Ricardo Americo Broglia (1939-2022)

We started working with Ricardo in 1983-1984, when we went to Copenhagen after our master's degree, and we have collaborated with him without interruption until his death on October 4th, 2022. In the following, we provide an outline of his scientific activity. This is not an easy task, because Ricardo coauthored around 500 papers, collaborating with around 150 theorists and with many experimentalists as well. A comprehensive curriculum can be found at the following link: `https://home.mi.infn.it/broglia_CV.pdf`

Ricardo Americo Broglia was born in Cordoba, Argentina, in 1939. He started his Master studies at Instituto Balseiro of the University of Cuyo in Bariloche and then went to Buenos Aires to pursue his Ph.D. under the supervision of Daniel R. Bès. This is how he later recollected those years:

I went to Buenos Aires to do my doctoral thesis with Daniel Bès, who had just returned from the Niels Bohr Institute in Copenhagen after a 10-year internship. In his luggage, in addition to porcelain from Kongelig Fabrik, he carried three or four central problems of nuclear physics of the time, problems that in less than two years a group of four very young people (Zuker, Federman, Maqueda, Broglia) have solved,in a continuous discussion, and open to all members of the group. So open that we often forgot to whom the research topic under discussion "belonged". Typical of this magical atmosphere of a high-level school is the fact that I wrote Maqueda's doctoral thesis and he wrote mine (the assignments had already been approved by the teaching staff).

In 1965 Ricardo published his first scientific work about the pairing plus quadrupole interaction, together with Daniel R. Bès and Ernesto Maqueda. Shortly thereafter, he published with Bès the first quantitative study of collective vibrational modes based on fields which create or annihilate two particles, *i.e.*, pairing vibrations. The fundamental importance of these modes had been underlined a few years earlier by Aage Bohr. This would become one of Ricardo's favourite research themes throughout his scientific life.

In 1965 Ricardo moved to Copenhagen, where he became a fellow of the Niels Bohr Institute (NBI) up to 1968, and then a staff member in 1970, after a two-year stay at the University of Minnesota. The NBI had been founded in 1921 by Niels Bohr, and had been one of the cradles of quantum mechanics. When Ricardo arrived in Copenhagen, the NBI was hosting one of the most important groups in the world for the study of nuclear physics, led by Niels Bohr's son Aage Bohr and by Ben R. Mottelson, who would jointly be awarded the Nobel Prize in Physics in 1975. Ricardo joined this group with much success, working on many different aspects of nuclear structure and reactions. Scientific activity at the NBI was characterized by a strong collaboration between theorists and experimentalists. Ricardo recalled his first impressions of the NBI as follows:

In the morning of 4th October 1965, I sat in a rather crowded Auditorium of the NBI to attend the first of a series of lectures on nuclear reactions which were to be delivered by Ben Mottelson. In the following spring term, the Monday lectures were expected to deal with the subject of nuclear structure and the lecturer to be Aage Bohr. After Ben's lecture, an experimental group meeting took place in which experimentalists, as it was the praxis, showed their spectra, likely not yet completely analyzed, while theoreticians attempted at finding confirmation of their predictions in connection with specific peaks of the spectra.

Ricardo embarked on a systematic study of two-nucleon transfer reactions, calculating cross sections for the population of 0+ states, clarifying the role of pairing vibrations as elementary modes of excitations in closed shell nuclei and of pairing rotations in superfluid nuclei as well as establishing the parallel between pairing and surface vibrational modes. This work was summarized in a review written together with Ole Hansen and Claus Riedel (1973). He carried out intense and important work on direct, deep inelastic and fusion reactions in collaboration with a number of theorists, including Carlos H. Dasso, Henning Esbensen, Stephen Landowne, Giovanni Pollarolo and Andrea Vitturi. He developed a particularly close collaboration with Aage Winther, that subsequently led to their well-known monograph on direct *Heavy Ion Reactions* (1991) based on semiclassical theory. All along his career, Ricardo viewed structure and reactions as the two inseparable sides of the same coin, striving to get a coherent description of the two fields, as evidenced by another book on the subject published in 2021 with Gregory Potel (see the contribution by Potel himself).

