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Transfer reaction code with nonlocal interactions☆

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ABSTRACT

We present a suite of codes (NLAT for nonlocal adiabatic transfer) to calculate the transfer cross section for single-nucleon transfer reactions, (d, N) or (N, d), including nonlocal nucleon–target interactions, within the adiabatic distorted wave approximation. For this purpose, we implement an iterative method for solving the second order nonlocal differential equation, for both scattering and bound states. The final observables that can be obtained with NLAT are differential angular distributions for the cross sections of $A(d, N)B$ or $B(N, d)A$. Details on the implementation of the T-matrix to obtain the final cross sections within the adiabatic distorted wave approximation method are also provided. This code is suitable to be applied for deuteron induced reactions in the range of $E_d = 10$–70 MeV, and provides cross sections with 4% accuracy.

Program summary

Program title: NLAT

Catalogue identifier: AFAY_v1_0

Program summary URL: http://cpc.cs.qub.ac.uk/summaries/AFAY_v1_0.html

Program obtainable from: CPC Program Library, Queen's University, Belfast, N. Ireland

Licensing provisions: GNU General Public License, version 3

No. of lines in distributed program, including test data, etc.: 662136

No. of bytes in distributed program, including test data, etc.: 15253066

Distribution format: tar.gz

Programming language: Fortran 90.

Computer: Dell Poweredge R620 (Intel XEON E5-2650v2) 2.9 GHz Intel Core i5.

Operating system: Linux (Debian 7) Mac OSX.

RAM: Around 3 GB

Classification: 17.8, 17.9, 17.11, 17.16.

Nature of problem:
Calculates cross sections for deuteron induced single-nucleon transfer reactions using nonlocal potentials within the adiabatic distorted wave approximation.

Solution method:

See 'Nature of problem'.

Running time:
Less than 2 hours. See sample output files without extension for indication of time taken.

☆ This paper and its associated computer program are available via the Computer Physics Communication homepage on ScienceDirect (http://www.sciencedirect.com/science/journal/00104655).

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1. Introduction

Transfer reactions are a standard probe in nuclear physics. Single-nucleon transfer in particular provides information concerning the spin and parity of single-particle states of the desired nucleus, as well as the probability associated with specific configurations. For this reason, these reactions are widely used in our field. Transfer reactions induced by deuterons are especially appealing because the scattering problem can be cast as a three-body problem involving only nucleon–target interactions and the well-known NN interaction. Nevertheless, solving the three-body scattering problem $n + p + A$ exactly (e.g. [1]) is computationally intensive, and an alternative method has been proposed [2]. This method, referred to as the adiabatic distorted wave approximation (ADWA), includes deuteron breakup to all orders, compares well with the exact approach [3], and has been successfully used to analyze several experiments (e.g. [4,5]).

The effective interactions between the nucleon and the composite target are a critical input to the transfer problem in ADWA. These so-called optical potentials are often extracted from elastic scattering data and made local and strongly energy dependent. However, from the microscopic point of view, it is understood that they should be nonlocal. Several studies have now demonstrated that the resulting transfer cross sections are indeed very sensitive to nonlocality [6–8]. As microscopic approaches to the optical potential become better suited to describe the scattering process for the isotopes of interest, it is important for the nuclear community to have access to codes that allow for the explicit inclusion of nonlocality in the optical potentials. This is the purpose of the current work. The code NLAT (NonLocal Adiabatic Transfer) provides transfer cross sections for (d, N) or (N, d) processes in the adiabatic distorted wave approximation. It does that through solving integro-differential wave equations through an iterative method and constructing a T-matrix with the wave functions resulting from the explicit inclusion of nonlocality.

This paper is organized in the following way. In Section 2 we describe the T-matrix needed to compute the transfer cross sections. In Section 3 we provide a brief description of the adiabatic distorted wave approximation along with the final expressions that were implemented in NLAT for the deuteron adiabatic distorted wave. In Section 4 we specify the wave functions that enter our transfer calculation, and in Section 5 we describe in detail the numerical method used for solving the integro-differential equation for both scattering and bound states. Computational checks on NLAT are provided in Section 6 and a guide to using the NLAT package is presented in Section 7. Finally, we summarize and draw our conclusions in Section 8.

