Nuclear pair correlations probed via proton-induced transfer and knock-out reactions

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I. SCIENTIFIC ISSUE

In the nuclear structure, one of the main fields of investigation is to know how the shell structure changes, as a function of the neutron-proton number asymmetry. This requires to determine the evolution of the low-energy properties of nuclei and to explore new phenomena in the nuclei far from the valley of stability, e.g. neutron-halo or neutron-skin structures as well as the change of the shell structure and of the magic numbers. The experiments are done in the new regions of the nuclear chart, to characterize the spectroscopy.

Experimentally, to establish as complete a picture of low-lying nuclear properties as possible, several techniques and reactions are combined using beams in different energy regimes. The properties of the nuclear correlations can be investigated using specific reaction probes in an energy regime where the process of interest is dominant in terms of production yields. In particular, detailed spectroscopic information can be deduced from direct reactions, i.e.

- elastic and inelastic (p,p') scattering to probe wave functions and neutron excitations ;
- one-nucleon transfers (p,d), (d,p) (E∼10-30 MeV/n) on proton-rich or deuteron-rich targets to probe the single-particle shell structure and overlap wave functions,
- (p,t) reactions (E∼10-100 MeV/n) to obtain information on pairing correlations as well as 0^+ excited states when using beams of even nuclei.
- High-energy (E∼100-400 MeV/n) (p,2p), (p,3p), (p,pn), (p,p2n) "knock-out" reactions to probe the angular momentum of the ejected proton(s) and the associated spectroscopic factors.

Experimental results obtained with the exotic nuclei are compared to theoretical calculations, to extract structure information and to check the validity of nuclear models so as to shed light on inter-nucleon interactions. The protocol used to extract the information on the underlying nuclear structure from the reaction cross section is currently amongst the burning questions. Theoretically, the validity and limits of applicability of the reaction mechanism is also under discussion. The questions of the sensitivity of the probe, and of the best choices to access to the nuclear correlations and to disentangle structure from reaction effects -as unambiguously as possible- are also currently under debate. For instance, the interest of two-nucleon knock-out with respect to one-nucleon knock-out reactions and the advantages offered by (p,3p) to populate exotic nuclei and to probe the spatial correlations between the knocked-out nucleons have to be examined.

An important issue for the studies of exotic nuclei is to examine the validity of the nuclear reaction frameworks, to check the assumptions, to include as much as possible the microscopic descriptions obtained from the structure calculations (form factors, correlations, ...) so as to remove the phenomenological "ad hoc" parameters usually kept as inputs for the reaction models.

The above studies rely on a reaction framework to

i) calculate cross sections for the expected yields that are given in experimental proposals,

ii) interpret the reaction data and extract the nuclear structure information. However, the validity of the reaction framework itself has to be questioned, both for the point of view of potential used to describe the projectile target interaction and of the processes between the various reaction channels at play. In this context, the aims of the present workshop are :

i) First, to compare two available reaction models for transfer reactions at low energy, i.e. CRC (*Coupled Reaction Channel*) and 2−step DWBA (*Distorted Wave Born Approximation*) models. To do so, a series of benchmark cases

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will be first examined on the basis of existing data obtained in the recent past at SPIRAL. Then, both approaches will be applied to future transfer reactions to be done soon at GANIL or foreseen at SPIRAL2 and their predictions will be compared.
ii) Second, to test the validity of a new microscopic DWIA (*DW Impulse Approximation*) code adapted to (p,2p) and (p,3p) reactions using form factors from two different microscopic structure theories as inputs. This in-house code developed by the SPhN-SPN collaboration will be especially useful in the context of the MINOS project [Minos]. Having such a code at hand will represent a strong asset for the interpretation of the next data set collected at RIKEN during the next 5-10 years. The present workshop is a step in a global exciting program aiming at the development of the microscopic structure and reaction models adapted to experimental needs.