The essential role played by the concept of elementary degrees of freedom in the approach of the Copenhagen school led to the development of a theoretical framework able to deal with the coupling between the particles and the collective nuclear motion systematically. In the introduction to a recent collection of Aage Bohr's works (see the contribution by Christian Joas), Ricardo vividly recalls the development of Nuclear Field Theory (NFT), that he carried out in collaboration with Aage Bohr, Ben R. Mottelson, Roberto Liotta, Pier Francesco Bortignon and with the Buenos Aires group led by Daniel R. Bès between 1972 and 1976. Patterned after Quantum Electrodynamics, NFT is built on a basis of single particles and phonons. The overcompleteness of the basis, ensuing from the underlying fermionic nature of nuclear vibrations, as well as the Pauli principle are both taken exactly into account, by introducing a set of appropriate diagrammatic rules to be adopted in the perturbative expansion. NFT was explicitly proven to be equivalent with the Feynman-Goldstone approach based on fermionic degrees of freedom. The advantage of NFT rests on its rapidly convergent character, and this theory was applied by Broglia and Bortignon in systematic studies of the strength functions of single-particle states as well as of Giant Resonances. The main results were reported in two well-known review papers written in collaboration with George F. Bertsch (1983) and Claude Mahaux (1985).

Their findings highlighted the fundamental role of the particle-hole interaction mediated by the exchange of low energy phonons, which gives rise to a systematic reduction of the width of the Giant Resonances, as compared to the sum of the widths of the particles and of the holes on which they are built. The extension of these works to the case of collective motion at finite temperature and angular momentum was particularly fruitful.

On the one hand, Broglia and Bortignon studied the different processes leading to the relaxation of Giant Resonances, disentangling the role played by static deformations as well as by quantal and large amplitude thermal fluctuations, together with (among others) Isabel Gallardo, Erich Ormand, Gianluca Colò and Paola Donati, and in close collaboration with the experimental groups (see the book on *Giant Resonances* they wrote together with Angela Bracco, Ricardo's wife (1998)).

On the other hand, together with Bent Lauritzen, Thomas Døssing and Ben Mottelson, Broglia provided a seminal contribution to the understanding of the properties of rotational motion in warm deformed nuclei at high spin (see the contribution by Døssing). It was found that the gamma-gamma correlation pattern expected for regular collective rotational bands is washed out by the mixing produced by the residual interaction, which leads to a fragmentation of the quadrupole strength. This is the phenomenon of rotational damping, which was confirmed by intense experimental investigations carried out with the technique of gamma ray coincidences by Bent Herskind and his collaborators, including Angela Bracco and Silvia Leoni from Milano and the Japanese theorist Masayuki Matsuo. Ricardo developed a close collaboration with the international experimental gamma spectroscopy community, and he was for some time the chairman of the steering committee of the EUROBALL project. He was also a member of the Program Advisory Committee of the INFN Laboratories in Legnaro.

In 1985, Ricardo became Professor of Physics at the University of Milano, keeping his research chair at NBI. He was called to Milano "*per chiara fama*" (because of high distinction), to create a theoretical nuclear physics group, that would collaborate with an active experimental group in gamma spectroscopy. In the following years, Enrico Vigezzi, Pier Francesco Bortignon and Gianluca Colò joined the group in Milano. Furthermore, Ricardo attracted several master's and PhD students. The proper understanding of the interweaving of the single-particle motion with the static and dynamic deformations of the surface of finite many-body systems remained a red thread of Ricardo's research. NFT was applied to the study of density distributions, providing a microscopic foundation for the picture of zero-point fluctuations of the nuclear surface, which was applied rather successfully to isotope charge-radius and mass-radius anomalies. This study was carried out in collaboration with George F. Bertsch, who was one of Ricardo's long-term collaborators (they published a monograph on *Oscillations in quantal Fermi systems* together in 1994). Bertsch, Broglia, Francisco Barranco and Enrico Vigezzi devised a "*hopping model*" for large amplitude motion based on configurational changes occurring by jumps of two neutrons between the members of a discrete Hartree-Fock basis under the action of the residual pairing force. The hopping model was applied to the calculation of the lifetimes associated with fission and cluster emission, as well as to the decay of K-isomers and superdeformed bands, in collaboration with Yoshifumi R. Shimizu.

