The main aim of the field of nuclear astrophysics is to understand the production of energy and the synthesis of elements in stars and during stellar events. Both processes occur through nuclear reactions [1]. In "quiet" stars like our sun, and in general during non-violent stellar events, the rate of these nuclear reactions is much smaller than the average decay rate of the radioactive nuclei which are often produced by the reactions. In consequence, these radioactive nuclei have ample time to decay before becoming involved in other nuclear reactions, so that mostly reactions between stable nuclei are important.

It is believed that, during "violent" stellar events, examples of which will be given below, the opposite situation prevails, i.e. the average time between successive nuclear reactions is much shorter than the average decay time of the radioactive nuclei. These nuclei do not have time to decay before participating in new nuclear reactions, so that reactions in which at least one of the two partners is radioactive (the other one often being a proton or an α-particle) then become very important. It is thus essential, in order to fully understand these violent events, to know the decay properties of the radioactive nuclei produced (half-lives, decay modes etc.) and the cross sections for nuclear reactions in which they are involved. In the present article, we will show that radioactive beams are very useful for the determination of these decay properties and nuclear reaction cross sections.

To measure the cross section of a nuclear reaction in which one of the two partners is radioactive and the other is stable, two methods can be used: the "radioactive target" method, in which the radioactive partner is incorporated in a target which is bombarded by beams of the stable partner; or the "radioactive beam" method, in which a beam of the radioactive partner is produced and used to bombard a target containing the stable partner. It can be shown [1] that, for half-lives of the radioactive partner less than about one hour, the radioactive beam method is more efficient, whereas above one hour, the radioactive target method is preferable.

Most of the radioactive nuclei involved in stellar nuclear reactions belong to the first category, so that the development of radioactive beams is necessary for these cross section measurements. Furthermore, radioactive beams are also very useful to determine the decay properties mentioned above, in particular for very exotic nuclei which often play important roles in the violent stellar events. These statements will be illustrated below.

Violent stellar events

The most spectacular violent stellar events are supernovae, during which the luminosity of a pre-existent star increases suddenly, by factors of 10^6 to 10^9, and later returns to the luminosity of a "normal" star. The so-called type II supernovae correspond to the "death" of a massive star, with a mass between 8 and 100 solar masses, which has undergone the various stages of stellar evolution, from the main sequence phase to the formation of an iron core [1]. At the end of the "life" of such a star, the core collapses as a result of gravity, leading to an implosion followed by a gigantic explosion, the origin of the luminosity increase.

The remnants of such an event include a neutron star, i.e. a very small and very dense object which has many similarities with a giant nucleus, and the supernovae ejecta [2]. During a supernovae event, the temperatures and densities are such that the conditions described above, viz. nuclear reaction rates much higher than average radioactive decay rates, are fulfilled: radioactive nuclei, and the nuclear reactions in which they are involved, play important roles. One of the stellar processes which probably occurs in supernovae is the so-called r-process or rapid-neutron-capture nucleosynthesis [3]. This process involves multiple radiative neutron capture by some target or "seed" nucleus, which are so rapid that the radioactive nuclei created generally do not have time to decay between successive neutron captures.

The r-process is responsible for the

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**Fig. 1. Schematic model of a novae phenomenon.** Matter ejected from a (large) red giant is attracted by a (small) white dwarf, and splashes onto its surface.

**Fig. 2. The cold and hot CNO cycles.**
existence, in the universe, of the so-called r-nuclei, i.e. the neutron-rich isotopes of the stable elements, and of the heavy radioactive elements Th and U. In order to fully understand the r-process, the decay properties of many very exotic neutron-rich nuclei, and the cross sections for the radiative neutron capture reactions in them, have to be determined.

The most frequent violent stellar events which can be observed in the sky are novae, during which the luminosity of a pre-existent star increases suddenly, as for supernovae, but only by factors of 10⁴ to 10⁵, and later decreases to the original star luminosity. The "star" in which this occurs is a close binary system (about 50% of the "stars" observed in the sky are in fact binary systems), which comprises a white dwarf and a red giant. A white dwarf represents the outcome of the white dwarf and a red giant. Matter emitted by the red giant is attracted by the members of the binary system, matter burning phase [1]. As shown in Fig. 1, because of the proximity between the two members of the binary system, matter ejected by the red giant is attracted by the white dwarf. After some spiralling around it and formation of a so-called accretion disk, this matter splashes onto the surface of the white dwarf at a very high velocity.