A. Reaction studies at low energy

Using ^{8}He SPIRAL beam, we have obtained a complete data set for ^{8}He on proton target at low energy, i.e. elastic scattering cross sections as well as 1n and 2n transfer cross sections at 15.6A.MeV ([2n8He08], [2n8He12] and ref. therein). The data for ^{8}He(p,t) transfer to ^{6}He ground and 2^+ excited states were compared to CRC calculations [Sat83] based on a JLM microscopic potential [JLM77] in the entrance channel. The data set was described consistently and the spectroscopic amplitudes associated with the transfers from ^{8}He g.s to ^{7}He($3/2^-$) ground state as well as ^{6}He(0^+) ground state and ^{6}He(2^+) excited state were extracted, as explained in Ref.[2nHe08]. From this analysis, the ground state structure of ^{8}He was interpreted as a mix between $(1p_{3/2})^4$ and $(1p_{3/2})^2(1p_{1/2})^2$ shell-model configurations, contrarily to the usual assumption of a pure $(1p_{3/2})^4$ structure. Additionally, the complete data set allowed a consistent interpretation of coupling effects between the various reaction channels at play. In particular, it was shown that the necessary modification of the optical potential to reproduce elastic scattering was mainly due to the loss of flux going into the one-neutron transfer reaction.

With ^{8}He(p,t) data at hand, our first objective is to compare results from CRC calculations to those obtained using the 2−step DWBA formalism (see e.g. [Iga91] and references therein). The latter approach was revived recently by G. Potel and collaborators [Pot09] to describe two−nucleon transfer reactions in terms of microscopic degrees of freedom, i.e. individual coordinates of the transferred particles. In the context of the 2−DWBA formalism, the two−nucleon transfer appears to be dominated by a sequential process populating states of the intermediate nucleus. Using such a picture, an impressive description of the low-energy 2n transfer reaction on the Borromean nucleus ^{11}Li performed at TRIUMF with the MAYA detector [Tan10] was achieved [Pot10]. Consistently including all dominant reaction channels, i.e. transfer, inelastic and break-up channels, angular distributions and absolute differential cross sections for the transfer to ^{9}Li $3/2^-$ ground state and first excited $1/2^-$ state at 2.69 MeV were reproduced. Combined with microscopic structure inputs [Li11], such a reaction calculation has provided evidence for the phonon-mediated pairing interaction between the two halo neutrons in the ground state of ^{11}Li.

We plan to investigate the influence of the microscopic inputs on the modelling of direct reactions using the 2−step DWBA formalism and the CRC. The objective is to employ similar inputs in both CRC and 2−step DWBA calculations in order to compare the frameworks and to identify the key parameters. In the context of the program of direct reactions already done or foreseen at GANIL, the following systems will be selected, to calculate their cross sections :

- ^{8}He(p,p) (p,d) and (p,t) reactions at 15.4.A MeV, new calculations using 2-step DWBA will be compared to the previous CRC ones, and to the existing data [2n8He12] ; the influence of the form factors chosen for the unbound states of the ^{7}He, the nucleus in the intermediate state will be evaluated and discussed ;
- (p,t) reactions induced by ^{24}Si, ^{68}Ge and ^{72}Se beams, populating low-lying 0^+ excited states ;
- (d,p), (p,d) (p,t) reactions induced by the beams, delivered by the future SPIRAL2 machine, focusing on the studies planned for the investigation of the neutron shell structure evolution in Sn isotopes around N= 82 − 85 [LoISn][1] and for the deformation effects in Kr isotopes around N=60 [LoIKr].

For all these systems, the impact of the modelling of the exit channel will be examined, especially for cases where the final state is unbound. The sensitivity of the cross sections to the pair-transfer probabilities will be discussed ; the interpretation of these probabilities in terms of inputs related to the pairing interactions, tested with a different volume-to-surface mixing as in Ref. [GrL12], will be debated.

Accordingly, the energy dependence of relevant cross sections will be studied.

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[1] Letters of intent proposed in Nov. 2010 for experiments using the first radioactive beams (Day 1 Phase 2) and evaluated by the international scientific advisory committee of SPIRAL2 during the meeting in Jan. 2011, *http : //pro.ganil-spiral2.eu/spiral2/what-is-spiral2/physics-case/*

