CALCULATION OF DEUTERIUM-LITHIUM CROSS SECTIONS FOR ENERGIES UP TO 50 MEV USING REALISTIC NUCLEON-NUCLEON INTERACTIONS

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Objective: Test-facility neutronics calculation of Deuterium-Lithium cross sections for energies up to 50 MeV

Milestone: Calculation of Deuterium-Lithium cross sections for energies up to 50 MeV by using realistic nucleon-nucleon interactions

Progress of work

In order to improve the calculation of the D-Li neutron source term, a partial update of the $d+^{6,7}Li$ data evaluation[1] is carried on by calculation of the elastic scattering of deuteron on $^{6,7}Li$, for D-energies up to 50 MeV, by using a microscopic optical model potential (OMP) including nucleonic and mesonic form factors. The double-folding (DF) model[2,3] has been involved in this respect, while this work is based on previous studies[4-6] of the realistic effective nucleon-nucleon (NN) interactions within the DF model. The direct and exchange real parts of the microscopic optical potential are obtained within the double-folding model by summing the effective nucleon-nucleon (NN) interaction over the projectile and target nuclear densities, respectively. The knock-on exchange term of the folded potential has been calculated by using the approximation of Campi and Bouyssy[], which preserves the first term of the expansion given by Negele-Vautherin[8] for the realistic density-matrix expression, as well as the modified Thomas-Fermi approximation of Krivine and Treiner[9] for the kinetic-energy density. The key ingredients of the DF model calculations are however the nuclear-density distributions of the interacting nuclei and the effective NN interaction.

The deuteron density distribution has been obtained from the Machleidt[10] wave functions. We have considered only the ***S***-state of the deuteron ground state wave function, so that the effective NN-interaction used in the double folding procedure has had no tensor component The nuclear density distribution of the target nuclei $^{6,7}Li$ has been described by means of a gaussian form with parameters obtained from either the analysis of the electron scattering data of Bray et al.[11] for ^{6}Li, or the shell model calculations by Satchler and Love[2] for ^{7}Li. In this work we have chosen the Paris M3Y effective interaction[12]for consistency with the density distribution of the deuteron whose ground-state wave function has been obtained by using the Paris effective interaction[10]. Finally, the real DF potential $V_R^{DF}(r)$ has been applied for description of the deuteron scattering data from 1 to 50 MeV, in conjunction with appropriate Woods-Saxon imaginary and spin-orbit potentials.

The scattering cross sections have been calculated by using the code[13] SCAT2 modified to include the DF potential as an option for the OMP real part. *No adjustable parameter or normalization constant of the DF real potential was involved in this work.* The (a) trial for establishment of an energy-dependent phenomenological imaginary and spin-orbit parts of the OMP for d+^{6,7}Li from 1 to 50 MeV, and (b) completion of Deuterium-Lithium cross section calculations for energies up to 50 MeV by using a microscopic real potential based on realistic NN interactions and energy-dependent phenomenological imaginary and spin-orbit potentials are described in the following.

Average imaginary and spin-orbit parameterization

The phenomenological analysis of the deuterons elastic scattering experiments on ^{6,7}Li target nuclei provided a large variety of phenomenological OMPs at energies below 15MeV. However, apart from the discrete ambiguities in the real potential (which have been removed in this work by using the microscopic DF real potential), there are large variations of both the imaginary and spin orbit potential parameters as well as volume integrals corresponding to various elastic scattering data . Since these phenomenological analyses were performed at specific incident energies, the systematic behaviour of the mass or energy dependences of the corresponding OMP parameters was not considered. Therefore, we have looked for an imaginary and spin-orbit potentials parameter set able to describe, together with the microscopic real part the bulk of deuterons, elastic scattering data[14-21] on ^{6,7}Li target nuclei from 1 up to 50 MeV.

The optical potential involved in this work has, beyond the microscopic DF real potential, the standard form consisting of a derivative Woods-Saxon surface imaginary potential, a **L.S** spin-orbit potential of the Thomas form, and a Coulomb term:

$$U(r)=V_c(r)+V_R^{DF}(r) + i\, W_D\, g(r,R_D,a_D) + V_{SO}(r)\, (\hbar/m_\pi c)^2\, 1/r\, d/dr\, [f(r,R_{SO},a_{SO})]\ , \qquad (1)$$

where $f(r,R_i,a_i)=(1+exp[(r-R_i)/a_i])^{-1}$, $g(r,R_i,a_i)=-4a_i d/dr[f(r,R_i,a_i)]$, and $R_i=r_i\, A^{1/3}$, A being the target-nucleus mass number. $(\hbar/m_\pi c)^2$ is the square of the pion Compton wavelength of 2 fm^2, and $V_c(r)$ is the Coulomb potential of a uniformly charged sphere of radius R_C, while r_C=1.30 fm.

