

## **Workshop “The Nucleus-Nucleus Interaction and Reactions With Exotic Nuclei, a workshop dedicated to the Memory of Paulo Roberto Silveira Gomes”**

**April 10 – 13, 2017**

### **ABSTRACTS**

#### **Excitation of Giant and Pygmy dipole states in neutron-rich systems with isoscalar probes**

***Andrea Vitturi***

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We give estimates for the population of Giant and Pygmy dipole states in neutron-rich nuclei via inelastic processes induced by nuclear isoscalar probes. In the former case this is possible due to the occurrence of the neutron skin (and actually providing an estimate of its extension), while in the latter case this possibility arises from the isoscalar/isovector mixed character of the pygmy states. Both macroscopic and microscopic models are used for the description of the dipole response. Following experimental findings, special attention is given to the possible separation of the pygmy region into a “mainly isoscalar” and a “mainly isovector” parts in spherical nuclei, as well as to the splitting of the dipole pygmy strength into the  $K=0$  and  $K=\pm 1$  components in very neutron-rich deformed nuclei.

#### **Present and future experiments with RIBRAS**

***Alinka Lepine***

*(IF-USP)*

The high-lying resonances in  $^9\text{Be}$  were studied by measuring the excitation functions of reactions  $(p,p)$ ,  $(p,d)$ ,  $(p,d^*)$  and  $(p,\alpha)$  of the  $^8\text{Li} + p$  system. The simultaneous analysis by R-matrix formalism of these 4 channels allowed the determination of properties of these resonances.

The upgrade of the detection systems of RIBRAS will be also described, with several new large area, segmented Si telescopes (DSSSD) and a neutron wall being tested and installed. These new detectors will allow us to realize exclusive break-up measurements of our radioactive beams, as  $^6\text{He}$ ,  $^7\text{Be}$ ,  $^8\text{B}$ ,  $^8\text{Li}$ ,  $^{10}\text{Be}$  etc. on heavy and light targets and study the effect of break-up on the different reaction channels.

## Resonant reactions in nuclear astrophysics with the Trojan horse method

*Aurora Tumino*

The knowledge of energy production and nucleosynthesis in stars requires a precise determination of the nuclear reaction rates at the energies of interest. To overcome the experimental difficulties arising from the small cross sections at those energies and from the presence of the electron screening, the Trojan Horse Method has been introduced. The method represents one of the most powerful tools for experimental nuclear astrophysics because of its advantage to measure unscreened low-energy cross sections of reactions between charged particles, and to retrieve information on the electron screening potential when ultra-low energy direct measurements are available. This is done by selecting the quasi-free (QF) contribution of an appropriate three-body reaction  $A + a \rightarrow c + C + s$ , where  $s$  is described in terms of clusters  $x + s$ . The QF reaction is performed at energies well above the Coulomb barrier, such that cluster  $x$  is brought already in the nuclear field of  $A$ , leaving  $s$  as spectator to the  $A+x$  interaction. The THM has been successfully applied to several reactions connected with fundamental astrophysical problems as well as with industrial energy production. I will recall the basic ideas of the THM focussing on resonant reactions with stable and exotic beams and show some recent results.

## Inclusive deuteron breakup reactions

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In a deuteron-induced reaction, competition between elastic and inelastic breakup, absorption of only a neutron or a proton and absorption of the deuteron must be taken into account to determine the inclusive proton and neutron emission cross sections, as well as the formation or not of a compound nucleus [1]. The breakup-fusion reactions – those in which either only a neutron or a proton is absorbed – are particularly complex, forming compound nuclei with a wide range of excitation energies and angular momenta. We use the zero-range post-form DWBA approximation to calculate the elastic and nonelastic breakup cross sections [2-5] and estimate the breakup-fusion cross section. We compare the energy and angular momentum dependence of the breakup-fusion compound nucleus formation cross section with the corresponding neutron-induced cross sections and calculate the differential  $^{238}\text{U}(d,pf)$  cross section using the EMPIRE-3 nuclear model code [6]. Finally, we discuss how the formalism describing two-body fragmentation can be extended to take into account reactions in which the projectile dissociates into three fragments [7].

