The R3B (Reactions for Relativistic Radioactive Beams) collaboration at FAIR (Facility for Antiproton and Ion Research

R3B is an international sub-collaboration of the FAIR-Pillar NUSTAR, formed by more than 200 scientists from 23 different countries. The sub-collaboration was created as a strategic alliance for the design, construction, and exploitation of a versatile experimental setup with unprecedented efficiency, acceptance, and resolution for kinematical complete measurements of reactions with high-energy radioactive beams.

The R3B setup enables an extended scientific program comprising nuclear structure and dynamics as well as astrophysics. New possibilities of measurements of ground-state properties and nuclear excitations, for the understanding of the reaction mechanisms, for constraining the symmetry energy of the equation of state in asymmetric nuclear matter, for determining the role of nucleon-nucleon correlations including short-range correlations (SRC), for the investigation of hyper-nuclear matter, and for determining astrophysical reaction rates.

The R3B experimental setup is optimized for the kinematically-complete measurement of reactions at high beam energies up to around 1 GeV/u. Compared to competing projects worldwide, which are the SAMURAI spectrometer at RIBF at RIKEN, and a similar setup at the future FRIB facility, R3B will be unique in the foreseeable future due to the combination of high-energy beams, large acceptance, high resolution, and large efficiency including multi- neutron detection. Already in its present state of upgrading, R3B has reached a performance level beyond any other comparable setup being planned. The major part of the R3B physics program builds on the availability of 1 GeV/u beams. The concept of magnetic beam separation and magnetic analysis after the secondary target requires fully stripped ions. This implies that the competing projects at RIBF (SAMURAI, typical secondary beam energies around 250 MeV/u) and FRIB (similar to RIBF) will, in contrast to R3B, not be able to provide kinematically-complete measurement of reactions with heavy beams (Z>50). Moreover, due to the higher beam energies employed by R3B, thicker targets can be used and the acceptance is generally larger as compared to the competing projects at RIBF and FRIB. The detection efficiency of R3B for multi-neutron decays is unprecedented in comparison to any other running facility or planned project. It is worthwhile to mention the performance of the TRT Si-tracker setup based Si Pixel detectors that will allow to perform (p,2p) experiments in full kinematics. This configuration is currently being developed and already in use during the R3B Phase-0 experiments, and provides an intermediate step towards the realization of the full- fledged system with 4p solid-angle coverage expected for 2028.

Research program with R3B at GSI/FAIR and complementary facilities.

The use of relativistic radioactive ion beams for reaction experiments in inverse kinematics was introduced into the GSI scientific program approximately 30 years ago. From the beginning, it became evident that this technique offers exceptional opportunities to elucidate the structure of extremely exotic nuclei near and beyond the dripline.

Our interest has primarily focused on light nuclei in the range Z=5 to Z=9, conducting experiments under kinematically complete conditions. In particular, reactions induced on proton targets in quasi-free scattering regimes, such as (p,2p) and (p,pn) studied in the S393 experiment, have been crucial for studying single-particle properties (Pan16, Pan19, Rib18, Syn20), understanding nuclear Shell evolution through investigations of the quenching of spectroscopic factors (Ata18,Dia18,Hol19, JM Boillos PhD) and exploring the halo characteristics exhibited by certain isotopes (Leh22,Mar15,Mar16a,Mar16b, War18,War23, War24 and G. Ribeiro PhD).
These studies have also provided valuable insights into the structure of unbound isotopes, opening pathways to explore the nuclear continuum (Rev18,Van17). Additionally, we have conducted systematic investigations of projectile fragmentation involving light exotic projectiles (Boi22,Thi16), which hold relevance for various applications.

We have also systematically investigated the proton and neutron knockout cross sections using tin isotopes covering a wide range in isospin. These measurements showed that the proton knockout cross sections in neutron-rich nuclei were significantly smaller than expected from realistic model calculations. This quenching was explained as due to the presence of neutron-proton short-range correlated (SRC) pairs (Rod17, Dia20, J. D.az PhD). The previous results were obtained using inclusive measurements of the nucleon knockout. Using R3B we can now perform exclusive measurements of quasi-free (p,2p) and (p,pn) reactions.

R3B has also proposed a dedicated research program to investigate SRCs. A first experiment, S522, was performed in 2022 to investigate the presence of SRC pairs in different carbon isotopes. We are involved in the analysis of these data and results should be published soon. SRCs can also be investigated on the basis of the presence of clusters of nucleons in the ground state of nuclei. The existence of these clusters can be proven by using quasi-free cluster knockout reactions, as (p,pd) or (p,pa), but also by means of transfer reactions. In 2024 R3B ran the S091 experiment aiming at investigating (p,pd) reactions on different carbon isotopes. Also in this case, we are involved in the sorting of the data obtained in these measurements.

