Laser ion source for the Leuven Isotope Separator On-Line

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An on-line laser ion source has been developed and coupled to an on-line isotope separator for the production of isotopically and isobarically pure beams of radioactive ions. It is based on element-selective resonant laser ionization of nuclear reaction products thermalized and neutralized in a high-pressure noble gas after their recoil out of the target. Pure beams of ^{54,55}Ni and ^{54}Co, produced in a light-ion-induced fusion-evaporation reaction, and of ^{113}Rh, produced in a proton-induced fission of ^{238}U, were obtained. A preliminary efficiency of the ion source of ~6% for fusion reactions and of ~0.2% for fission reactions has been obtained. A selectivity of the ion source of 300 for fusion and 50 for fission reactions limited by the evacuation of non-neutralized reaction products has been achieved. © *1996 American Institute of Physics.* [S0034-6748(96)00402-9]

Modern studies of exotic nuclei far from stability require the development of an on-line element-selective target-ion source system that can deliver ion beams free of isobaric contamination.[1] The target-ion source system should fulfill the following requirements: fast extraction of the reaction products, high ionization efficiency, and high selectivity. Resonant photoionization using lasers provides a unique possibility to develop an element-selective ion source. Unlike ionization in a gas discharge plasma or unlike surface ionization, laser light can only ionize a selected element or even a selected isotope.

Radioactive atoms released from a target have to be ionized and extracted before they stick to the inner surface of an ion source. To solve this problem the method of storage in a hot cavity connected to a target has been proposed and developed.[2–6] An alternative method for storing radioactive atoms on a cold surface was proposed in Refs. 7 and 8. In this source recoil products are stopped in helium gas and transported through a capillary to the cold surface. Then the deposited activity is ablated by a laser pulse and only the desired atoms are selectively ionized by a laser beam.

Another type of an on-line laser ion source has been proposed[9,10] and a prototype was realized.[11] It combines the fast and universal thermalization of nuclear reaction products in a buffer gas, used in He jet and ion-guide techniques,[12] the high selectivity and efficiency of resonant photoionization, and the ion-storage capacity of noble gases. In this article we describe the laser ion source that was developed for the Leuven Isotope Separator On-Line (LISOL)[13] and was used for the production of isotopically and elementally pure beams of atoms produced in light-ion-induced fusion evaporation and proton-induced fission reactions.

The operational principle of the ion source is based on the resonant laser ionization of nuclear reaction products stopped in a high-pressure noble gas.[9] The cyclotron beam hits a thin target located in a chamber filled with noble gas. The nuclear reaction products recoiling out of the target are thermalized as neutrals or as 1^+ charged ions and move together with the noble gas in the direction of the exit hole. After a few milliseconds, essentially all ions are neutralized due to recombination with plasma electrons created by the primary cyclotron beam.[14] This short ion survival time is the main limiting factor in the efficiency of the standard ion guide ion system.[15] When moving toward the exit hole the atoms are irradiated by the laser beams and only the atoms of interest are selectively ionized. The laser produced ions are then transported by the gas flow through the exit hole, behind which most of the gas is removed by differential pumping. The ions are directed by the negatively polarized skimmer electrode toward the extraction electrode and the analyzing magnet of the mass separator. At the exit of the mass separator an isotopically and elementally pure beam is obtained. The element selectivity is ensured by laser resonance ionization and the isotope selectivity by the mass separator.

In order to obtain an optimal system in the sense of maximal efficiency and maximal selectivity several requirements have to be fulfilled: (1) The reaction products, recoiling out of the target, have to be stopped in the buffer gas. (2) All reaction products must be neutralized in an atomic form where laser ionization can start from. (3) The evacuation time of reaction products should be shorter than the mean diffusion time to the wall. (4) The evacuation time of reaction products should be shorter than the formation time of molecules with impurities. (5) The evacuation time should be shorter than the lifetime of the radioactive isotope. (6) The pulse repetition rate of the lasers has to be chosen in such a way that the time between the subsequent pulses is smaller than the evacuation time of the laser ionization region. (7) The survival time of laser produced ions has to be longer than their evacuation time.

