Institut national de physique nucléaire et de physique des particules

COLLABORATION AGREEMENT

IN2P3 - COPIN

I. Identification of the laboratories	
Partner	COPIN
IN2P3 laboratories	**IPHC**
Partner laboratories	Cracovie (IFJ PAN)

II. Identification of the collaboration	
Title of the collaboration	Advanced Monte-Carlo and GEANT4 simulations for optimizing future experiments dedicated to nuclear dynamics
Number of the collaboration	12-145
IN2P3 spokesperson	C. SCHMITT
COPIN spokesperson	M. CIEMALA
Scientific Domain	Nuclear Physics

Status of the collaboration	
Status	The renewal of the collaboration is requested for the period January 1st - December 31st, 2023

III. Status report for the period January 1st to December 31st, 2022	
III.1 IN2P3 scientists in COPIN	
Total time approved for 2022	20
Total time used for 2022	20
List of scientists	1. C Schmitt (20 days)
III.2 COPIN scientists in France	
Total time approved for 2022	32
Total time used for 2022	30

List of scientists	1. M Ciemala (3 days) 2. A Maj (3 days) 3. M Kmiecik (3 days) 4. K Mazurek (3 days) 5. R Kaminski (3 days) 6. C Mieszczynski (3 days) 7. I Jozwik (3 days) 8. J Jagielski (3 days) 9. J Zejma (3 days) 10. P Jó?wik (3 days)

III.3 Scientific results of the above-mentioned collaboration

Description	

The decay of compound nuclei (CN) produced in heavy-ion collisions permits to study the interplay between static vs. dynamical, and macroscopic vs. microscopic, effects under extreme conditions in temperature and/or angular momentum. On the experimental side, the necessity of measuring various observables, and their correlations, is well established. On the theoretical side, two kinds of calculations are mandatory. Obviously, interpretation of the measurement has to rely on as realistic as possible model calculations, namely because experiments are often inclusive. In addition, due to necessarily limited detection efficiency, simulations of the experimental arrangement are required for an unbiased analysis. Calculations of both the physics process and the influence of experimental conditions are also mandatory for planning and assessing the sensitivity of new measurements.

Since the beginning of our collaboration, we performed a two-fold investigation in the aforementioned directions, with: i) a theoretical study of the complex interplay between various features affecting the decay of excited rotating nuclei, and ii) the development of advanced simulations to define the optimal experimental set-up for addressing a specific physics case. In both types of calculations, we adopt the Monte Carlo approach. While the scheme is rather general, our main motivation is set in the context of studies employing the PARIS gamma-array [1]. The work is therefore performed in close connection with the associated experiments. The focus of the collaboration during the past year is developed below. The achievement by our collaboration was presented at international workshops and at various seminars. Publications in peer-reviewed journals appeared and still more are in progress.

1) Study of nuclear dynamics within the Langevin approach

Heavy-ion fusion followed by either evaporation or fission is a relevant reaction mechanism for probing nuclear dynamics, as well as its connection with, and dependence on, nuclear structure. Yet, it still remains to be determined what are most sensitive signatures of specific dynamical or structural aspects, and how to access them un-ambiguously in experiment. To do so, within our collaboration, we use a stochastic approach based on the transport theory. The dynamical (time) evolution of the system is computed by solving a four-dimensional (4D) Langevin classical equation of motion coupled to particle evaporation, within a Monte Carlo framework [2]. Since the beginning of our collaboration, we performed various investigations with, and development of, the Omsk code implementing the Langevin approach [3-7]. Based on our previous results [8] about the influence of excitation energy (E*) and angular momentum (L) in the Businaro-Gallone region, we recently enlarged the investigation to a wider CN fissility domain and to various projectile-target combinations, with the attempt to unfold the respective influence of the fusion and fission stages on typical fission observables. We proposed a multi-dimensional analysis of the respective role of entrance-channel asymmetry, bombarding energy, compound-nucleus fissility, angular momentum and excitation energy [9] by combining the Langevin fission code with the dynamical HICOL fusion code. We demonstrated the possibility of delicate compensation effects in governing the measured fission observables, and the need of a multi-dimensional survey to ensure robust conclusions. Our observations showed able to explain previous apparent unresolved inconsistencies. In the line of tracking entrance-channel effects, we most recently enlarged our scope by considering as well quasi-fission reactions. In experiment, discrimination between compound-nucleus (i.e. fusion) fission and quasi-fission events is hard, what substantially hampers the understanding of heavy-ion collision dynamics. Our theoretical model does not calculate quasi-fission. However, it can be used as a reliable estimate of the fusion-fission component, and which can then be subtracted from the measured spectra, and thereby deduce the quasi-fission contribution. In this respect, we proposed a new procedure to isolate the fragment mass and emission angle information pertaining to the sole quasi-fission component. The approach is currently benchmarked [9]. It is expected to provide essential "experimental" information to dedicated models of quasi-fission, and more generally heavy-ion collision dynamics. Based on the idea of Ref. [9], in 2020 we started a widespread theoretical study of the elaborate experimental results in collaboration with the experimentalists of ANU, Canberra. The work is still in progress. With the acceptance in July 2021 of our common experimental proposal to study the energetics of fission with PARIS@VAMOS (see below), a main focus of our theoretical work in 2022 was on the detailed investigation of the de-excitation of the fission fragments. The fragments produced in a fission reaction are typically neutron-rich. Nuclear properties away from stability are poorly known for most of them. A few years ago, Al-Quraishi et al. [10, 11] discussed the dependence of the nuclear-level density (NLD) on isospin, and suggested that it the NLD away from stability might substantially deviate from the prescription validated around stability. During the past years, several studies based on the detection of fusion evaporation residues addressed the isospin dependence of the NLD, triggered by the proposition of Al-Quraishi [12, 13, 14, 15]. Unfortunately, the outcome is still controversial. Since the CN formed in fusion and the fragments produced by fission lie in different isospin regions (being respectively n-poor and n-rich), we propose to use fusion-fission observables as a new route to study the isospin dependence of the NLD, and which would be complementary to the evaporation channel. In 2022 we performed an extended investigation theoretical study in order to proof the relevance of the idea. Our calculations show that the fission channel should be an effective probe of the isospin dependence of the NLD. For so-far available data sets, all using stable beam and target combinations, the fission observables allow excluding some specific NLD prescriptions. Unfortunately, they are not capable to un-ambiguously discriminate between the remaining existing formulas within the experimental and theoretical uncertainties. Our investigations further permitted to propose a list of new reactions involving either radioactive or stable projectiles in order to decide between the aforementioned remaining NLD prescriptions. The pre- and post-scission neutron multiplicities are shown to be particularly efficient quantities in this respect. They can be measured at existing accelerator facilities without major difficulty with the available beam intensities. A manuscript detailing our proposal is in preparation [16]. Finally, we note that, based on our previous-years demonstration [17] of the utility of the Langevin approach for the describing the last stage of heavy-ion reactions at ultra-relativistic energies, we pursued our investigations in this domain looking namely at the properties of fission observables in this energy domain [18].

