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REFERENCES AND APPLICABLE DOCUMENTS

Bellow are the references published during the project in direct connection with the deliverable.

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LIST OF ACRONYMS AND ABBREVIATIONS

DEA	Dynamical eikonal approximation
EFT	Effective field theory
CDCC	Continuum-discretised coupled-channels
OLA	Optical limit approximation
RIB	Radioactive-ion beam

Executive Summary

This report presents the status of the deliverable D11.3 (« *Eikonal-based code to describe dynamical effects in scattering, breakup and knockout reactions* »). This deliverable aims at producing computer codes to describe nuclear reactions, like elastic scattering and breakup, measured at radioactive-ion beam (RIB) facilities to study the exotic nuclear structure of halo nuclei. These codes are based on the eikonal approximation and its extensions and aim at improving the analysis of the aforementioned experiments to improve our understanding of nuclear structure away from stability. They have been developed within the group of theoretical nuclear physics at the Université libre de Bruxelles (ULB) in Brussels, Belgium, which collaborates to the JRA « TheoS: Theoretical Support for Nuclear Facilities in Europe », one of the Work Packages (WP) of ENSAR2. They contribute 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 ».

Introduction

TheoS aims at providing a reliable support to the experiments performed within the various TNAs of ENSAR2. This JRA is composed of five nodes: CNRS Paris-Orsay (France), University of Seville (Spain), University of Milan (Italy), INFN Catania (Italy), and Université libre de Bruxelles (ULB, Belgium).

The goal of task 2 of TheoS is to perform « Calculation of reaction observables to compare state-of-the-art structure models with novel experimental data in exotic nuclei ». It is decomposed into two subtasks. **Subtask 2.1 is the** « Development of new reaction formalisms », while **Subtask 2.2 aims at the** « Improvement of the interface between nuclear structure and nuclear reactions ».

The present deliverable addresses both subtasks within the framework of the eikonal approximation. Three lines of developments have been followed:

1. the extension of the eikonal approximation down to low energies, viz. 10*A*MeV, now reachable at HIE-ISOLDE (CERN);

2. the development of a relativistic correction to allow the description of reactions at beam energies up to 600AMeV, such as the ones measured at GSI/FAIR;

3. include a Halo-EFT description of the projectile within eikonal codes of reactions to account for the output of *ab initio* nuclear-structure calculations within state-of-the-art models of reactions.

The first two items of this deliverable have led to the development of new codes of reactions, while the third one has been embedded in existing computer programs. As explained below, none of the extensions tested so far has proven to satisfactorily improve the eikonal approximation at low energy for both elastic scattering and breakup. We have therefore decided not to publish these codes. On the contrary, the development of a relativistic correction has enabled us to reproduce the existing data on the breakup of ^{11}Be on both Pb and C targets at about 520*A*MeV and ^{15}C on Pb at 605*A*MeV. This suggests that the relativistic effects are properly included in the code. Unfortunately, being not user-friendly, it is not yet at the level of a code that can be distributed for a public usage. We plan to do that once all our tests have been achieved, i.e. within a few months. Since it requires no complex developments, a Halo-EFT description of the projectile has been included in both codes from the start of their development.

LOW-ENERGY CORRECTIONS TO THE EIKONAL APPROXIMATION

The eikonal approximation is a high-energy model of reactions, in which the projectile-target relative motion is assumed not to deviate much from the initial plane-wave motion [1]. Within a semiclassical interpretation of this approximation, the projectile is thus seen as following a straight-line trajectory along which its wave function accumulates a complex phase. This eikonal phase simulates its interaction with the target. This significantly simplifies the Schrödinger equation that needs to be solved to model the reaction and hence leads to much shorter computational times compared to other reaction models such as the continuum-discretised coupled-channel method (CDCC) [2]. Moreover, albeit simplifying, its semiclassical interpretation enables a clear analysis of the collision and hence helps better understand the reaction mechanism.