Thus we have analyzed the elastic-scattering angular distributions measured at deuteron energies[14],[16-18],[21] between 3 and 50 MeV for the target nucleus ^{6}Li (Figure 1), and at energies[1415],[17-19] between 1 and 14.7 MeV for the target nucleus ^{7}Li (Figure 2). Unfortunately a χ^2 analysis, which would have been the optimal procedure, has not been possible due to the lack of numerical cross sections including the errors for all experimental data involved in the present work. However, the good overall agreement finally obtained with the experimental data for both ^{6,7}Li target nuclei from 1 to 50 MeV can be considered as a suitable validation of the actual potential.

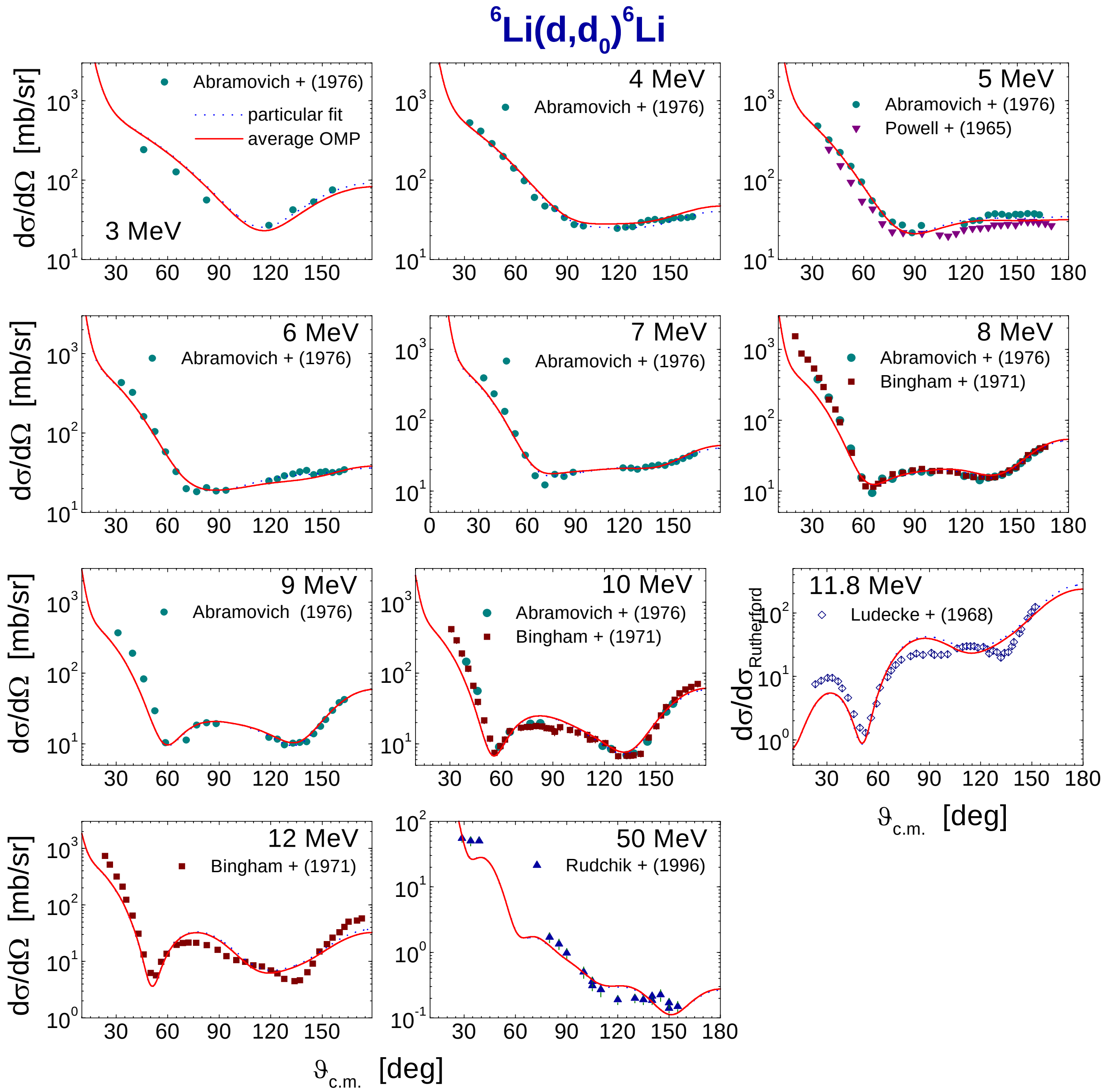


Figure 1. Comparison of experimental[14],[16-18],[21] and calculated angular distributions of the elastic scattering of deuterons on ^{6}Li between 3 and 50 MeV by using the microscopic DF real potential and particular (dotted curves) as well as average (solid curves) imaginary surface and spin-orbit potential parameters.