The impact causes a rapid increase in the surface temperature, up to values between 0.1 and 0.5 x 10⁶ K, leading to the so-called thermonuclear runaway, triggering an explosion at the surface and inducing the luminosity increase [4]. The temperatures and densities which prevail at the surface of the white dwarf during the nova phenomenon are such that some nuclear reaction times become shorter than the decay times of the radioactive nuclei produced. The most important of these reactions is the radiative proton capture on ¹⁴N, i.e. ¹⁴N(γ,p)¹⁵O. The latter reaction distinguishes the so-called "hot CNO cycle", with the following reaction and decay sequence:

\[
¹⁴C(p,γ)¹⁵N(p,γ)⁰⁴O(β⁺νe)¹⁴N(p,γ)⁰⁴O(β⁺νe)\]
\[
¹⁴N(p,α)⁰⁴C
\]  

(1)

from the so-called "cold CNO cycle", with sequence:

\[
¹⁴C(p,γ)⁰⁴N(β⁺νe)⁰⁴C(p,γ)¹⁴N(p,γ)⁰⁴O(β⁺νe)\]
\[
¹⁴N(p,α)⁰⁴C
\]  

(2)

The cold CNO cycle is an important source of energy in the main sequence stars, i.e. stars at the hydrogen burning stage, and it contributes a few percent to the energy generation by our sun. The hot CNO cycle is a crucial element in the thermonuclear runaway during the nova events: its characteristic time is that of the longest half-life of the radioactive nuclei it contains, i.e. ⁴⁰Ca (T₁/₂ = 2 min.), which is five times smaller than for the cold CNO cycle which includes the β⁺-decay of ¹⁵N (T₁/₂ = 10 min.). Consequently, the rate of energy production by the hot CNO cycle is about five times higher than by the cold CNO cycle. The two cycles are schematically represented in Fig. 2. In order to determine the stellar conditions under which the cold and the hot CNO cycles respectively dominate, it is crucial to know the cross section of the ¹⁴N(p,γ)⁰⁴O reaction, which competes with the β⁺ decay of ¹⁵N as shown in (1) and (2) above.

A third type of violent stellar event is represented by X-ray bursts, during which "objects" emitting X-rays undergo a sudden increase in their X-ray luminosity followed by a fading to the preburst level of X-radiation; these bursts are repeated by the same object at irregular intervals. The origin of these events is believed to be similar to that of novae. X-ray bursters are also close binary systems, comprising a neutron star and a companion star, for example a red giant. Matter emitted by the companion star is also accreted at the surface of the neutron star, where it induces uncontrolled thermonuclear reactions leading to the sudden increase of X-ray emission [5]. The temperatures and densities at the surface of the neutron star during an X-ray burst are also high enough to allow nuclear reactions between radioactive nuclei to occur. They are however higher than during the nova phenomenon (the temperatures ranging from 0.7 to 1.5 x 10⁹ K), so that "more difficult" reactions, i.e. with lower cross sections, may occur. Of the latter reactions, the sequence:

\[
α(α,γ)⁰⁴Ne(γ,p)⁰⁴Na
\]  

(3)

leads to a so-called "escape" from the CNO cycles, because it transforms CNO elements into ⁰⁴Na, which cannot be converted back into lighter nuclei. From there on the so-called r-process, or rapid-proton-capture nucleosynthesis, may occur. This process is somewhat analogous to the r-process mentioned above since it involves multiple radiative proton capture reactions on proton-rich nuclei, and it may lead to the nucleosynthesis of medium mass nuclei up to the Kr region. In order to fully understand the escape from the CNO cycles and the rp-process, the decay properties of the very exotic proton-rich nuclei up to mass 80, and the cross sections for nuclear reactions involving them, such as those of sequence (3), have to be determined.

These are some examples of violent events encountered in nuclear astrophysics. Others, like type I supernovae, primordial nucleosynthesis and possibly γ-ray bursts, will not be discussed further.

Production of radioactive beams for nuclear astrophysics

Two general methods are used to produce radioactive beams for nuclear astrophysics: the Isotope Separator On Line (ISOL) or two-accelerator method, and the fragmentation method. In the ISOL method large quantities of radioactive nuclei are generated by bombarding a thick (primary) target with high-intensity primary stable beams, protons, light or heavy ions, produced by a first accelerator (or with the neutrons of a nuclear reactor). Many different radioactive nuclei are thereby produced, depending on the type and energy of the projectiles, which are stopped in the target. These nuclei are extracted from the target as atoms or molecules, transformed into ions by a suitable ion source, mass-separated by an Isotope Separator On Line, and subsequently accelerated by a second accelerator.

The radioactive secondary beams thereby obtained are projected onto a (secondary) target, where nuclear reactions of astrophysical interest can be observed, or are collected by a catcher, where nuclear spectroscopic experiments can be performed. The energies of these secondary beams range from a few tens of keV (absolute) to a few tens of MeV per nucleon, depending on the subsequent accelerating scheme. In the lower limit, i.e. near Isotope Separators On Line, spectroscopic experiments on very exotic nuclei, proton- or neutron-rich, can be performed whose significance for nuclear astrophysics has been emphasized above. In the upper limit, and especially between 0.2 and 1 MeV per nucleon, one can directly measure the cross sections for nuclear reactions of astrophysical interest involving radioactive nuclei. Examples of such experiments carried out in European laboratories will be described below.

In the fragmentation method, a high energy (from several tens to several hundreds of MeV per nucleon) primary heavy-