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## Pigmy resonances, symmetry energy and neutron stars

**C. A. Bertulani**

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The electric dipole (E1) response of exotic nuclei has been studied for several decades, leading to the famous discovery of the giant dipole resonance in 1947 and of the double giant resonance in 1993. In the last three decades the focus of this research is on the pygmy dipole resonance (PDR) appearing in neutron-rich nuclei, and it was possibly discovered in the late 1980's. I will discuss how the PDR has been firmly identified experimentally and how it has theoretically been linked to the physics of neutron stars. In particular, one has shown that it displays sensitivity to bulk properties of the nuclear matter, such as the symmetry energy in the equation of state of asymmetric nuclear matter

## Sensitivity of breakup observables and fusion to sub-zeptosecond resonance lifetimes

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Nuclear reaction dynamics at energies near the fusion barrier is sensitive to the quantum structure of colliding nuclei. For reactions involving weakly bound nuclei, the presence of low energy unbound states leading to cluster breakup is crucial. If the states have decay lifetimes comparable to the reaction timescale ( $\sim 10^{-21}$ s), then the reaction observables (particularly fusion) depend sensitively on the location of the decay with respect to the collision partner. Recent measurements at the Australian National University have allowed detailed investigation of sub-barrier breakup in reactions with  $^6\text{Li}$ ,  $^7\text{Li}$  and  $^9\text{Be}$  with a wide range of targets. Helped by breakup simulations, experimental observables have been identified that probe the location of breakup. Sensitivity even to sub-zeptosecond decays is found. These results provide clear insights into near-barrier reaction dynamics of weakly bound nuclei.

## Investigation on the projectile break-up mechanism in $7\text{Li} + 208\text{Pb}$ reaction around the Coulomb barrier

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Interactions of the most weakly bound stable nuclei,  $6,7\text{Li}$  and  $9\text{Be}$ , display a range of anomalous behaviors, all attributed to the low break-up threshold. For instance, projectiles break-up into their cluster constituents is expected to be highly probable. Projectile dissociation in the field of the target nucleus is a topic of continued interest also because of its application to the determination of radiative capture cross section of astrophysical interest. Over the last decade, with the availability of secondary radioactive ion beams, the role played by projectile break-up has become a major research issue [1]. Understanding the reaction mechanisms of loosely bound projectiles and the coupling of their break-up on various channels therefore becomes very important. Projectile break-up modifies the accepted picture for complete fusion of strongly bound nuclei. Measurements involving the projectiles  $6,7\text{Li}$ ,  $6\text{He}$  with  $\alpha+x$  cluster structure show significantly larger cross sections for the inclusive alpha particle production [2] compared to the production of the complementary fragment (x). This indicates that there are mechanisms other than  $\alpha+x$  breakup responsible for the inclusive production of alpha particles[3,4].

In this presentation, the different outgoing channels leading to break-up of the projectile at the beam energy from 31 to 39 MeV for the system  $7\text{Li}+208\text{Pb}$  will be discussed. An interpretation for  $\alpha$  spectra from projectile break-up will be proposed and that will shed light on the implications of the higher binding energy of  $7\text{Li}$  with respect to  $6\text{Li}$  on the exclusive break-up.

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## Exploring the single particle structure of $^{10}\text{Li}$ by the $d(^9\text{Li},p)^{10}\text{Li}$ reaction

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The study of the unbound system  $^{10}\text{Li}$  is of great interest since the knowledge of its structure is a crucial ingredient in the description of the two-neutron halo nucleus  $^{11}\text{Li}$ . Despite the significant amount of experimental information gathered during the last years, the properties of the  $^{10}\text{Li}$  continuum remains unclear, to the extent that even the energy and the spin-parity of the ground state are still controversial [1,2]

We have investigated the  $^{10}\text{Li}$  structure via the  $^9\text{Li}(d,p)^{10}\text{Li}$  transfer reaction in inverse kinematics at TRIUMF [3]. A 100 MeV  $^9\text{Li}$  beam, produced by the ISAC-II facility, impinged on a  $\text{CD}_2$  target. The recoiling protons were detected at backward angles by the LEDA array of silicon strip detectors [3], thus allowing the study of the  $^{10}\text{Li}$  emitted in the crucial region at forward angles. Protons are detected in coincidence with the  $^9\text{Li}$  fragments produced from the breakup of the corresponding  $^{10}\text{Li}$ .  $^9\text{Li}$  fragments have been detected and identified by using a  $\Delta E$ -E telescope of S2 annular DSSD detectors located downstream the target.