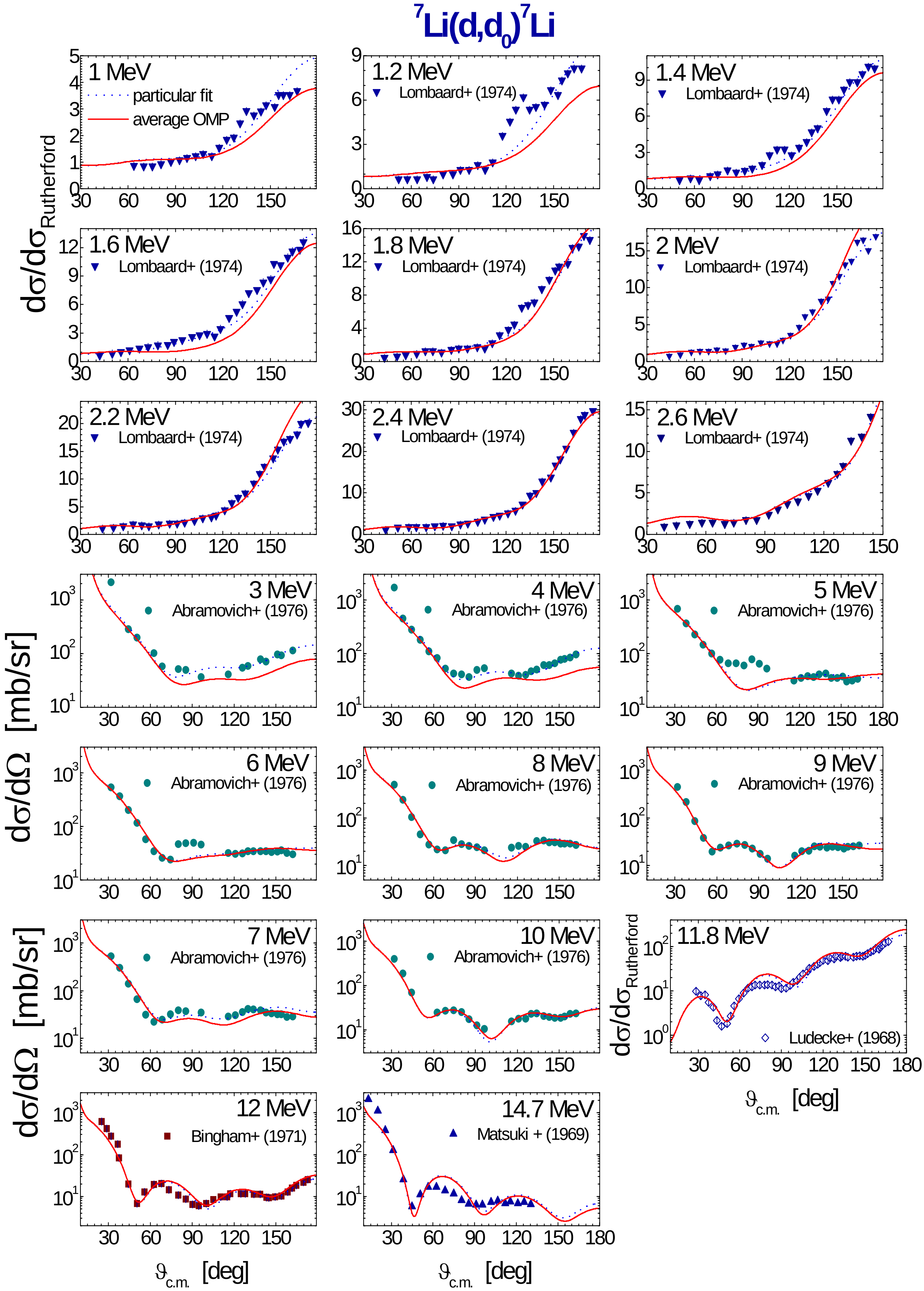