The PARIS array [1], under-completion, will be particular well suited to study “L-driven” effects as well as the tagging of quasi-fission events by means of the accurate measure of the prompt-fission gamma-rays. Therefore, calculations of the kind of [8, 9] are used within our collaboration to support proposals for experiments with PARIS at various facilities. The relevance of the idea was corroborated in Ref. [19]. We consequently elaborated at the end of 2021 a proposal dedicated to the investigation of the fusion-fission, fast fission and quasi-fission processes of pre-actinide and actinide compound systems formed in the reactions with 28Si ion beams [20]. The proposal was accepted at the IJCLab PAC in 2022, and the experiment may be scheduled in 2023 or 2024.

Finally, in 2021 we had proposed an experimental campaign using PARIS coupled with the VAMOS heavy-ion spectrometer of GANIL, in order to measure the properties of the prompt gamma-ray spectrum over a wide dynamical range, vz. covering the statistical and discrete radiations emitted in fission at moderate excitation energies. For the first time, this information will be available for uniquely identified in mass and charge fission fragments. The campaign was enthusiastically acknowledged by the GANIL PAC in July 2021, and the first experiment took place in March 2022 [21]. The primary results extracted within our collaboration agreement 12-145 show to be very promising. The implementation of PARIS at VAMOS is a unique opportunity to provide exclusive measurements, which are expected to improve the current understanding on fission, and namely generation and sharing of excitation energy and angular momentum. The elaboration of the proposal made intense use of calculations made by us with the GEF [22] and FIFRELIN [23] codes, for generating the fragments and computing their decay, respectively. The utility of these simplified models rely, among others, in the reduced required computing resources as compared to full dynamical calculations. They are therefore planned to be used in the first step of the interpretation, in order to guide some uncertain ingredients of Langevin models. The latter would then be considered effectively in the second step.

2) Advanced Monte Carlo GEANT4 simulations in parallel with experiment

As noted in introduction, once the reaction and observables are defined, realistic simulations are mandatory to choose the set-up, evaluate its performance, and optimize it. Simulations are crucial also for extracting properly the underlying physics from the data actually recorded on tape.

According to the large amount of open channels for the heavy-ion collisions of interest here, to achieve the required selectivity and sensitivity it is very desirable to measure the gamma–rays in coincidence with the reaction products. This usually means a complex set-up, with only partial coverage for specific particles or channels. Altogether may bias the collected data set. Thus, to compare theory and experiment requires, either to correct the measurement for the angular un-efficiency of the set-up, or to filter the theoretical predictions by the geometrical and dynamical coverage of the detectors. In both cases, elaborate simulations of the experiment are necessary. In parallel to exclusive measurements, inclusive experiments are a rich source of information, allowing to investigate in detail the correlation between observables. In that configuration, simulations of the physics connection between different quantities are necessary also in order to un-fold the contributions of different channels to a specific observable.