2. Calculating the cross section for transfer

The standard way to obtain the cross section for a single-nucleon transfer reaction is through the exact T-matrix [9]. This quantity relates directly to the scattering amplitude, that when squared provides the differential cross section. We thus proceed with the exact T-matrix written in post-form [9]: the post-form is most convenient for (d, N) reactions. We will also neglect the remnant term for simplicity. This term has an insignificant effect for reactions on intermediate mass and heavy nuclei (e.g. [8]). For the sake of clarity, we will focus all our formulation on (d, p) although a trivial reorganization of indices provides the results for the corresponding (d, n) reactions.

The exact post-form T-matrix for the $A(d, p)B$ reaction is written as:

$$T_{\mu_A M_d \mu_p M_B}(\mathbf{k}_f, \mathbf{k}_i) = \langle \Psi_f^{\mu_p M_B} | V_{np} | \Psi_i^{\mu_A M_d} \rangle, \tag{1}$$

where M_d, μ_p, μ_A, and M_B are the projections of the spin of the deuteron, the proton, the nucleus A, and the nucleus B, respectively. The T-matrix is related to the scattering amplitude by:

$$f_{\mu_A M_d \mu_p M_B}(\mathbf{k}_f, \mathbf{k}_i) = -\frac{\mu_f}{2\pi\,\hbar^2}\sqrt{\frac{v_f}{v_i}}\,T_{\mu_A M_d \mu_p M_B}(\mathbf{k}_f, \mathbf{k}_i), \tag{2}$$

with the velocity factors given by $v_{i,f} = \hbar k_{i,f}/\mu_{i,f}$, the wave number $k_i = \sqrt{2\mu_{i,f}E_{i,f}/\hbar^2}$, $\mu_{i,f}$ the reduced mass, and $E_{i,f}$ the center of mass energy in the entrance or exit channel. The differential cross section is found by averaging the modulus squared of the scattering amplitude over initial projections, and summing over final projections,

$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{1}{\hat{J}_d^2 \hat{I}_A^2} \sum_{\mu_A M_d \mu_p M_B} \left| f_{\mu_A M_d \mu_p M_B}(\mathbf{k}_f, \mathbf{k}_i) \right|^2 \\ &= \frac{k_f}{k_i}\frac{\mu_i \mu_f}{4\pi^2\,\hbar^4}\frac{1}{\hat{J}_d^2 \hat{I}_A^2} \sum_{\mu_A M_d M_B \mu_p} \left| \langle \Psi_f^{\mu_p M_B} | V_{np} | \Psi_i^{\mu_A M_d} \rangle \right|^2, \end{aligned} \tag{3}$$

where we define the quantity $\hat{X} = \sqrt{2X+1}$.

We first focus on the initial state which describes the three-body scattering between $d + A$. As we briefly describe in Section 3, the entrance channel wave function in the adiabatic distorted wave approximation can be expanded as:

$$\begin{aligned}|\Psi_i^{M_d \mu_A}\rangle &= \frac{4\pi}{k_i}\sum_{L_i J_{P_i}} i^{L_i} e^{i\sigma_{L_i}}\, \Xi_{I_A \mu_A}(\xi_A)\phi_{j_i}(r_{np})\frac{\chi_{L_i J_{P_i}}(R_{dA})}{R_{dA}}\frac{\hat{J}_{P_i}}{\hat{J}_d}\left\{ \tilde{Y}_{L_i}(\hat{k}_i) \otimes \left\{ \left\{ \Xi_{I_p}(\xi_p) \otimes \left\{ \tilde{Y}_{\ell_i}(\hat{r}_{np}) \otimes \Xi_{I_n}(\xi_n) \right\}_{j_i} \right\}_{J_d} \otimes \tilde{Y}_{L_i}(\hat{R}_{dA}) \right\}_{J_{P_i}} \right\}_{J_d M_d} \\ &= \Xi_{I_A \mu_A}(\xi_A)\phi_{j_i}(r_{np})\chi_i^{(+)}(\mathbf{k}_i, \mathbf{r}_{np}, \mathbf{R}_{dA}, \xi_p, \xi_n), \end{aligned} \tag{4}$$

where $\Xi_{I_p}(\xi_p)$, $\Xi_{I_n}(\xi_n)$ and $\Xi_{I_A}(\xi_A)$ are the spin functions for the proton, neutron, and target, respectively, each with projections μ_p, μ_n, and μ_A. $\tilde{Y}_{\ell_i}$ is the spherical harmonics for the relative motion between the neutron and proton in the deuteron, and $\tilde{Y}_{L_i}$ is the spherical harmonic for the relative motion between the deuteron and the target ($\tilde{Y}_{\ell_i} = i^{\ell_i} Y_{\ell_i}$ with Y_{ℓ_i} defined on p. 133, Eq. (1), of [10]).