The  $^{10}\text{Li}$  excitation energy spectrum was reconstructed with significant statistics up to about 4 MeV, allowing, for the first time, to explore the completely unknown high excitation energy region. The highly segmented detection system allowed to also measure the angular distributions of the observed resonances at forward angles. The comparison with an extended mean-field approach, where the pairing correlations are introduced [4], allows to disentangle the s, p and d orbital contributions in the different portions of the energy spectrum.

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## Is the complete fusion suppression energy independent?

**Jesus Lubian**

*(If - UFF)*

In a recent years many works have shown that the complete fusion of the reaction of weakly bound nuclei with medium-heavy and heavy targets is hindered for about 30 - 40%, when compare to benchmark UFF (Universal Fusion Fusion). Is this systematic valid for the reaction with light and medium targets? Here we want to prove that for the reactions of weakly bound projectile with lighter targets the hindrance is much more lower, or does not exist at all.

## Neutron +<sup>19</sup>C elastic scattering near critical conditions for an excited <sup>20</sup>C state

**Lauro Tomio**

*(IFT-UNESP)*

Low-energy properties are investigated for the neutron<sup>19</sup>C elastic s-wave scattering, near the critical condition for the occurrence of an excited bound state in <sup>20</sup>C, within a neutron-neutron+<sup>18</sup>C configuration, by considering finite-range potentials. The results for the s-wave scattering amplitude present universal scaling features, with the variation of the <sup>19</sup>C binding energy for fixed <sup>20</sup>C binding and neutron-neutron singlet virtual state energies. The scaling of the effective-range parameters and the pole position of  $k \cot(\delta_0^R)$  are in general consistent with the scaling obtained with a zero-range potential. Perspective applications of the analysis to other similar three-body imbalance-mass systems will also be discussed.

## São Paulo potential: twenty years later

**L. C. Chamon**

*(IF-USP)*

The São Paulo potential is a theoretical model for the nuclear interaction between heavy nuclei. The model has been successfully used in elastic scattering data analyses for many systems and in a very wide energy range. Due to the lack of adjustable parameters, the São Paulo potential can also be assumed as a standard bare interaction in applications involving coupled-channel calculations. We will present a brief review of the São Paulo potential and will show some examples of application in heavy-ion reactions.

## **Fusion function: an efficient procedure to reduce fusion data**

***L. F. Canto***  
*(IF-UFF, UFRJ)*

The traditional reduction methods to represent the fusion cross sections of different systems are flawed when attempting to completely eliminate the geometrical aspects, such as the heights and radii of the barriers, and the static effects associated with the excess neutrons or protons in weakly bound nuclei. We remedy this by introducing a new dimensionless universal function, which allows the disentanglement of the static and dynamic aspects of the low binding energy of the weakly bound collision partner. We discuss the application of this reduction procedure to collisions of weakly bound projectiles with targets in different mass ranges. The extension of the method to reaction cross sections is briefly discussed.

## **Study of reactions involving weakly-bound nuclei**

***Leandro Gasques***  
*(University of São Paulo, Nuclear Physics Department)*

Recently, an experimental campaign was performed at the Laboratório Aberto de Física Nuclear of the University of São Paulo. Various angular distributions were obtained at energies around the Coulomb barrier for the  $10,11\text{B}+120\text{Sn}$  reactions. Besides the elastic scattering, other reaction channels, such as projectile and target-like excitation, and transfer of nucleons, were observed. Details on the experiment, and a theoretical analysis performed within the coupled-channel formalism, will be presented.

## **Electron Capture and Pycnonuclear Fusion Reactions in Magnetized White Dwarfs**

***Manuel Malheiro and Edson Otoniel***  
*(Departamento de Física - Instituto Tecnológico de Aeronáutica)*

In this work, we study the properties of magnetized white dwarfs taking into account possible instabilities due to electron capture and pycnonuclear fusion reactions in the cores of such compact objects. The stellar interior is composed of a regular crystal lattice made of carbon ions immersed in a degenerate relativistic electron gas. The onsets of electron capture and pycnonuclear fusion reactions are determined with and without magnetic fields. These reactions constrain the maximum value of central density in order to avoid white dwarf instabilities.

## Universality in light halo nuclei

***Marcelo Takeshi Yamashita***

In this seminar I will present a short review of our main results about universality in light halo nuclei. I will discuss the possibilities to observe Efimov states in the nuclear context.

