Exotic beams produced by fast neutrons

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First results from the research and development program PARRNE (Production d'Atomes Radioactifs Riches en NEutrons) are presented. Its aim is the investigation of the optimum conditions for the production of neutron-rich fission fragment beams extracted from thick targets irradiated by fast neutrons. [S1098-4402(98)00001-9]

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On several recent occasions, it has been established that neutron-rich beams with energies around the Coulomb barrier will provide a wealth of new opportunities in nuclear structure physics [1,2]. Fission is a very powerful mechanism to produce such beams, e.g., the ISOLDE facility has used high-energy proton induced fission for many years [3]. Inverse kinematic fission of relativistic projectiles has allowed the first synthesis of ^{78}Ni [4] at the GSI fragment separator; thermal neutron induced fission is used to study the region around ^{132}Sn at Studsvik [5] and is at the basis of projects for radioactive beam facilities at Grenoble (ILL) and at Munich [6]. Proton induced fission allows particularly high luminosities ($L \sim 10^{13}$ b^{-1} s^{-1}), fragment separators excel in the efficient selection of very short-lived species ($L \sim 10^3$–10^6 b^{-1} s^{-1}), whereas the highest cross sections in the top of the isotopic distribution are found for thermal neutrons ($L \sim 10^{11}$ b^{-1} s^{-1}).

A novel concept has been proposed by Nolen [7]: Fast neutrons may be used for achieving the highest possible luminosities without dissipating too much power in the fissioning target, the traditional Achilles heel of charged-particle-induced reactions. Indeed, by breaking up an intense deuteron beam ($E = 100$–300 MeV) in a dedicated (and well-cooled) converter, and irradiating a thick fission target by the secondary neutrons flux, the luminosities may, at least in principle, exceed $L = 10^{15}$ b^{-1} s^{-1} [7]. Of course, the challenge consists in the research and development (R&D) for a device in which the produced activities are transferred to an ion source with high efficiency. This will be crucial for the viability of projects like the one proposed by the Argonne laboratory [8]. It will also be of high interest for radioactive beam facilities under construction [1,2], which like SPIRAL at GANIL (Caen, France) may benefit from an intense deuteron beam.

We have decided to build a test bench for the R&D with thick fission targets at the 15 MV tandem of IPN Orsay where a 1 μA deuteron beam is available. Literature on cross sections [9] shows that the threshold for fast neutron induced fission on ^{238}U is at 2 MeV. It rises from 0.5 b by a factor of 3 for a tenfold energy increase.

In a first test, PARRNE-0, a 1 mm thick and 30 mm diameter uranium disk was irradiated for 2 min by neutrons produced from a 20 MeV, 100 nA deuteron beam stopped in a carbon covered Faraday cup 7 cm in front of the U disk. Under these conditions the neutron flux estimated with a Rem counter is about 10^8 n/s. Off-line γ-ray spectroscopy showed that it is easy to identify numerous radioactive species with a neutron excess of up to 10; see Table I. This validates the method in accordance with a somewhat similar recent test at Cyclotron Laboratory of Michigan State University (see [8]).

We now have constructed a first version of an UC_x target, PARRNE-1, containing 20 g of uranium, which is heatable up to 2000 °C for fast effusion of the produced activity. A graphite container housing 50 disks of UC_x with a diameter of 14 mm, surrounded by a heated Ta tube, was kept in a vacuum vessel with 1 mm thin Al window. This vessel was installed at the end of a beam line from the tandem. The deuteron to neutron converter was a 3 mm thick Be disk placed 8 cm in front of the UC_x target. The neutron flux was about 10^8 n/s, derived from an activation measurement. The effective deuteron energy after a window in the beam pipe was about 15 MeV. The target container had a 10 mm opening in the middle to which a 7.2 m long transfer line, through a 1 m concrete shielding, was connected. Thus the activity could be collected under good background conditions for γ-spectroscopy measurements. We collected the noble gases Kr and Xe on a cold Cu finger. The latter was kept below 20 K by means of a cryogenerator. Table II

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TABLE I. Production of neutron-rich species in a 1 mm thick U metallic disk by neutrons from a C target exposed to a 20 MeV, 100 nA deuteron beam. N_0 indicates the total number of atoms produced and R the rate per micro Coulomb of deuterons and gram of uranium.