B. Discussion of the new reaction code for high−energy (p,2p) and (p,3p) reactions

A code based on the DWIA framework will be developed under the auspice of the ESNT, with preliminary works starting in October 2012. The code should be written from November till December 2012 and became operational for the benchmarks calculations intended in early 2013 and for the workshop discussions proposed hereafter. The goals are to make the evaluation of the cross sections and the discussion on the input parameters during the workshop. We will focus on the nuclear systems matching the experimental program of (p,2p) and (p,3p), (p,p2n) reactions induced by exotic nuclei foreseen at RIKEN using $300-400$ MeV/n RIBF beams, and the MINOS array developed at SPhN. In order to exploit the data coming out of such experiments, to take advantage of the latest developments of the microscopic structure theories and to question, remove or refresh the set of approximations made in the previous frameworks [Nor08], a new DWIA code is mandatory. The new code will provide the community with a useful tool to evaluate cross sections by including microscopic structure inputs into the reaction framework. Indeed, an important aspect of the present project is to generate the form factors that serve as an input to DWIA calculations from two different state-of-the-art nuclear structure methods :
(i) within the frame of self-consistent multi-particle/multi-hole (mp-mh) configuration mixing calculations [Pil08,Pil12] which consists of a unified variational treatment of nuclear long-range correlations. The same effective nucleon-nucleon interaction, namely the D1S Gogny effective force, is used in both the mean-field and the residual channels. These results can be compared to those obtained from a standard GCM-type method [Del10] using the same Gogny D1S interaction ;
(ii) employing shell-model calculations based on realistic effective interactions derived using renormalization group and many-body perturbation theory techniques [Sig11]. Based on such microscopic inputs, the coupling to core excitations will be added in a coupled-channel manner.
All in all, the development of the code and its evaluation will require the implementation and tests :

- Of various in-medium effective interactions adapted to high energies (>150 MeV/nucleon) ; e.g. the Paris-Melbourne G-Matrix [Dor94] ;
- Of the coupling to core excitations and the inclusion of the microscopic form factors provided by nuclear structure calculations ;
- Of the 2-step DWIA and the systematic checking of the microscopic form factors.

Eventually, reaction mechanisms associated with the knock-out of a nucleon-pair knock at high energy and with the transfer of such a pair will be compared on the basis of consistent nuclear-structure inputs. The sensitivity to inner degrees of freedom, e.g. correlations, core excitations, deformation, continuum coupling, pairing and spatial localization of the pair, will be tested for both processes.

Recently, an accurate method (the *eikonal reaction theory*, ERT) was developed [Ya11] for the modelling of the neutron removal reactions induced by both nuclear and Coulomb interactions at intermediate incident energies. The role of the nuclear and Coulomb break-up processes have been treated consistently by the method of the *Continuum Discretized Coupled Channels* (CDCC) [Ya12] without making the adiabatic approximation to the Coulomb interaction. The importance of the coupling of final breakup (continuum) channels was also shown for several cases of breakup and elastic calculations within the CDCC method [Mor09]. It is then meaningful to evaluate these break-up effects in the case of the proton-knock-out reactions within DWIA approaches.

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[LoiSn] *SP2-Ph2-33 Neutron shell evolution in weakly-bound neutron-rich* ^{134,135}*Sn beams via (d,p) reactions, V. Lapoux et al.*
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II. GOALS OF THE WORKSHOP

The general goals are the discussion of the recent progress and remaining issues with existing reaction theory frameworks for knock-out and pair transfer reactions on proton targets.

In summary, the goals of the workshop are :

1. To discuss and compare the microscopic optical models used for the (p,t) reactions, within the CRC and the 2-step DWBA frameworks, to determine their common features, by examining two examples, ^{8}He(p,t) and $^{68-76}$Ge(p,t), and to figure out the systematic error bars generated on the structure information by the use of these two reaction models (using the same input potentials) ;
2. To discuss and evaluate the proton-nucleus optical potentials to be used for reactions above 100 MeV/n ;
3. To present the new microscopic DWIA frameworks developed at SPhN for knock-out reactions on proton and their application to measured data for stable nuclei ;
4. To calculate the DWIA for (p,2p), (p,pn), (p,3p) reactions induced by exotic nuclei and to discuss their sensitivity to the microscopic inputs.Test cases to be considered are ^{16,18}O(p,2p) and ^{40}Ca(p,2p)^{39}K ; it is also planned to discuss the cases of $^{16-24}$O(p,pN) reactions.