The experience gained in the study of nuclei later benefited the investigation of the properties and the response of metal clusters and fullerenes leading to a book on the *Solid State Physics of Finite Systems* published with Gianluca Colò, Giovanni Onida and Hector E. Roman in 2004. The analogies between femtometer- and nanometer-materials were beautifully summarized by Ricardo in a paper for the 500th issue of *Surface Science* (2002). Ricardo also promoted the creation of a laboratory for the study of metal clusters in Milano (see the contribution by Paolo Milani).

In the second half of the 1990s, Ricardo started a long-term activity in the study of protein folding, which is summarized in the contribution by Guido Tiana. He continued working in nuclear physics, focusing on the interplay between surface vibrations and nuclear superfluidity. In collaboration with Henning Esbensen, Jun Terasaki and Peter Schuck, it was found that the interaction induced by the exchange of low-lying collective phonons significantly reinforces the bare pairing interaction inferred by the nucleon-nucleon phase shifts. The pairing gaps obtained by summing the two contributions lead to values compatible with those extracted from the odd-even mass differences or from effective interactions, like the Gogny force. These findings led to studies of many-body renormalization effects in superfluid nuclei, including the fragmentation of quasiparticle strength, which could shed light on the origin of superfluidity in nuclei (see the monograph on *Nuclear Superfluidity* (2005) written by Broglia together with David M. Brink); the parallel with the case of condensed matter exerted a strong fascination on Ricardo, who was much influenced by the work of Philip W. Anderson. He was struck by the fact that nuclear physics was almost ignored during the celebration of the 50th anniversary of BCS theory, and reacted by editing a volume on *50 Years of Nuclear BCS*, published together with Vladimir Zelevinsky in 2013.

Renormalization effects associated with the coupling of particles and vibrations play a particularly prominent role in the case of halo nuclei, where they can determine the stability of the system, as in the case of the paradigmatic two-neutron halo nucleus ^{11}Li, and can dramatically change the level ordering, as in the case of the parity inversion of the ^{11}Be ground state. The validity of the NFT approach was confirmed by a two-neutron stripping experiment on ^{11}Li populating the ground and excited states of ^{9}Li. The experimental cross sections were accurately reproduced using the NFT wave functions as input of the second order DWBA calculations.

Ricardo was fascinated by the parallel between two-nucleon transfer between superfluid nuclei and Josephson electron tunneling in superconductors. In either case, the probability of successive transfer of the members of a Cooper pair is enhanced by strong coherence effects, and is of the same order as the one-particle transfer probability. Taking into account the effective charge of neutrons due to the recoil effects of the centers of mass of the colliding nuclei, Broglia predicted the emission of electromagnetic radiation of frequency Q/h in a two-nucleon transfer collision between two superfluid nuclei, where Q denotes the Q-value. He worked in close collaboration with Lorenzo Corradi and other colleagues to determine the best way to detect such radiation. As a result, an experiment is scheduled for 2023 at Legnaro Laboratories. This represents a great challenge, stemming from Ricardo's restless scientific spirit, on which he kept working almost until his passing.

Ricardo has taught nuclear structure theory for over 40 years, and he was the director of various international schools including several "Enrico Fermi" Schools in Varenna and several Heavy Ion Physics Schools at the Ettore Majorana Center in Erice. Several of his students have become established researchers in their own right. People who discussed with Ricardo have always been struck by the way in which he explained the topics that fascinated him. Ricardo captivated his listeners, making them feel part of a world of important research. This enthusiasm sustained him right up to the end.

Francisco Barranco
Departamento de Física Aplicada III, Escuela Superior de Ingenieros, Universidad de Sevilla
Enrico Vigezzi
Istituto Nazionale di Fisica Nucleare, Milano

Ricardo was an excellent science manager, with a true sense of the potential for progress in each topic, and of the qualifications of his coworkers, who gathered around him. Discussions in his research groups were focused, and often Ricardo would ask for more evidence and for more calculations.