## Instrumental developments to study weakly bound and exotic nuclei reactions at USP

***Marcos Aurelio Gonzalez Alvarez***

*(University of Seville)*

We present two new detection and acquisition systems dedicated to study nuclear reactions at the Open Laboratory of Nuclear Physics of the University of São Paulo (USP), in Brazil. SATURN (Silicon Array and Telescopes of USP for Reactions and Nuclear applications) has been coupled to the 30B experimental beam line and reaction chamber, to study weakly bound nuclei reactions. STAR (Silicon Telescopes Array of RIBRAS) has been developed to be coupled to the 45B experimental beam line and the RIBRAS (Radioactive Ions Beams in Brazil) system, to study exotic nuclei reactions. In 2016, the first experimental campaign using SATURN was performed with the aim of studying the  ${}^7\text{Li}$ ,  ${}^{10,11}\text{B}$  weakly bound nuclei reaction on  ${}^{120}\text{Sn}$ . In 2017, the E-125 experimental campaign will be performed with the aim of studying the  ${}^6\text{Li}$ ,  ${}^9\text{Be}$  weakly bound nuclei reaction on  ${}^{120}\text{Sn}$ . In order to test STAR and better explore the  ${}^9\text{Be}+{}^{120}\text{Sn}$  nuclear reaction, SATURN and STAR systems will be mounted in the same 30B nuclear reaction chamber. For the future, STAR should be coupled to RIBRAS for studying new exotic nuclear reactions. SATURN and STAR could also be coupled to the Neutron Wall system for coincidence measurements of charged and neutron particles.

## Recent results on light nuclear systems; progress and problems

***Martin Freer***

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It might feel as though a complete understanding of light nuclei should have been reached by now, and may be it should. However, and on the contrary, these systems have become the testing ground where state-of-the-art theory meets the incredibly rich spectrum of structural possibilities that light nuclei present. Such systems are dominated by correlations which are the finger-print of the strong interaction which generates everything from the collective to single-particle behavior and also examples where these mix. These correlations are manifest in cluster-like states and molecular exchange of neutrons between clusters (mixed bosonic and fermionic modes). This talk will be a review of the recent results of the Birmingham group, where they are helping to improve our understanding of nuclei such as  ${}^{12}\text{C}$ ,  ${}^{14}\text{C}$  and  ${}^{12}\text{Be}$  and where open questions remain



## Low energy Nuclear Physics at the French Atomic energy committee (CEA)

**Nicolas Alamanos**  
(Saclay, France)

Experimental and theoretical investigations in the domain of low energy nuclear physics at CEA/IRFU-Saclay will be presented. Contributions of the Institute (IRFU) at facilities under construction like the SPIRAL2 accelerator in France or the FAIR facility in Germany will be discussed with emphasis to major technical contributions of the Institute

## Breakup of three-cluster systems

**Pierre Descouvemont**  
(ULB, Belgium)

The breakup of  ${}^6\text{He}$ ,  ${}^9\text{Be}$  and  ${}^{17}\text{Ne}$  are investigated in the CDCC framework. We use a three-cluster model for  ${}^6\text{He}$  ( $=\alpha+n+n$ ),  ${}^9\text{Be}$  ( $=\alpha+\alpha+n$ ) and  ${}^{17}\text{Ne}$  ( $={}^{15}\text{O}+p+p$ ), and simulate the breakup by three-body pseudostates. These 3 systems cover different situations: 1, 2 and 3 charged particles, respectively. The separation between nuclear and Coulomb breakup is also discussed.

## Halo EFT and nuclear astrophysics

**Renato Higa**  
(IF-USP)

Light and medium nuclei far from the stability line have proven to be fascinating and mysterious systems where quantum effects dominate and conspire to form loosely bound structures. Many of these nuclei are pivotal in describing relevant processes in astrophysics, mainly in the very low-energy Gamov band where dedicated experiments have many technical difficulties to access. Within the halo effective field theory framework, these experimental barriers turn into theoretical gifts. I will highlight some of astrophysically important radiative reactions and results of t

## Recent results from RIBRAS

**Rubens Lichtenthaler**  
(IF- USP)

Results of elastic scattering experiments using exotic  $^6\text{He}$ ,  $^8\text{B}$ ,  $^7\text{Be}$  secondary beams will be presented. Continuum Discretized Coupled Channels calculations seem to reproduce quite well most of the the angular distributions without the need of parameter variations. A systematics of the nuclear radii obtained from total reaction cross sections allow a comparison between exotic and stable projectiles. Recent results of the  $^7\text{Be}+^9\text{Be}$  scattering and the two neutron elastic transfer reaction  $^9\text{Be}(^7\text{Be},^9\text{Be})^7\text{Be}$  will also be presented.