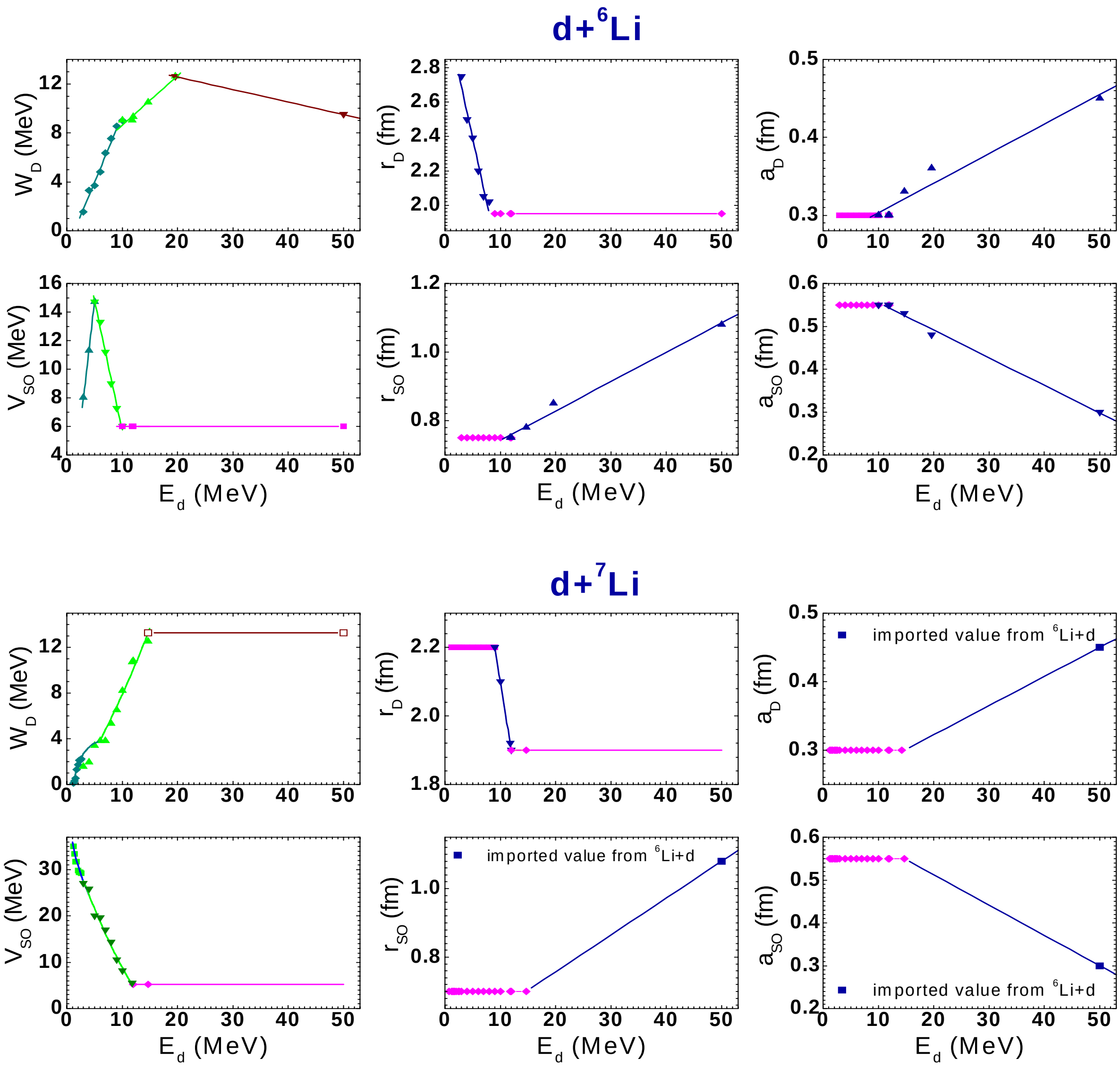


