  |
| N3LO-Idaho/N2LO     | 6.6             | 159.4| 84.3    | 2.1     | 3.9     | 2.8     | 42.4  |

| $E_{cm} = 2$ MeV    | $d\sigma/d\Omega$ | $A_y$ | $iT_{11}$ | $T_{20}$ | $T_{21}$ | $T_{22}$ | total |
|---------------------|-----------------|------|---------|---------|---------|---------|-------|
|                     | $N$             |      |         |         |         |         |       |
| AV18                | 29.5            | 236.3| 148.7   | 3.7     | 5.0     | 12.5    | 67.1  |
| N3LO-Idaho          | 21.7            | 186.0| 108.3   | 1.1     | 2.8     | 4.4     | 49.7  |
| AV18/UIX            | 3.7             | 198.5| 99.1    | 4.9     | 11.9    | 2.5     | 49.2  |
| N3LO-Idaho/UIXp     | 4.3             | 152.4| 81.8    | 3.1     | 5.5     | 1.6     | 38.1  |
| N3LO-Idaho/N2LO     | 7.5             | 114.0| 85.8    | 3.6     | 8.3     | 1.6     | 34.7  |

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