For all these reasons, it would be useful if this approximation could be used for all measurements. Unfortunately, it is restricted to intermediate and high beam energies, viz. above 40*A*MeV. Recently, a simple semiclassical correction of the eikonal approximation for Coulomb-dominated reactions, i.e. on heavy targets, has been shown to provide excellent results for the breakup of one-neutron halo nuclei down to at least 20*A*MeV [3]. In that correction, the impact parameters of the eikonal straight-line trajectories are replaced by the distance of closest approach computed on the corresponding Coulomb trajectory [4]. This elegant and successful Coulomb correction has led us to the search of similar ways to improve the description of nuclear-dominated reactions, i.e. on light targets.

We have first considered the expansion suggested by Wallace that extends the range of validity of the eikonal approximation [5]. Unfortunately, only marginal improvement for the elastic-scattering could be reached through this correction [6,7]. Taking a leaf out of the book of Fukui *et al.* [3], we have then studied semiclassical corrections in which the impact parameter of the eikonal straight-line trajectory is replaced by the distance of closest approach of the trajectory computed with both the Coulomb and nuclear interactions between the projectile and the target. The nuclear interaction is usually simulated by optical potentials, which contain, in addition to their real part, an imaginary part that simulates the absorption from the elastic channel due to other open reaction channels. In a first attempt, we have considered only the real part of the optical potential to compute a classical trajectory for the projectile and its distance of closest approach to the target. However, replacing the actual impact parameter by this distance actually worsen the eikonal calculation [7], leading to too large a cross section compared to exact calculations. Generalising Ref. [8] to two-body projectiles, we have then considered a complex distance of closest approach, whose imaginary part simulates the absorption missing in the previous correction. This improves the description of the elastic scattering of weakly bound two-body projectiles on light targets [6], however it was not sufficient to reproduce the accurate CDCC calculations of the breakup of the projectile [9]. This results shows that such a semiclassical correction is not sufficient to fully grasp the complexity of the collision at low energy.

Following a suggestion of Tostevin, we have then considered yet another correction, in which the eikonal phase is replaced by the actual phase shift computed quantum mechanically [10]. This correction provides the best estimate of the elastic-scattering cross section within the eikonal framework. However, as the other corrections mentioned above, it is not sufficient to correctly describe the dissociation of two-body projectiles [9].

From these various tests, we conclude that improving the modelling of the scattering within an eikonal description of the collision is not sufficient to fully account for the complexity of the reactions involving loosely bound projectiles, like halo nuclei, at low energy. It seems that more complex corrections need to be considered to properly include the dynamics of the collision at these energies. We have a few ideas on how to proceed and we plan to explore them in the future. However they require developments that go beyond the project initiated within TheoS.

RELATIVISTIC CORRECTIONS AT HIGH ENERGY

As mentioned above, the eikonal approximation is a high-energy model of the reaction and is thus well suited to describe reactions measured at GSI/FAIR, i.e. at and above 400*A*MeV. However, at these energies, relativistic corrections become necessary. To account for them, we have followed Satchler, who has proposed an eikonal approximation derived from the Klein-Gordon equation [11], in which the relativistic kinematics is properly taken into account. One of the issues at these energies is to find proper optical potentials to reliably simulate the nuclear interaction between the projectile—or the projectile constituents—and the target. To circumvent this issue, we have followed Ref. [12] and considered the optical limit approximation (OLA) of the eikonal model [1], which enables us to build the nuclear part of the eikonal phases from a double-folding procedure. Interestingly, Satchler's kinematics choice is consistent with the way the OLA is implemented.

To properly describe the breakup of the projectile during the collision, a special treatment of its Coulomb interaction with the target needs to be considered because the usual eikonal description of Coulomb breakup diverges [13]. For this, we follow this reference and include a first-order correction of the eikonal treatment of that Coulomb interaction. This correction requires the calculation of a matrix element within the projectile centre of mass rest frame, which then needs a proper boost to account for this change of frame [14].

This new model has been first applied to the breakup of ^{11}Be on both Pb and C targets at 520*A*MeV [15], which has been measured at GSI [16]. The results obtained are in excellent agreement with the data, which confirms the validity of our treatment of special relativity within this new reaction model. Interestingly, this good agreement has been obtained using the Halo-EFT description of ^{11}Be fitted on an *ab initio* calculation of this nucleus [17], which has shown an excellent agreement with similar data measured around 70*A*MeV in RIKEN [18,19] (see next section). In addition to confirming the quality of the nuclear-structure observables predicted by the *ab initio* calculation, this nice result solves the apparent inconsistence in the $dB(\mathrm{E}1)/dE$ extracted from both experiments [17]. This development has thus enabled us to solve this long-standing issue.