We have been part of the research program on fission using inverse kinematics at GSI since its conception almost 25 years ago. In the last 10 years we would like to highlight our contribution to the SOFIA setup, which for the first time provided access to the complete identification in atomic and mass number of both fission fragments (Mar15,Mar21,Pel17). Using this setup, we coordinated the S393 experiment to study the dynamics of fission using spallation-induced fission reactions. This experiment allowed us to constrain the value of the dissipation parameter that determines the fission time in model calculations of the fission process based on transport equations. Two PhD theses were carried out on this topic (J.L. Rodr.guez and M. Feijo.) and five papers were published (Rod15a, Rod15b, Rod16a, Rod16b, Rod17). We also participated in the investigation of shell effects measuring fission yields in Coulex induced fission reactions (Cha19,Cha20,Cha22).

More recently, we have proposed to merge the SOFIA and R3B setups to obtain complete kinematic measurements of the fission process. This new setup allows us not only to fully identify both fission fragments, but also to measure the gammas and neutrons emitted by chance. We can also use quasi-free scattering (p,2p) reactions to induce fission and determine the excitation energy of the fissioning nuclei by measuring the momenta of the two outgoing protons. This new technique was the basis of the S455 proposal led by our group. The aim of the experiment was to study the evolution of the fission shell effects with the excitation energy.
Contrary to the current understanding that fission yields are dominated by deformed nuclear shells, the results obtained in this experiment allowed us to demonstrate that both types of nuclear shells, spherical and deformed, determine the fission yields. These results have been included in two doctoral theses (A. Graña and G. García) and will be published shortly.

Additionally, as members of the R3B collaboration, we actively participate in its experimental campaigns. In particular, throughout 2025, we will be involved in two key campaigns: one focused on studying the nuclear matter equation of state, specifically its asymmetric term (ASY-EOS II), and the other dedicated to the first study of hypernuclei production and characterization. In this second campaign, we aim not only to gather data on the production cross-sections of various light hypernuclei but also to determine the matter radius of the hyperhalo candidate 3ΛH through interaction cross-section measurements in heavy-ion collisions.

Contribution to the design and construction of the R3B experiment at GSI/FAIR.

Since the inception of R3B, we, the signatories of this project, have made clear our commitment to the development of advanced instrumentation for this versatile but complex experimental setup. Our main contribution is the CALIFA calorimeter, the key detector in this experiment, which will be used to study most of the physical cases presented in R3B. The PI of this project, DCG, coordinated the R3B calorimeter working group until 2018 (since then, she has been the spokesperson of the R3B experiment) for the period 2017-2025.) The main results of this working group are summarised in the approved Technical Design Reports for the CALIFA Barrel and Endcap sections (DCG as convenor of the documents). We have had a leading role in the tasks related to the general design of CALIFA, the selection and characterisation of the detection units necessary to meet the requirements of CALIFA, the selection and characterisation of the readout, the construction and commissioning of the different demonstrators and the decisive contribution to the design and construction of the internal (the entire production of the carbon fibre moulds of CALIFA were built in UVigo) as well as the external mechanical and support structure, both completely manufactured in Galicia.

In the last years, our main contribution has been the completion, installation and commissioning of the detection units covering the most forward angles, which were installed in CALIFA in January 2024 and performed excellently during the 2024 campaign .

Some publications related to this work are (Gar24,Kny19,Kny20,Kny21,Pie16).
All these achievements have been made possible thanks to the funding secured through various projects: PID2021-125771NB-C2, PGC2018-099746-B-C2, FPA2015 -69640-C2-1-P, FPA47831-C2-1P, FPA2012-39404-C02-01, FPA2009-14604 -C02 -01).