The laser ion source has been installed at the front end of the mass separator LISOL, which is coupled on-line to the isochronous cyclotron CYCLONE at Louvain-la-Neuve.[16] The cyclotron delivered $^3He^{++}$ beams with an energy of 45 MeV to test the laser ion source for a light-ion-induced fusion-evaporation reaction and a $^1H^+$ beam with an energy 65 MeV for a proton-induced fission reaction.

A design of the laser ion source is shown in Fig. 1. The body of the cell is made of brass. The cyclotron beam enters the source through a 5 μm Havar window and hits one or

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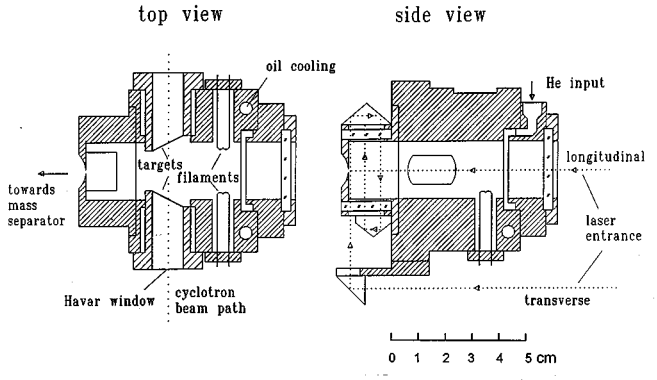

FIG. 1. Design of the on-line laser ion source. Only the configuration with uranium targets is shown.

two targets. The buffer gas (He, 500 mbar or Ar, 150 mbar) enters the cell (inner diameter 2 cm) in an axially symmetric way and moves laminarly into the direction of the exit hole, which has a diameter of $d=0.5$ mm. The measured evacuation time for atoms stopped in the center of the cyclotron beam path (29 mm away from exit hole) is equal to 25 ms in the case of He. The conductance of the exit hole (in cm^3/s) is given by the formula $c=450d^2$ for He or $140d^2$ for Ar and the evacuation time does not depend on the pressure inside the cell. Two types of targets were used. In the case of the light-ion-induced fusion-evaporation reaction an enriched ^{54}Fe target (3 mg/cm^2) was used. It was located at a distance of 3 mm from the entrance havar window and perpendicular to the cyclotron beam (not shown in Fig. 1). In the case of proton-induced fission two ^{238}U targets (10 mg/cm^2 each) were installed at the angle $\sim 30°$ relative to the cell axis in order to increase the stopping efficiency of the high recoil energy fission reaction products and to stop the reaction products further from the exit hole. To tune the mass separator, a beam of stable nickel ions can be obtained by laser ionization of nickel atoms produced by resistive heating of a Ni filament. The laser beams can enter the source in two ways, longitudinally or transversely. In most experiments we used transverse entrance and a multipass optical system consisting of two 90° quartz prisms.

To ionize the atoms a two-step two-color ionization scheme was used. The atoms thermalized in the ground state are excited by the first step laser λ_1 to the intermediate level. The second step laser λ_2 ionizes excited atoms through an autoionizing state. Table I shows wavelengths, transitions, and ionization limits of Ni, Co, and Rh. With commercially available lasers it is possible to ionize 80% of the elements of the periodical table using this two-color two-step scheme. The laser optical system consists of two excimer XeCl lasers (Lambda Physik LPX240i, 400 Hz, 150 mJ/pulse, 15 ns) and two dye lasers (Lambda Physik, Scanmate2, spectral band width 0.15 cm^{-1}). The radiation from the first-step laser is doubled in a BBO crystal to get light in the wavelength region of 230 nm. The laser beams are focused by telescopes and directed by a set of prisms into the ion source located at a distance of 15 m from the laser optical system. To tune the laser wavelengths in resonance with the atomic transitions and to keep them tuned during the experiment, a fraction of the laser beams was directed into a reference cell in which an atomic beam is produced by evaporating the investigated element from a resistively heated crucible.