Following this initial success, we have applied this model to describe the Coulomb breakup of ^{15}C [20], which has been measured by the same group at 605*A*MeV [21]. As for ^{11}Be, thanks to this new model of reactions and using one single Halo-EFT description of ^{15}C we have been able to describe simultaneously a wide range of data: the aforementioned GSI experiment [20], the RIKEN data measured at 70*A*MeV [22], ^{14}C(d,p)^{15}C transfer cross sections [23,24], and the ^{14}C(n,γ)^{15}C radiative capture [25].

In the near future, we plan to use this model to theoretically study other reactions measured at GSI and RIKEN at high energy, at which these corrections need to be considered (see, e.g., Refs. [26,27]).

INCLUSION OF HALO-EFT IN ACCURATE REACTION MODELS

Halo nuclei exhibit a very exotic structure in which one or two loosely bound neutrons can be found at a large distance from the other nucleons. They hence form a sort of diffuse halo around the compact core of the nucleus. Although qualitatively understood as resulting from the quantum tunnelling of these valence nucleons in the classically forbidden region, they challenge microscopic nuclear models. Only recently could they be described *ab initio* [17].

Despite their unusual structure, halo nuclei can be phenomenologically described by taking into account their strongly clusterised structure, seeing them as one (or two) neutron(s) loosely bound to a structureless core. The clear separation of scales between the large halo size and the compactness of the core enables the use of an effective field theory (see Ref. [28] for a recent review). The low-energy constants of this Halo-EFT can be fitted on actual data, like the neutron-core binding energy, or predictions from nuclear-structure theory, like the asymptotic normalisation constant.

In Ref. [18], we have implemented this new effective structure model within the dynamical eikonal approximation (DEA) [29]. As mentioned in the previous section, this Halo-EFT was systematically included in all our recent developments of reaction models. The results obtained show excellent agreement with the breakup data [18] measured at RIKEN [19]. Including the same Halo-EFT description of ^{11}Be within the relativistic code described in the previous section, we have obtained an excellent agreement with the GSI data [15,16]. This shows that Halo-EFT is an efficient way to bridge accurate nuclear-structure calculations and reaction models. Moreover, it also naturally enables us to estimate the degrees of freedom in the projectile description that matter to properly describe the reaction [28,18]. The inclusion of such description of the projectile in reaction models is thus an asset in the analysis of experiments performed at RIB facilities. Moreover, since it requires very little change in the computer program, it is simple to implement.

So far, we have successfully used this model in exclusive reactions: breakup, transfer and radiative-capture (see previous section). In the near future, we plan to extend this description of the projectile to inclusive reactions, like knockout.

Conclusion

In this deliverable of the Task 2 of the TheoS JRA of ENSAR2, we have worked on the eikonal description of reactions involving halo nuclei to improve the analysis of measurements performed in RIB facilities, and in particular the TNAs within ENSAR2.

Our efforts to extend this description of nuclear reactions towards low energies have unfortunately been unsuccessful. Most of the corrections studied here provide a correct description of the elastic-scattering channel [6,7], but they cannot properly account for the dynamics of the reaction in the breakup channel [9]. For this reason, we do not plan to publish the code in which they have been implemented.

On the contrary, a very successful result has been obtained in the inclusion of efficient relativistic correction within an eikonal code [15]. Thanks to this recent development, we have been able to solve the apparent discrepancy between the E1 strength in ^{11}Be extracted from the high-energy GSI data and the intermediate-energy RIKEN experiment. Our predictions for the ^{15}C breakup are also in excellent agreement with the experimental cross sections measured by the same groups [20]. This confirms the validity of this new approach. The code is not yet user-friendly. In the next months, we plan to polish it to provide a robust version that can then be published.

Finally, related to the Subtask 2.2 of the TheoS JRA, we have successfully included a Halo-EFT within accurate reaction codes, which allowed us to include *ab initio* predictions for nuclear-structure properties in reaction calculations [18,15]. This has enabled us to obtain excellent agreement with existing data, confirming the quality of the *ab initio* calculations [17].

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