III. LIST OF SPEAKERS

List of talks related to microscopic form factors, structure inputs, reaction frameworks and optical model potentials :

- Francesco Barranco (*barranco@cica.es*), Univ. de Sevilla, *"Interplay of collective and single particle modes in the structure of exotic nuclei"*
- Ricardo A. Broglia (*ricardo.broglia@mi.infn.it*), INFN-Milano, *"Pairing correlations, 2-step applied to transfer reactions"*
- Thomas Duguet (*thomas.duguet@cea.fr*), CEA, IRFU, SPhN, *"Effective single-particle energies in correlated many-fermion systems : meaning and usefulness"*
- Marc Dupuis (*marc.dupuis@cea.fr*) CEA, DAM, DIF, *"G-matrix microscopic optical model potential calculations and structure inputs"*
- Marcella Grasso (*grasso@ipno.in2p3.fr*), IPN-Orsay, *"Low-energy excitations and pair transfer of exotic nuclei"*
- Nicholas Keeley (*Nicholas.Keeley@fuw.edu.pl*), National Centre for Nuclear Research, Warsaw, *"(p,t) transfer reactions studied in Coupled reaction channel framework"*
- Denis Lacroix (*lacroix@ganil.fr*), GANIL, *"Effect of collective and non-collective pairing excitation in transfer reaction near the Coulomb barrier"*
- Julien Le Bloas (*julien.lebloas@cea.fr*), CEA, DAM, DIF, *"Description of light nuclei (8<Z<20, 8<N<20) with the mp-mh Gogny energy density functional"*
- Antonio Moro (*moro@us.es*), Facultad de Fisica, Univ. de Sevilla, *"Core excitation in transfer and break-up reactions"*
- Tetsuo Noro (*noro@nucl.phys.kyushu-u.ac.jp*), Kyushu University, *"Single particle properties investigated via (p,2p) reactions"*

- Kazuyuki Ogata (*kazuyuki@rcnp.osaka-u.ac.jp*), RCNP Osaka, *I. " CDCC methods" II. "Status of breakup reaction theory"*
- Sophie Péru (*sophie.peru-desenfants@cea.fr*), CEA, DAM, DIF, *"Excitations and QRPA calculations"*
- Nathalie Pillet (*nathalie.pillet@cea.fr*), CEA, DAM, DIF, *"Nuclear form factors with multi-particle multi-hole configurations"*
- Grégory Potel (*gregory.potel@cea.fr*), CEA, IRFU, SPhN, *"Nuclear structure via proton-induced knock-out - development of a multi-step finite-range DWIA code"*
- Angelo Signoracci (*angelo.signoracci@cea.fr*) , CEA, IRFU, SPhN, *"Correlations and spectroscopic factors"*
- Enrico Vigezzi (*enrico.vigezzi@mi.infn.it*), INFN-Milano, *"Induced interaction and pairing in nuclei"*.

Talks introducing the workshop (Experimental overview, needs and questions) :
- Anna-Maria Corsi, CEA, IRFU, SPhN, *"Experimental studies of shell effects via (p,2p) and (p,pn) reactions"*
- Valérie Lapoux, CEA, IRFU, SPhN, *"Nuclear structure of exotic nuclei probed via direct reactions on proton target"*.

IV. PROGRAM

Wednesday 6th Feb room 135	Thrusday 7th room 125	Fri. 8th room 125
09h00 *(day plans)*	09h00 *(day plans)*	09h00 *(day plans)*
09h30 V. Lapoux	09h30 T. Duguet	09h30 A. Moro
10h10 A. Corsi	10h10 A. Signoracci	10h10 **Break**
10h50 **Break**	10h50 **Break**	10h20 K Ogata (II)
11h10 N. Keeley	11h10 N. Pillet	11h10 *Discussions*
11h50 *CRC/DWBA frameworks*	11h50 (*test* $^{68-76}$Ge(p,t))	*break-up effects*
12h15 **Lunch**	12h30 **Lunch**	12h00 **Lunch**
14h00 R. Broglia	14h00 M. Dupuis	13h30 *discussions*
14h40 D. Lacroix	14h40 J. Le Bloas	*pair transfer*
15h20 M. Grasso	15h20 K Ogata (I)	and (p,t) reactions
16h00 **Break**	16h10 **Break**	16h00 **Break**
16h20 F. Barranco	16h30 T. Noro	16h15 *Outlook :*
17h00 E. Vigezzi	17h20 G. Potel	*pair transfer,*
17h40 S. Péru	18h00 *Discussions*	*(p,t) and (p,pN) reactions*
18h20 *Discussions*	*DWIA frameworks*	*Workshop outputs*
CRC and 2-step	*Test cases* : ^{16,18}O(p,2p)	16h45 *Test cases*
18h40 *Test case* : ^{8}He(p,t)	*Test* : ^{40}Ca(p,2p)^{39}K	$^{16-24}$O(p,pN)
19h30 **End**	19h30 **End**	18h00 **End**