HORIZON 2020

Research Infrastructures

H2020-INFRAIA-2014-2015

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ENSAR2

European Nuclear Science and Application Research 2

Grant Agreement Number: 654002

D11.2 - Codes for transfer and CDCC calculations with core excitation

Version: 1.1
Author: A.M. Moro, R. de Diego, M. Gómez-Ramos, J.A. Lay
Date: 27/02/18

PROJECT AND DELIVERABLE INFORMATION SHEET

ENSAR2 Project Ref. №	654002
Project Title	European Nuclear Science and Application Research 2
Project Web Site	http://www.ensarfp7.eu/
Deliverable ID	D11.2
Deliverable Nature	Computer code
Deliverable Level*	PU
Contractual Date of Delivery	28 February 2018
Actual Date of Delivery	27 February 2018
EC Project Officer	Mina Koleva

* The dissemination level are indicated as follows: PU – Public, PP – Restricted to other participants (including the Commission Services), RE – Restricted to a group specified by the consortium (including the Commission Services). CO – Confidential, only for members of the consortium (including the Commission Services).

DOCUMENT CONTROL SHEET

Document	Title: Codes for transfer and CDCC calculations with core excitation	
	ID: D11.2	
	Version: 1.1	
	Available at: github.com repository	
	Software Tool:	
	File: ENSAR2_deliverable_D11.2	
Authorship	Written by:	A.M. Moro, R. de Diego, M. Gómez-Ramos, J.A. Lay.
	Contributors:	J.M. Arias, J. Gómez-Camacho
	Reviewed by:	Jochen Wambach
	Approved by:	

DOCUMENT STATUS SHEET

Version	Date	Status	Comments
0.0	17.01.2018	For internal review	
1.0	14.02.2018	For internal review	
1.1	27.02.2018	Submitted on EC Participant Portal	
		Final version	

DOCUMENT KEYWORDS

Keywords	Coupled-channels, few-body structure and reactions, halo nuclei, particle-rotor model.

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D11.2 Codes for transfer and CDCC calculations with core excitation.

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EXECUTIVE SUMMARY

This report describes the status of the deliverable D11.2 ("*Codes for transfer and CDCC calculations with core excitation*"). These codes are being developed by the Seville nuclear physics group as part of the activities of the JRA3 "TheoS: Theoretical Support for Nuclear Facilities in Europe", one of the Work Packages (WP) of ENSAR2. These codes are related to the task 2 of this WP: "Calculate reaction observables to compare state-of-the-art structure models with novel experimental data in reaction formalisms". They are designed to provide to the nuclear physics community with reliable computational tools incorporating some state-of-the-art reaction models for the evaluation of differential cross sections corresponding to reaction observables commonly measured in reactions involving weakly-bound nuclei (elastic, inelastic, breakup...).

REFERENCES AND APPLICABLE DOCUMENTS

We list here the references of works published in conecction with the development or applications of this deliverable, since the starting of the project (March 2016)

[1] M. Gómez-Ramos and A.M.Moro, *Interplay of projectile breakup and target excitation in reactions induced by weakly bound nuclei*, Phys.Rev. C 95, 034609 (2017).

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LIST OF ACRONYMS AND ABBREVIATIONS

CDCC	Continuum-discretized coupled-channels
XCDCC	Extended Continuum-discretized coupled-channels
LST	Local scale transformation
PRM	Particle-rotor model
PVM	Particle-vibrator model
DWBA	Distorted Wave Born Approximation

INTRODUCTION

The main objective of TheoS is to provide a strong and reliable theoretical support to the experiments that will be performed at the TA's of ENSAR2, including the projects FAIR, SPIRAL2 and ELI-NP. The groups conforming TheoS are based at Brussels (ULB), Milano (University of Milano), Catania (INFN), Paris-Orsay (CNRS), and Seville (University of Seville).

The present deliverable is linked to Task 2, namely:

Task 2: Calculation of reaction observables to compare state-of-the-art structure models with novel experimental data in exotic nuclei.

which, in turn, involves the following subtasks:

Subtask 2.1: Development of new reaction formalisms.

Subtask 2.2: Improvement of the interface between nuclear structure and nuclear reactions.

Within the scope of these tasks, the Seville group has been working in several developments of existing reaction formalisms in order to extend their applicability and improve their structure inputs.

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Some recent developments are as follows:

I) The inclusion of target excitations concomitant with deuteron breakup in transfer reactions of the form A(d,p)B have been investigated using an extended version of the distorted-wave Born approximation (DWBA) [Phys.Rev. C 92, 014613 (2015), Phys. Rev. C 95, 044612 (2017)].

ii) The effect of the projectile fragment's excitations in breakup reactions induced by two-body weakly-bound nuclei: a+A→ (b+x)+A (including "b" and/or "x" excitations) has been investigated and calculations have been performed and published for several reactions induced by the halo nuclei ^{11}Be [Phys. Rev. C 89, 064609 (2014)] and ^{19}C [Phys. Rev. C 94, 021602 (2016)].

iv) A formalism for the evaluation of three-body observables (i.e., angular and energy distribution of the emitted fragments) from CDCC calculations with core excitations has been developed and implemented [Phys. Rev. C 95, 044611]. This task has been done in collaboration with researchers from the University of Lisbon, one of the partners of TheoS.

These theoretical achievements have required the development of appropriate computational tools. The deliverable D11.2 consists of two codes: one for transfer reactions and another for breakup reactions. The code for transfer reactions, while operational, is still under development and requires some further work to make it sufficiently user-friendly in order to be distributed publicly. We focus here on the code for breakup reactions, which is in a more advanced stage of development and ready for public usage.