Figure 2. The same as in Figure 1 but for a target nucleus ^{7}Li and energies[14,-15],[17-19] between 1 and 14.7 MeV.

The common feature of the elastic scattering angular distributions of deuterons on ^{6,7}Li shown in Figures 1-2 mainly at low incident energies (1-4 MeV) is a strong backward scattering. The same behaviour was reported by Igo *et al.[22]* within the study of the 11.8 MeV deuterons scattered on C, Al and Mg targets. Moreover, Abramovici *et al.*[14] have proved that an increase of the spin-orbit depth V_{SO} of up to four times the typical phenomenological values[23] (~7 MeV) raises the scattering cross sections at large angles and thus leads to a description of the experimental angular distributions. The strong effect of the spin-orbit potential strength at large angles (θ>45°) has also been pointed out by Daenick *at al.*[24] exhaustive study of the deuteron OMP, while the lowest limit of the incident energy range was 11.8 MeV on the lightest target nucleus ^{27}Al.

Figure 3. The deuteron energy dependence of average values of the depths and geometry parameters of the imaginary surface and spin-orbit potentials for ^{6}Li (upper part) and ^{7}Li (lower part) target nuclei. The symbols correspond to the values obtained by fits of experimental angular distributions (Figures 1-2).



The values of the imaginary surface and spin- orbit potential parameters W_D, r_D, a_D, and respectively V_{SO}, r_{SO}, a_{SO}, obtained by fits of the deuteron elastic-scattering data for ^{6,7}Li are presented in Figure 3. At the same time there are shown their average values. The parameter values for the imaginary surface and spin-orbit potentials at 14.7 MeV and 19.6 MeV for d+^{6}Li have been established by involving also the coupled reaction channels calculations[25] and taking into account the deuterium exchange effects in ^{6}Li target nucleus. On the other hand, since 14.7 MeV is the highest energy where there are experimental data for d+^{7}Li, the extrapolation up to 50 MeV has been done in close connection with the parameter trend obtained within the d+^{6}Li analysis. A constant depth for the imaginary and spin-orbit potentials as well as the r_s radius have been assumed in this respect for energies above 14.7 MeV. For the remaining geometry parameters a_D, r_{SO} and a_{SO}, the corresponding values found from the d+^{6}Li analysis at 50 MeV have been considered (see Figure 3).
Additional comments should concern the particular as well as average strengths of the spin-orbit potential obtained in the present work, in order to describe the backward scattering part of the deuteron angular distribution. Thus, at lowest incident energies below, e.g., 10 MeV their values are several times higher than the typical ones[23], while the geometry parameters r_{SO} and a_{SO} have the usual phenomenological values and behaviour[24]. Actually, high values of the spin-orbit potential strength for ^{7}Li from 1 to ~ 10 MeV[14,15] have already been pointed out by Abramovici *et al*.[14]. We have found similar values by analyzing their data for ^{6}Li (Figure 3), while for higher energies starting from 11.8 MeV the V_{SO} values become consistent with the results of Daehnick et al.[24], i.e. the typical phenomenological ones.

The elastic scattering angular distributions calculated by using this average parameter set of the imaginary surface and spin-orbit potentials in addition to the microscopic DF real potential are also shown in Figures 1-2, in order to establish the deviations of its predictions from the particular analysis results. One may find these deviations with more than an order of magnitude lower with respect to the predictions of the widely-used deuteron global optical potentials predictions of Lohr-Haeberli[26] and Perey-Perey[27], as shown for both target nuclei ^{6,7}Li (Figures 4-5). Indeed, neither Lohr-Haeberli nor Perey-Perey parameter sets may describe the backward behaviour of the experimental angular distributions with either[26] a spin-orbit depth of 7 MeV or without[27] the OMP spin-orbit component. Thus, it results from Figures 4 and 5 that it is not very successful an extrapolation of these global parameter sets[26,27] to energies and A-target masses outside their data bases, while the OMP given in the present work provides a suitable description of all experimental data for the target nuclei ^{6,7}Li.

The elastic-scattering, reaction, and total interaction cross sections for d+^{6,7}Li

The differences between the present calculation results and the predictions of Lohr-Haeberli and Perey-Perey OMP global parameter sets, important for calculations of data for which there is an increased interest from applications purposes[1], concerning their predictions for elastic-scattering, reaction, and total interaction cross sections of d+^{6,7}Li are shown in Figure 6. It is why our goal has been a systematic optical model description of the deuteron interaction with ^{6,7}Li target nuclei, leading to reliable elastic, reaction, and total cross sections values over a broad range of incident energies from 1 to 50 MeV.