Isotope	$T_{1/2}$	N_0 [10^6]	R [$10^3/\mu$C g]
^{84}Se	3.1 min	1	6.9
^{86}Br	54 s	0.8	9.7
^{89}Kr	3.07 min	4.1	30
^{90}Kr	32.32 s	1.6	25
^{94}Sr	1.24 min	5.7	54.9
^{103}Tc	54.2 s	6.3	6.9
^{132}Sn	40 s	0.5	6.2
^{132}Sb^m	2.8 min	3.4	25
^{133}Sb	2.3 min	3	23
^{136}I^g	1.38 min	2.3	20.8
^{136}I^m	46 s	0.8	9.7
^{140}Cs	1.07 min	3.8	39.6
^{137}Xe	3.83 min	6.6	45.2
^{139}Xe	39.5 s	1.4	20.1
^{144}La	40.7 s	2	27.8
^{145}Ce	3 min	3.7	26.4

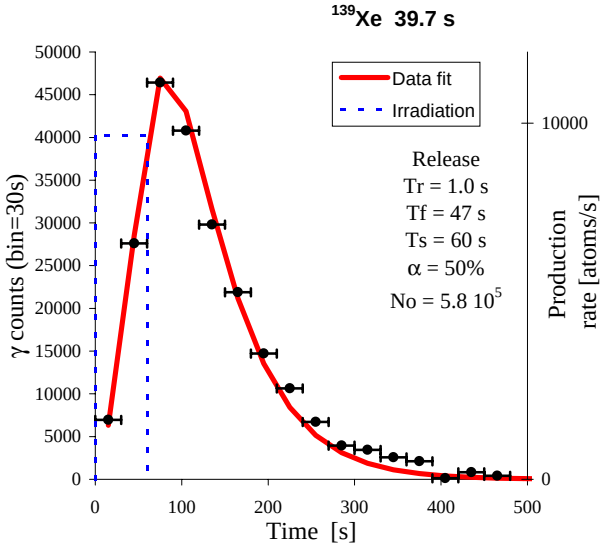

FIG. 1. (Color) Time distribution for release and transport of ^{139}Xe observed at cold finger. The solid line corresponds to a fit (see text).

shows the collected yields for ^{90,91,92}Kr and ^{139}Xe. In this first test the target was intentionally kept at a relatively modest temperature ($T = 1560\,^{\circ}$C) in order to be saved for further experiments. The release and transport time distributions could be studied by pulsing the deuteron beam. Figures 1 and 2 show such distributions. The solid line corresponds to a fit with one set of four parameters developed for describing the behavior of targets at ISOLDE [10].

It is interesting to note that the observed yields (neutron luminosity $L \sim 10^7$ b^{-1} s^{-1} are only about a factor of 10^4 below those from 1 GeV protons (luminosity $L \sim 6 \times 10^{12}$ b^{-1} s^{-1}) impinging at ISOLDE on ThC targets [11]. This clearly shows the potential of the use of fast neutrons at a facility with an intense driver beam. One may note that substantially higher temperatures, i.e., 1900 °C have been used in [11], allowing significantly shorter releases. By modifications of the test setup at the Orsay tandem (effective deuteron energy, neutron angular distribution seen by the UC$_x$ target), an order of magnitude can be gained in the luminosity. The main goal of the R&D program will be to verify if a further improvement by one order of magnitude, by increasing the target thickness, can be obtained without a deterioration of the release properties. This is the aim of the setup PARRNE-2, presently under construction, where we will connect a 1^+ charge-state ion source followed by a small ISOL separator to UC$_x$ targets.

TABLE II. Yields for noble gas atoms collected on a cold finger.

Isotope	$T_{1/2}$ [s]	Yield [$1/\mu$C]
^{90}Kr	32.3	2×10^5
^{91}Kr	8.6	4×10^4
^{92}Kr	1.8	1×10^4
^{139}Xe	39.7	2×10^5

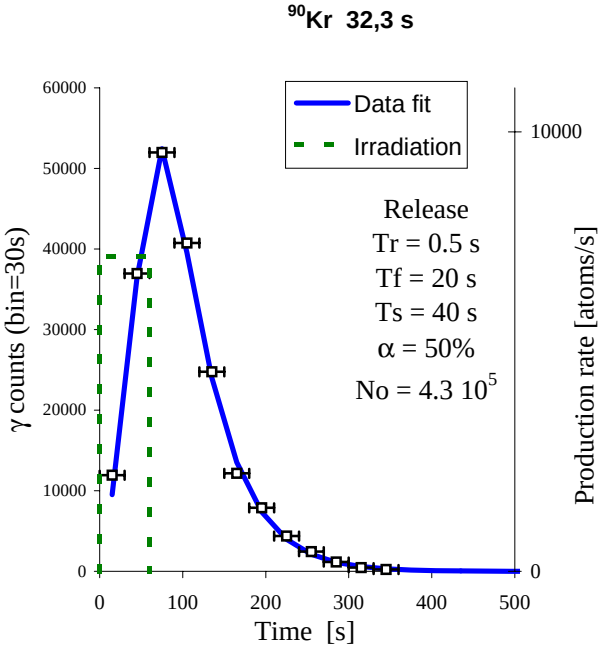

FIG. 2. (Color) Time distribution for release and transport of ^{92}Kr observed at cold finger. The solid line corresponds to a fit (see text).

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