Research Interests – Prof. Dr. Gabriel Martínez-Pinedo

Understanding the origin of the elements that surround us has been a question of humankind since immemorial times. Research performed during the last century demonstrated that Hydrogen and Helium were produced in the early Universe only minutes after the Big Bang. Elements up to Iron, including those of fundamental importance for life on Earth, Carbon and Oxygen, are produced during the life of stars and ejected into the interstellar medium by supernova explosions. However, the origin of the heavy elements, including precious metals like Gold and Platinum and Rare Earths, remained as one of the biggest unsolved questions in physics. The solution to this question was found only recently thanks in part to research performed by my group. Our research is at the interface between nuclear physics, astrophysics, astronomy, and neutrino physics. It aims to understand how processes that occur at microscopic scales impact the dynamics, nucleosynthesis, and observational signals of macroscopic objects like stellar explosions. It benefits from data obtained at earth- and space-bound telescopes, gravitational wave interferometers and large accelerator complexes.

Stars obtain their energy by nuclear reactions successively fusing lighter elements to heavier ones up to Iron. Under stellar conditions, the synthesis of elements heavier than Iron by fusion processes is suppressed due to the increasing charge of the involved nuclei. Production of elements heavier than Iron, hence, requires reactions involving neutrons. They are captured on nuclei producing new isotopes of the same element that are unstable to beta-decay. After the beta-decay, a new element is produced with a higher atomic number. Depending on the relative magnitude of the time scales for successive neutron captures and beta-decay, two possibilities emerge related to the neutron density of the astrophysical environment. At low neutron densities, the beta-decay time scale is shorter than the neutron capture time scale and we deal with the “slow” or s-process that is responsible for the production of half of the elements between Iron and Lead. For high neutron densities, the time scale for neutron captures becomes shorter than the one for beta-decay. The resulting sequence of reactions constitutes the “rapid” or r-process and involves nuclei with large neutron excess and such short lifetimes that they do not occur naturally on Earth. Hence, their study requires large accelerator facilities to produce them.

While the astrophysical site of the s-process, intermediate mass stars, is known for a long time, the identification of the site where the r-process operates remained a challenge. Research in this field faced two problems. One was to determine the astrophysical site – most likely related to stellar explosions – which provide the large amount of neutrons and matter at extremely high temperatures and densities. The second was to identify particular observational signatures that would prove the production of heavy elements at such site.

For a long time supernova explosions were considered as the astrophysical site at which heavy elements are produced by the r-process. Such an explosion is triggered by the gravitational collapse of the stellar core that leads to the ejection of the stellar mantle, including those elements produced by the star during its long life, and the formation of a neutron star. Weak interaction processes, including electron captures and neutrino matter interactions, determine the dynamics during the collapse and explosion. Our work led to an improved understanding of the conditions achieved during the supernova explosion showing that the ejected material is not neutron rich enough to allow for the operation of the r-process. Nevertheless, we showed that a new nucleosynthesis process, denoted νp-process by us, can operate in supernova explosions in which neutrinos catalyse the synthesis of nuclei like ^{92}Mo with no alternative production mechanism.

The merger of two neutron stars has been proposed as a site for the operation of the r-process as this scenario involves extremely large neutron densities found in the interior of the neutron stars. In 2010, we showed that if the r-process operates in neutron star mergers, it would produce a distinct electromagnetic signal whose observation will serve as the smoking gun conclusively demonstrating that heavy elements have been produced during the merger. The electromagnetic signal is powered by the energy liberated by radioactive decay of freshly synthesised r-process nuclei. We estimated that the signal will reach a peak luminosity corresponding to 1000 times the one of a typical nova in around a day and hence the transient was denoted a “kilonova”. In August 2017, a kilonova was observed for the first time following the merger of two neutron stars previously detected in gravitational waves (GW170817). The observed signal matched our predictions and demonstrated that neutron star mergers produce heavy elements answering the long-standing question of their origin.

The combined observation of neutron star mergers in both electromagnetic and gravitational waves constitutes a pioneering advance in multi-messenger astronomy that opens new possibilities to understand the dynamics of these objects, the physics of high density matter and the operation of the r-process. However, most of the nuclei involved in the r-process could not yet be produced in the laboratory. Hence, their properties, necessary to model the r-process, must be computed theoretically. An important focus of our research is the development and application of modern many-body methods to describe the nuclear reactions occurring during the r-process. These theoretical advances together with laboratory experiments and multi-messenger observations open new opportunities to understand which elements and under which conditions are produced in mergers. The focus of our future research is to identify signatures that characterise the production of specific elements in mergers. The aim is to clarify whether neutron star mergers are the only astrophysical site of the r-process or whether other sites also contribute to the production of heavy elements in the Universe. The answer to this question is fundamental to understanding the history of element production in our galaxy, the Milky Way.

Our research will benefit immensely from the construction of new accelerator facilities, which will for the first time allow for the production of hundreds of r-process nuclei and the measurement of their properties, the study of matter at the high densities and temperatures found in neutron star mergers using ultrarelativistic heavy ion collisions, and the determination of the atomic properties that influence the kilonova emission. The leading role is played here by the Facility for Antiproton and Ion Research (FAIR), which is currently being built as a large-scale international research facility as an extension of the GSI Helmholtz Center in Darmstadt.