## Suppression of complete fusion in reactions involving weakly bound nuclei with an empirical coupled-channel model

**Shan-Gui Zhou**  
(Institute of Theoretical Physics, Chinese Academy of Sciences)

Abstract: Complete fusion excitation functions of reactions involving breakup are studied by using the empirical coupled-channel (ECC) model with breakup effects considered. An exponential function with two parameters is adopted to describe the prompt-breakup probability in the ECC model. These two parameters are fixed by fitting the measured prompt-breakup probability or the complete fusion cross sections. The suppression of complete fusion at energies above the Coulomb barrier is studied by comparing the data with the predictions from the ECC model without the breakup channel considered. The results show that the suppression of complete fusion is roughly independent of the target for the reactions involving the same projectile.

## Characteristic structure of weakly bound and unbound neutron-rich nuclei

**Takashi Nakamura**

*(Department of Physics, Tokyo Institute of Technology)*

I present the recent experimental studies on nuclei near and beyond the neutron drip line to probe their characteristic structures. The results to be shown are based on the experiments performed at RIBF at RIKEN. First topic is on the neutron halos. I present the study on deformation-driven p-wave halo configuration revealed in  $^{29}\text{Ne}$ [1],  $^{31}\text{Ne}$ [2,3] and  $^{37}\text{Mg}$ [4] using the breakup reactions at intermediate energies. I also present the results on two-neutron halo nuclei,  $^{19}\text{B}$  and  $^{22}\text{C}$ , using the reaction cross sections [5] and the breakup reactions. Then, for the unbound nuclei, I will report on the recent experiments to investigate structures of 25-280. In particular I will focus on  $^{260}$ [6], which has been found to have extremely small decay energy with respect to the two neutron emission, and thus may have strong two-neutron correlation. Finally, I will provide perspectives on experimental studies on nuclei near the neutron drip line.

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## Incomplete Fusion Theory of Three-Body Halos

**Tobias Frederico**

*(Instituto Tecnológico de Aeronáutica)*

We present a four-body reaction model to treat the inclusive non-elastic break up reactions involving weakly bound three-cluster nuclei. Borromean, two-nucleon, halo nuclei are candidates of unstable three-fragments projectiles. The reaction model generalizes the theory of inclusive breakup reactions commonly employed in the treatment of incomplete fusion and surrogate method with two fragment projectiles. The four-body incomplete fusion model follows the three-body theory developed in the 80's by Ichimura, Austern and Vincent [Phys. Rev. C 32, 431 (1985)], Udagawa and Tamura [Phys. Rev. C 24, 1348 (1981)], and Hussein and McVoy [Nucl. Phys. A 445, 124 (1985)]. The extension of these three-body theories allows to derive an expression for the spectator fragment yield in the reaction  $A(a,b)X$ , where the projectile is  $a = x_1 + x_2 + b$ . The inclusive breakup cross section of the spectator fragment  $b$  is found to be the sum of a generalized four-body form of the elastic breakup cross section plus the inclusive non-elastic breakup cross section which involves the incomplete fusion cross section of the participant fragments,  $x_1$  and  $x_2$ .

The final result for the four-body case extends the three-body formalism reviewed in Austern, et al. (Phys. Rep. 154, 125 (1987)), including genuine four-body effects, both in the elastic breakup cross section and in the inclusive non-elastic breakup. We hope that these developments will encourage further experimental and theoretical works to extend the surrogate method with three-body projectiles, based on the inclusive non-elastic breakup part of the  $b$  spectrum.

## A Systematic Approach to Halo and Cluster Nuclei

**U. van Kolck**

*(Institut de Physique Nucleaire d'Orsay and University of Arizona)*

Halo and cluster nuclei display a separation of scales between the sizes of tight subsets of nucleons ("cores") and of the entire system, which form an ideal playground for effective field theories (EFTs). I present the systematic framework to describe these nuclei with Halo/Cluster EFT, a low-energy version of QCD whose degrees of freedom are nucleons and cores that provides a generalization of simple, successful models with short-range interactions. In this EFT, light, halo and cluster nuclei are arrangements with, respectively, no, one, and multiple cores. I discuss in particular core-size effects, which become more important as cores become heavier.