Based on his immense knowledge, he was a master of widening the perspective on results. For example the rather limited scope of "mixing of rotational bands" was correctly seen by him as "damping of rotational motion". He had a keen eye for grasping the essence of each topic and the results, asking for illustrative figures, which were not initially appreciated by collaborators, but which later would be shown again and again at conferences.

Ricardo could also be sharp in discussions, when assumptions or notions were contrary to his knowledge and interests. For example, in our discussions of fluctuations of rotational spectra he initially sharply opposed the assumption of random transition energies within ensembles of rotational bands, asking "how can you ignore nuclear structure?" Such a conflict inspired more investigations, a synthesis of the different perspectives was reached, and a very illustrative figure was drawn, displaying the roles of both structure and of random statistical properties.

Ricardo's extraordinary skills also encompassed writing up of results, getting them published, and making them known within the broader international community of nuclear physicists. After an afternoon discussion and collection of results, Ricardo could come to the Institute in the middle of the next day with a hand-written version of an almost complete manuscript.

Ricardo was the co-organizer of numerous workshops and conferences. He knew precisely which topics to cover, and which could lead to fruitful discussions and to progress. He created a positive atmosphere, welcoming each participant on equal footing.

Thomas Døssing
Niels Bohr Institute, Copenhagen

I met Ricardo at the beginning of the 1990s during a School in Erice. At that time, I was a PhD student working at the EPFL under the mentorship of Walt A. de Heer on the electronic and magnetic properties of small metal clusters in supersonic beams. Nanotechnology was in its infancy and a broad scientific community was interested in using the shell model developed for nuclei to model the stability and the magic numbers in the abundancies of free metal clusters.

Ricardo was one of the leading scholars in this field and I was very impressed and fascinated by his enthusiasm and broad vision. At the end of my PhD Ricardo suggested I apply for a position at the University of Milano to set up an experimental activity on free metal clusters.

When I arrived in Milano, I found a skeptical attitude toward nanotechnology among the solid state physics community. In contrast, the nuclear physics community, led by Ricardo, was very enthusiastic and gave me a lot of support. Ricardo was a very charismatic leader capable of motivating colleagues working in fields quite far from metal clusters. He was able to grasp very important aspects related to experimental activities in solid state physics, providing logistic and economical support. He was a brilliant leader, organizer and an excellent scholar able to conduct insightful connections among different disciplines.

Paolo Milani
Dipartimento di Fisica, Università di Milano

I first met Ricardo at the Milan University, where I was to spend more than 4 years, in October 2005, freshly graduated from the Sevilla University: I had to be interviewed for my first postdoc position. My PhD dealt with the foundations of quantum mechanics, and I had hardly any knowledge of nuclear physics at all! But this turned out not to be a problem: Ricardo took me to his office, where we had a lively informal discussion in front of his large blackboard about the nature of virtual states and other general aspects of quantum mechanics. I was hired, and, instead of prompting me to read a long list of papers and books on nuclear theory, Ricardo handed me two papers: one by Bohr, Mottelson, and Ulfbeck concerning the ontology of quantum mechanics, and one by P. W. Anderson discussing life as an emergent physical phenomenon. As I quickly found out, this holistic approach was typical of him. When talking about a physics problem, he would end up quoting Antonio Machado about as often as Bohr (both father and son). For him, physics was an essential element of his life, and at the same time a human activity not substantially different from that of Jordi Savall or Ortega y Gasset, for example. He didn't see physics as disconnected from art, philosophy, or music; at the same time, he found natural to work on different fields of physics, like biophysics or metallic clusters. He would often say to me "Gregory, es todo la misma cosa!" (it is all the same thing), about general subjects or problems which, unfortunately, felt completely different to me! Such was the depth of his physics insight. I will venture to say that his paradigm (for science and everything else) was to find the right degrees of freedom: once those were determined, all the mysteries would be unveiled. This gave him a sense of extreme urgency and importance to his quest for understanding ("you need to be willing to get hungry to solve a problem", he would say), and his focus and drive were truly extraordinary, unlike anything I've seen. When we were working on some particular physics problem, he would send me dozens of handwritten pages, often with wonderful drawings and interspersed with quotes from Pauli or Kierkegaard. Sometimes, he would draw in the margin a little circle with a dot in the center, with lines emanating radially from it like the rays of a small sun. This indicated the presence of particularly illuminating ideas, some of which would end up in the resulting publication.