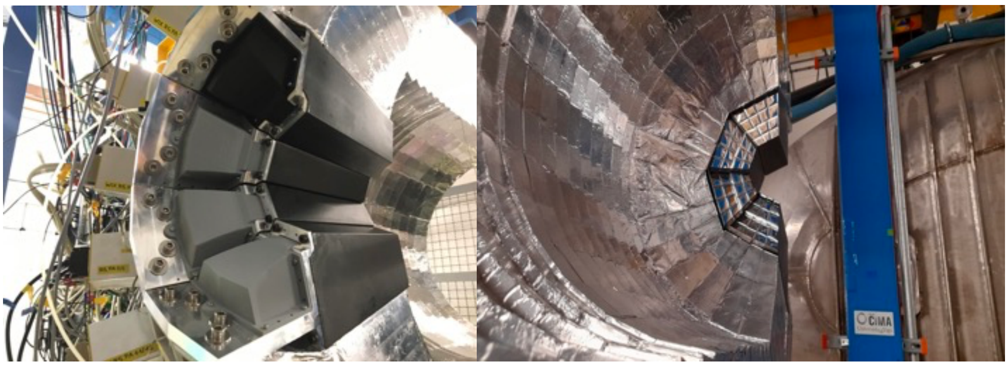

Fig.3 - Pictures showing the implementation of CEPA-CsI @ R3B cave

REFERENCES

[Ata18] L. Atar et al. with D. Cortina and J. Benlliure, PRL 120 (2018) 052501
[Ben19] J. Benlliure et al. NIMA 916, 158 (2019)
[Boi22] J.M. Boillos et al. with D. Cortina and J. Benlliure, PRC 105 (2022) 014611
[Bri22] J.A. Briz et al. with E. Nacher, IEEE Trans. on Nucl. Science 69 (2022) 696
[Cha17] S. Chakraborty et al. with D. Cortina, 96 (2017) 034301
[Cha19] A. Chatillon et al. with J. Benlliure and D. Cortina, PRC 99 (2019) 054628
[Cha20] A. Chatillon et al. with J. Benlliure and D. Cortina, PRL 124 (2020) 202502
[Cha22] A. Chatillon et al. with J. Benlliure and D. Cortina, PRC 106 (2022)024618
[Dat16] U. Datta et al. with D. Cortina, PRC 94 (2016) 034304
[Dia20] J. DÍaz-Cort.s et al. with J. Benlliure, PLB 811 (2020) 135962.
[Dia18] P. Diaz Fernandez et al. with D. Cortina and J. Benlliure, PRC 97 (2018) 024311
[Due22] M. Duer et al. with D. Cortina, Nature 606 (2022) 678
[Gar24] G. Garcia-Jimenez et a with J. Benlliure and D. Cortina, NIM A 1059 (2024) 169003.

[Hei23] M. Heil et al. with J. Benlliure and D. Cortina EPJA 58 (2023) 248
[Hol19] M. Holl et al. with D. Cortina, PLB 795, (2019) 682 – 688
[Kny19] A. Knyazev et al. with D. Cortina, NIMA 940 (2019) 393 - 404
[Kny20] A. Knyazev et al. with D. Cortina, NIMA 975 (2020) 164197
[Kny21] A. Knyazev et al with D. Cortina, NIMA 1003 (2021), 165302
[Leh22] C. Lehr et al. with D. Cortina, PLB 827 (2022) 136957
[Leh22] C. Lehr et al. with D. Cortina, PLB 827 (2022) 136957
[Mar15] J. Marganiec et al. with D. Cortina, EPJA 51 (2015) 9
[Mar16a] J. Marganiec et al. with D. Cortina, PLB 759 (2016) 200-205
[Mar16b] J. Marganiec et al. with D. Cortina, PRC 93 (2016) 045811
[Mar15] J.F. Martin et al. with D. Cortina, EPA. 51 (2015)
[Mar20] L. Martin et al. with J. Benlliure, HPLSE 8, e18 (2020)
[Mar21] JF. Martin et al. with D. Cortina, PRC 104 (2021) 014611
[Nac15] E. Nacher et al. with D. Cortina, NIMA 769 (2015) 105-111
[Nac23] E. Nacher et al., EPJ Web of Conferences 290, 08007 (2023)
[Nac24] E. Nacher et al. EPJPlus 139 (2024) 404
[Osv24] K. Osvay et al. with J. Benlliure, Scientific Reports 14, 25302 (2024)
[Pan16] V. Panin et al. with D. Cortina, PLB 753 (2016), 204 - 210
[Pan19] V. Panin et al. with D. Cortina, PLB 797 (2019) 134802
[Pon24] L. Ponath et al. with J. Benlliure and D. Cortina, PLB 855 (2024) 138780
[Pel17] E. Pellereau et al. with J. Benlliure and D. Cortina, PRC 95 (2017) 054603
[Pie16] B. Pietras et al. with D. Cortina, NIMA 814, (2016) 56 - 65
[Rev18] A. Revel et al. with D. Cortina, PRC 120, (2018) 152504
[Rib18] G. Ribeiro et al. with E. Nacher and D. Cortina, PRC 98 (2018) 024603
[Rod15a] J. L. Rodriguez-Sanchez et al. with J. Benlliure, PRC 91 (2015) 064616
[Rod15b] J. L. Rodriguez-Sanchez et al. with J. Benlliure, PRC 92 (2015) 044612
[Rod16a] J. L. Rodriguez-Sanchez et al. with J. Benlliure, PRC 94 (2016) 034605
[Rod16b] J. L. Rodriguez-Sanchez et al. with J. Benlliure, PRC 94 (2016) 061601
[Rod17] J. L. Rodriguez-Sanchez et al. with J. Benlliure, PRC (2017) 034303
[Rod20] J.L. Rodriguez-Sanchez et al. with J. Benlliure, PLB 807 (2020) 135565.
[Roe16] M. Roeder et al. with D. Cortina, PRC 93 (2016) 065807
[Syn20] I. Syndikus et al. with D. Cortina, PLB 809 (2020) 135748.
[Thi16] R. Thie et al. with D. Cortina, PRC 93 (2016) 054601.
[Van17] M. Vandebrouck et al. with D. Cortina, PRC 96 (2017) 054305
[War18] F. Warmers et al et al. with D. Cortina, PRC. 97 (2018) 03461
[War23] F. Warmers et al. with D. Cortina, EPJA 59 (2023) 154
[War24] F. Warmers et al. with D. Cortina, PRC 109 (2024) 054602