THEORETICAL BACKGROUND

Nuclei in the proximity of the proton and neutron drip-lines are often weakly bound, or even unbound, and hence their properties are influenced by positive-energy states. Collisions of these systems with stable nuclei will also be influenced by the coupling to the unbound states. This effect was first investigated in deuteron-induced reactions, and later observed in the scattering of other loosely bound nuclei, such as halo nuclei. Several formalisms have been developed to account for the effects of the coupling to breakup channels on reaction observables: Continuum-Discretized Coupled-Channels (CDCC) method [Aus87], the adiabatic approximation, the Faddeev/AGS equations [Fad60], and several semi-classical approximations.

The standard CDCC method considers the collision of a two-body projectile by a target nucleus. This constitutes a complicated three-body scattering problem, whose rigorous solution if provided by the Faddeev equations. The CDCC method seeks for an approximate solution of this problem in a truncated model space. This model space is composed by the projectile bound two-body bound and a discrete representation of the continuum states. To make the number of states finite, the continuum is truncated in energy and angular momentum. The total wave function of the system is then expanded in this truncated two-body basis. When inserted into the Schrodinger equation, $[H-E]\Psi=0$, this gives rise to a set of coupled differential equations, which are to be solved under appropriate scattering boundary conditions. The method provides the elastic, inelastic and breakup differential cross sections and has been successfully applied to many systems, such as deuterons, ^{6}Li (alpha+d), ^{7}Li (alpha+t), and ^{11}Be (^{10}Be+n), among others.

The original formulation of the CDCC method, as well as other few-body formalisms, ignores possible excitations of the constituent clusters. While this approximation can be well justified in the case of deuteron scattering, it is more questionable for more complex systems. For example, it is well known from experimental and theoretical studiesthat the ^{11}Be states contain significant admixtures of ^{10}Be excited states. These configurations are completely ignored in the traditional CDCC method. The purpose of the extended CDCC method (XCDCC) is to include these "core-excited" components in the structure of the projectile nucleus, as well as the possibility of core excitation and de-excitation during the reaction process. This extension has been carried out by two different groups. Summers, Nunes and Thompson [Sum06] employed a binning discretization procedure, in which the discrete continuum states are described by wave packets generated from the multichannel scattering states of the valence+core system. The other implementation [Die14], due to the nuclear physics group based at Seville, employed a pseudo-state (PS) discretization procedure, in which the projectile (two-body) Hamiltonian is diagonalized in a truncated basis of square-integrable functions. Although both methods should be equivalent, each of them results more advantageous than the other depending on the reaction and on the observables to be calculated. For example, the PS method has been shown to be particularly useful to describe resonant breakup [Lay16], whereas the binning procedure has proven more stable to describe reactions of halo nuclei on heavy targets [Pes17].

DESCRIPTION OF THE CODE

TREX is a self-contained coupled-channels fortran code that solves the a three-body scattering problem consisting on a two-body projectile impinging on a target nucleus using the Continuum-Discretized Coupled-Channels (CDCC) formalism [Aus87]. A key feature of this code is the possibility of including collective excitations of the projectile constituents (commonly referred to as «core excitations»). These capabilities are done with appropriate extensions of the CDCC formalism [Sum06,Die14].

Two different continuum discretization methods are used: a pseudo-state method (PS) and a binning method. In the former method, the code diagonalises the projectile two-body Hamiltonian in a Transformed Oscillator Basis (THO). This basis is obtained by applying a suitable analytical local scale transformation (LST) to the harmonic oscillator wave functions [Lay12]. In the binning method, continuum states are obtained as a linear superposition (i.e. a wave packet) of the scattering states of the two-body projectile [Aus87,Sum06].

In addition to the single-particle (few-body) excitation between the clusters, possible collective excitations of these clusters can be included. This permits, for example, the description of the projectile states in terms of the particle-plus-rotor (PRM) and particle-plus-vibrator models (PVM). To account for the possible excitation and de-excitation of the clusters during the reaction, a deformed potential can be used between the clusters and the target.

To solve the scattering problem, the code computes first the coupling potentials between the considered projectile states. These coupling potentials are later used to solve the system of coupled differential equations, using either the Numerov or the R-matrix methods. An algorithm of stabilization is also included, which is particularly suitable for situations for which linear independence is partially lost due to numerical instabilities, as it happens when closed-channels are included.

As in other coupled-channels codes, such as the popular code FRESCO [Tho88], the code TREX provides differential cross sections for each included state as a function of the projectile c.m. scattering angle. Three-body observables, i.e., cross sections as a function of the energy and/or angle of the projectile constituents emitted after the breakup are also computed by means of an appropriate transformation of the computed two-body scattering amplitudes [Die17].

In addition to the scattering calculations, the program can be used to study several properties of the projectile, such as: bound-state eigenvalues and wave functions, scattering state wave functions and phase-shifts and reduced electric transition probabilities [B(Eλ)].

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STATUS

The status of the D11.2 delilverables is as follows:

D11.2 Codes for transfer and CDCC calculations with core excitation.

- The DWBA code with core excitations has been concluded and successfully applied to some reactions (see publications above). However, it is not in a user-friendly stage and lacks a proper documentation. These pending issues will be concluded in the following months and we will report on them in the next periodic report.

- A first version of the CDCC code with core excitations is available and ready for use by the community. It will be placed at the gibhub repository, which is a convenient way of distributing and updating it with the newest versions. Further extensions of the code are planned for the near future and will be reported in subsequent status reports, and updated in the online repository.