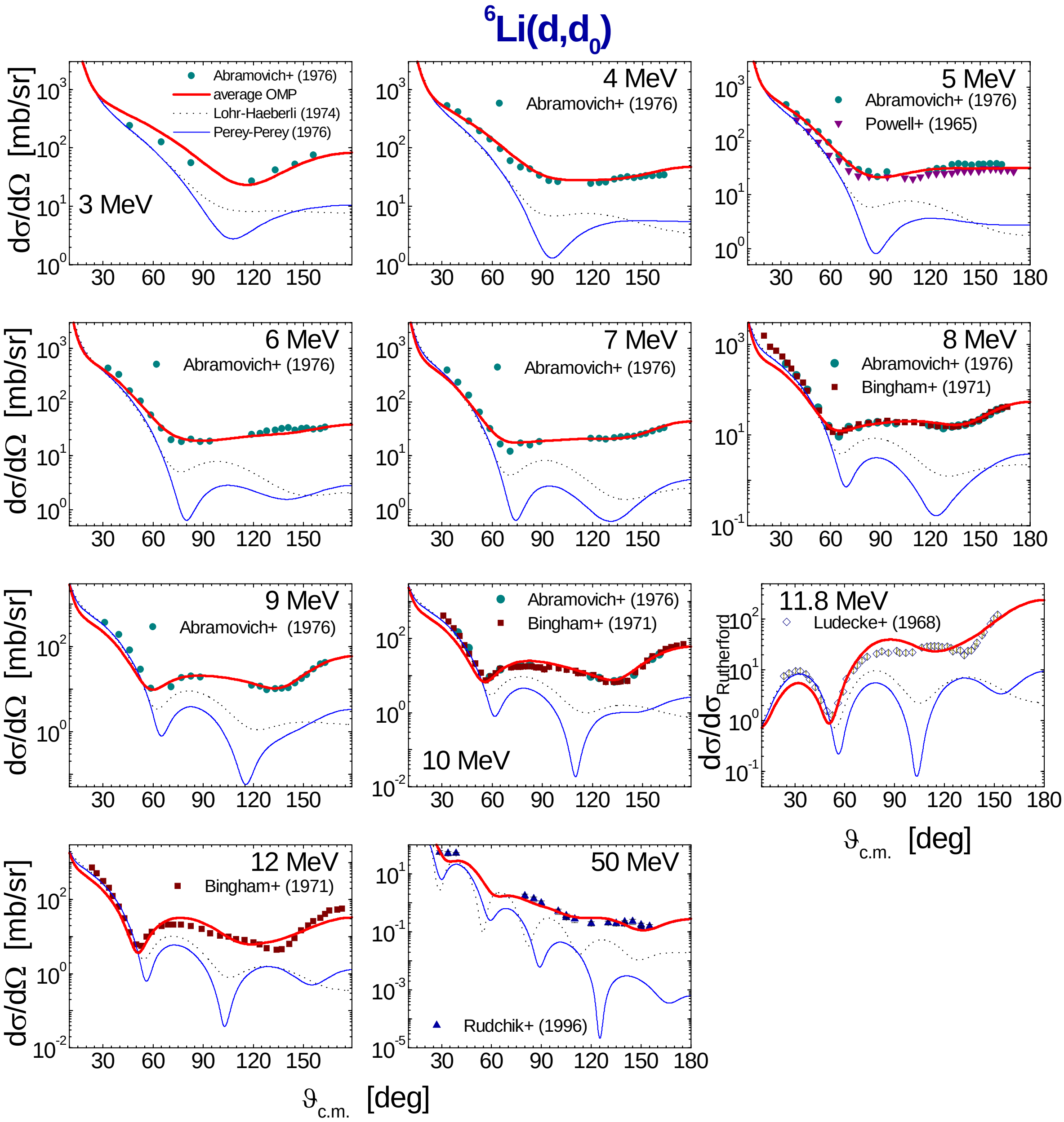


Figure 4. The same as in Figure 1, by using the present microscopic DF real potential and average imaginary surface and spin-orbit potentials (thick solid curves) as well as the OMP global parameter sets of Lohr-Haeberli[26] (dotted curves) and Perey-Perey[27] (thin solid curves).

Conclusions

The analysis of the deuterons elastic scattering on ^{6,7}Li nuclei at energies from 1 to 50 MeV has been performed by using the microscopic DF real potential and phenomenological imaginary surface and spin-orbit potentials. A comparison of the calculated results with the bulk of experimental elastic scattering angular distributions has provided particular values of imaginary surface and spin-orbit potential parameters for each incident energy and Li isotope. Their analysis has provided average parameter values for deuterons interaction with ^{6,7}Li nuclei.

By using the real DF potential the number of free parameters were decreased, while the accuracy of the results increases adjusting only the imaginary as well as the spin-orbit potential parameters.