During the past years, we worked on the development and improvement of simulations of both the set-up arrangement and the physics of interest using the GEANT4 toolkit. Work along this line was done in close connection with the experiments in which PARIS was used over the period 2016-2019. Physics models implemented in GEANT4 involving fusion, evaporation, fission [24], as well as some direct and transfer reactions [25], were improved. In parallel, the considerable work started in 2015 on simulations involving the PARIS array in combination with various ancillary detectors, namely the high-resolution gamma–array AGATA, the HECTOR gamma detectors, the heavy-ion spectrometer CORSET and VAMOS, the neutron detectors NBall/2 and NEDA, and the charged particle devices DIAMANT and KRATTA is being updated whenever suited. In the follow up of the determination of the response function of PARIS and its combination with other single LaBr3 detectors, done for a series of experiments at the neutron facility LICORNE at IJCLab [26-29], particular emphasis was set in 2020 and 2021 to the simulations of the coupling of PARIS with CORSET [19, 30], VAMOS [21, 31, 32], and KRATTA [33, 34, 35], in parallel with the analysis of the experiments which took place recently at the corresponding facilities. These simulations in general include the physics of the reaction, the kinematics of the products, and the full layout and response of the detection system. The outcome of the experiments, for PARIS+CORSET and PARIS+NuBall at IJCLab, PARIS+VAMOS+AGATA at GANIL, and PARIS+KRATTA at CCB, permitted to explore and further investigate the potential of the array at different stages of its completion. The results in the field of fission reactions, giant dipole resonances, nuclear structure of very exotic C, N and O isotopes, respectively; several of these works have been published in the period 2020-2022 as cited above.

The above summary shows the intense activity with and around PARIS during the last few years, with several experiments and the discussion and continuous publication of physics results. The calculations and simulations performed within our collaboration were essential in this respect. They will be even the more important in the coming year, with growth of the PARIS array (presently 8 clusters), and associated complexity of the set-up.

Finally, we note that the completion of the White Book (WB) of PARIS in 2021 [36], which collects the physics cases and proposals for the period 2020-2024. Several members of our COPIN collaboration were part of the Editorial Board.

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Those with asterisk * is mark publications or communications of our collaboration.

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IV. Renewal of the collaboration for 2023

IV.1 Proposed scientific program

Description

The road map which we define for 2023 is the continuation of the work done during the last years, in connection with experiments to come at various places (IJCLab, CCB, GANIL) using the extended version of the PARIS array. The main lines of our research plans are given below.

1) Study of nuclear dynamics within the Monte Carlo approach

We plan to continue our theoretical investigations within the framework of the stochastic Monte Carlo Langevin approach, the Hauser-Feschbach FIFRELIN de-excitation model and the semi-empirical GEF code. The main focus will be on reaction investigations which can be performed at GANIL and IJCLaB, in order to support our previous and more recent experimental program. Emphasis will be set on L-driven phenomena, entrance-channel effects, and the evidence of quasi-fission, generation and sharing of excitation energy and angular momentum at scission. The prompt fission ï•§-ray spectrum (PFGS) as can be obtained with PARIS is also expected to be of high importance for assisting our investigations on quasi-fission based so far on the fragment mass-angle correlation.

2) Advanced Monte Carlo GEANT4 simulations

Our plan on GEANT4 simulations is in straightforward line of the work done during the last years. One part concerns the continuous development of new toolkits in connection with the experiments with PARIS, namely coupled to other detectors (AGATA, VAMOS, NEDA, DIAMANT, NuBall/2, KRATTA). These will naturally be refined whenever applicable, i.e. with the number of PARIS clusters available. The complexity of the planed experiment absolutely requires such elaborate simulations. A major extension of our simulations is anticipated in 2023 since the first experiments involving 8 clusters took place in 2022. In particular, extensive and specifically dedicated (i.e. including the specificities pf the experimental environment and conditions) simulations of the VAMOS@GANIL and ALTO@IJCLab runs; the simulations for the former have been initiated in the second half of 2022, in the follow up of the experimental run of March.

We emphasize that 2023 is expected to be again a particularly rich year for our collaboration on the "practical" side. On one hand, the progressive completion, testing, etc, of the array is continuing (whenever additional detectors will be available). On the other side, the preparation and running of experiments (at IJCLab and CCB namely) will require substantial manpower on site. Preparation and analysis of these measurements will also imperatively need simulation work of the type conducted by our collaboration. We hope therefore that the current collaboration agreement can be supported again in the next year.

IV.2 Estimated duration for IN2P3 scientists in COPIN

Total time requested for 2023	28
List of scientists	1. C Schmitt (15 days) 2. O Dorvaux (7 days) 3. I Matea (3 days) 4. O Stézowski (3 days)

IV.3 Estimated duration for COPIN scientists in France

Total time requested for 2023	28
List of scientists	1. M Ciemala (14 days) 2. A Maj (6 days) 3. M Kmiecik (4 days) 4. K Mazurek (4 days)

Comment Validation	
Unity Director	Sandrine COURTIN (IPHC) - 2022-09-27 14:18:05