After our first meeting in Milano, we collaborated uninterruptedly, talking almost every day (literally!). Sometimes, I would be in Oakland and he would be in his apartment in Copenhagen, and we would talk over the Internet. He would have a record on, and I could hear the faint sound of classical music coming out of my computer's speakers. Eventually, some papers and a book were published for everyone to see, but I also got something for myself. Now I know that I need to look forward to the moment in which I'll be able to say "es todo la misma cosa!".

Gregory Potel
Lawrence Livermore National Laboratory

Ricardo applied concepts of many-body theory to fields that did not seem to share anything with nuclear physics. This was the case with the problem of protein folding. In the mid-1990s, he became interested in the question of how a protein of specified amino-acid sequence can fold fast into a unique three-dimensional "native" conformation, which contributes to determining its biological function. This was one of the most challenging problems in science, and following one of his mottos, "if you want to play, play in the top league", Ricardo started collaborating with one of the top physicists studying it, Eugene Shakhnovich at Harvard University. With him and with students at the University of Milano, Ricardo started playing around with a minimal model of proteins, based on a polymer moving in a cubic lattice with heterogeneous interactions. This kind of model was barely convincing for the biochemists and biologists he tried to interact with at the time, but proved very useful to understand the physics of protein folding. Ricardo's first article in the field dates back to 1998 and was about the effect of mutations in proteins. Ricardo was very careful in writing scientific articles: polishing and adjusting the text he could easily reach twenty versions of the same manuscript.

This was the beginning of a series of works developing the idea that the folding of a protein is controlled by a few elementary structures ("hot spots") made up of a small subset of its amino acids. He borrowed this idea from his previous knowledge about the role of specific key orbitals in determining the collective properties of the atomic nucleus. With proteins, this led to interesting results in natural evolution, in pathogenic aggregation and in algorithms to predict the native conformation of proteins.

In the first years of the 2000s he started applying the results obtained with simple protein models to design a new class of drugs that inhibit the folding of proteins by blocking the formation of their hot spots, instead of capping their active site, as usual drugs do. In 2003 he promoted an experimental activity to inhibit a protein of the HIV virus. Eventually he realized that the only way to play in the top league with this project was to collaborate with a pharma company. Together with some collaborators and with Rottapharm, a company headquartered near Milano, he founded a startup to develop antiviral drugs. This project was not successful. His previous experience about physical systems helped him to focus onto the core of the problems, but was not enough to deal with all the complex details of the biological processes involved in protein folding. Nonetheless, this experimental activity yielded important byproducts in terms of basic science, improving our understanding of the non-native, disordered state of proteins.

Ricardo kept on working on the denatured state of proteins until his last days, co-authoring an article in the field in 2022, aged 82, and never losing interest in the design of folding inhibitors.

Guido Tiana
Dipartimento di Fisica, Università di Milano

I have learned a lot about physics and its history from Ricardo since I first met him in 2015. He had a very deep knowledge of nuclear physics as well as a keen awareness of the upsides and the significant limitations of the multitudinous analogies between nuclear and condensed matter physics, which is something I myself study from an historical angle. Ricardo also had a very acute understanding of the history of his own field as well as of the methods of professional historians of science. Our intention was that he would be centrally involved in a project on the history of nuclear structure physics, ca. 1950–1975, as the link between the historians and other actors in that field who are still alive, but sadly his passing has made that impossible.

A first result of this collaboration, however, did manage to see the light of day: the book titled *The Finite Quantum Many-Body Problem* (2018), an edition of selected papers of Aage Bohr, which contains an introduction that is at the same time an introduction into Aage Bohr's thought and an introduction into Ricardo's own approach to nuclear physics.

I should mention that I also learned a lot from Ricardo when it comes to matters beyond physics and its history. He was interested in the arts, music, literature, and general philosophy, and he often came to my office telling me about something or someone he just had read or re-read and thought I ought to read as well, such as most recently Simone Weil, Max Scheler, and José Ortega y Gasset.

Christian Joas
Niels Bohr Archive, Copenhagen