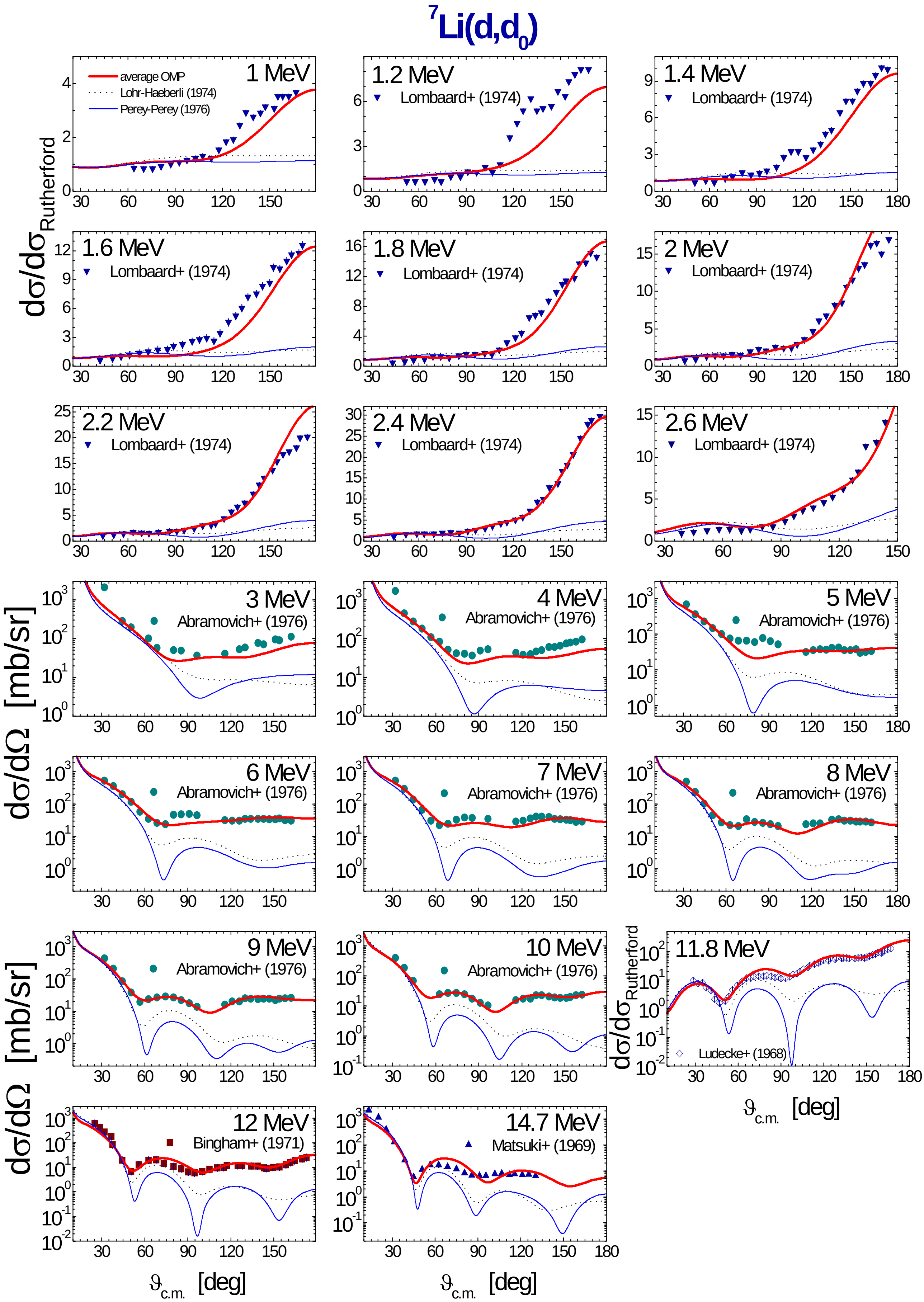


Figure 5. The same as in Figure 2, by using the same phenomenological OMP parameter sets as in Figure 5.

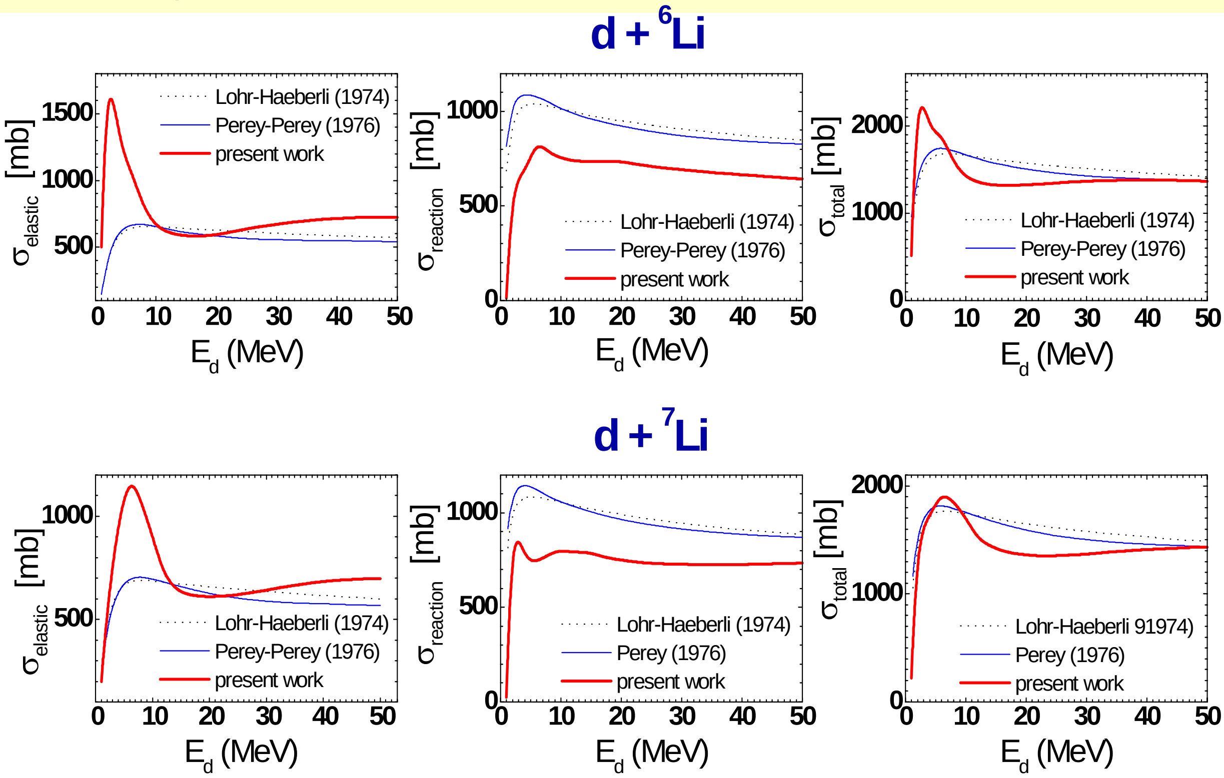


Figure 6. Comparison of the elastic, reaction and total cross sections for d+^{6,7}Li calculated by using the microscopic DF real potential and average imaginary surface and spin-orbit potentials (thick curves), and the OMP global parameter sets of Lohr-Haeberli[26] (dotted curves) and Perey-Perey[27] (thin solid curves).

Altogether the results of this analysis[28] support the concept to reduce the phenomenological part for the potentials to describe deuteron scattering data by the use of microscopic calculations. Finally, the microscopic DF real potential and the energy-dependent phenomenological imaginary and spin-orbit parts, which were obtained from the analysis of the systematics of the experimental elastic scattering angular distributions, have been used to complete the Deuterium-Lithium cross section calculations for energies up to 50 MeV. These results have been made available and used for to update the FZK/INPE evaluated data files[29].
However, having already determined the average imaginary and spin-orbit potentials, further work should concern the adjustment of only the real phenomenological potential parameters while the imaginary and spin-orbit components remains unchanged from the present work. This last step should be performed, as in the α-particle case[6], in order to provide a full average parameter set which can be more easily used in further analyses or still missing predictions of deuteron interaction with ^{6,7}Li. On the other hand, additional experimental data to guide and benchmark the model calculations at incident energies above 15 MeV are strongly requested.
Furthermore, similar attention should be paid to OMPs for reaction channels of the deuteron interaction with ^{6,7}Li target nuclei. A detailed analysis is thus needed for optical model potentials corresponding to the important reaction channels involving neutrons, protons and α-particles.

Forecast progress for next year

Development of a phenomenological real potential part while the present imaginary potential will remain unchanged, with analysis freedom degrees and results uncertainty well decreased.

Publications:

Journal papers

1. **Avrigeanu M ., Fischer U., and Avrigeanu V.** (to be submitted for publication).

Reports

2. **Avrigeanu M., Fischer U., Pereslavtsev P.E., and Avrigeanu V.**, Report EFFDOC-887, NEA/OECD Paris, 2003.

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(EXFOR stands for the EXchange FORmat data file system in use at the Nuclear Data Section of the IAEA-Vienna).

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