The single charged ions extracted from the ion source are accelerated to an energy of 50 keV. The accelerated ions are then separated according to their mass in a 55° dipole magnet with a radius of 1.5 m. The mass resolving power ($R=M/\Delta M$) is limited by the energy spread of the ions and amounts to 300. After mass separation, the radioactive isotopes were implanted in a movable collector tape that was 6 mm wide. Behind the tape a ΔE-E telescope, consisting of a thin silicon surface barrier detector (400 μm thickness, 150 mm^2 active surface) and a plastic scintillator detector was used for the detection of the β particles. The tape was also viewed by a Ge gamma-ray detector with 70% relative efficiency. The timing of the whole setup consists of a clock system which bunches the cyclotron beam and produces trigger signals with variable delay relative to the cyclotron pulse for the lasers, the mass separator, and the detection system. Using helium as a buffer gas, the typical value for the ''ON'' and ''OFF'' period of the cyclotron beam was 40 ms.

The performances of the laser ion source has been tested over a wide range of recoil energies by using light-ion-induced fusion-evaporation reactions (^{3}He on ^{54}Fe leading to neutron deficient ^{54,55}Ni and ^{54}Co) and proton-induced fission reactions (p on ^{238}U).

A 45 MeV ^{3}He beam (with typical beam intensity of 1 μA) was used to produce nickel-55 atoms from an enriched iron-54 target by the reaction ^{54}Fe (^{3}He,$2n$)^{55}Ni. After passage through an energy degrader and the entrance window, the beam at the target had an energy of 25 MeV. Cross-section calculation for these reactions was performed with the HIVAP code[18] yielding a maximum cross section of 1.5 mbarn at a He beam energy of 25 MeV. The recoil energy of the ^{55}Ni ($T_{1/2}=204$ ms) nuclei is equal to 1.3 MeV at a

TABLE I. Transitions used for two-step laser ionization of Ni, Co, and Rh. λ_1, λ_2—wavelengths of the first- and second-step transitions, E_1,E_2—energies of the intermediate and autoionizing levels, f_{01}—absorption oscillator strength.

	First step				Second step		Ionization limit
	λ_1 (nm)	E_0-E_1 (cm^{-1})		f_{01}	λ_2 (nm)	E_2 (cm^{-1})	cm^{-1} (eV)
Ni	232.003	0–43090	$^3F_4\rightarrow{}^3G_5^0$	0.69	537.84	61678	61619 (7.64) (Ref. 17)
Co	230.903	0–43295	$^4F_5\rightarrow{}^4F_5^0$	0.045	481.90	63787	63565 (7.88) (Ref. 17)
Rh	232.258	0–43042	$^4F_{9/2}$	-	572.55	60503	60200 (7.46)

TABLE II. Production yield, efficiency, and selectivity of the laser ion source for different isotopes.

Isotope ($T_{1/2}$)	Reaction (Cross section)	Production at/μC out the target[a] (calculation)	Production ions/μC in the beam[b] (experiment)	Efficiency[b] %	Selectivity[d]
^{55}Ni (204 ms)	^{54}Fe(^{3}He,2n)^{55}Ni (1.5 mbarn)	3.6×10^{4}	1654	4.6	280
^{54}Co (193 ms)	^{54}Fe(^{3}He,2np)^{54}Co (5 mbarn)	1.2×10^{5}	7884	6.6	$>$380
^{113}Rh (2.7 s)	^{238}U(p,f)^{113}Rh (30 mbarn)	1.9×10^{6}	4264	0.22[e]	51

[a]Number of radioactive atoms recoiling out of the target per μC of primary cyclotron beam.
[b]Number of radioactive ions in the mass separated beam per μC of primary cyclotron beam.
[c][ions/s in mass separated beam]/[atoms/s recoiling out the target] (%), preliminary number.
[d]Ions/s in mass separated beam (lasers on resonance)/ions in mass separated beam (lasers off resonance).
[e]Low value is explained by low stopping efficiency in buffer gas.

projectile beam energy of 25 MeV. This leads to an effective target thickness of 0.34 mg/cm^2 and a primary production yield 3.6×10^4 atoms/μC.

The measured mass separated production yield was 1654 at/μC. This leads to a preliminary number of the efficiency of the laser ion source defined as the ratio of the measured production yield to the primary ^{55}Ni production yield of 4.6%. Further analysis of the data will finalize this number.

The selectivity of the laser ion source can be defined as the ratio of the ^{55}Ni production yield with the lasers tuned in resonance to the production yield with the lasers off resonance. The measured selectivity is equal to 280^{+350}_{-100}.

The performances of the ion source have also been tested for the proton-induced fission reactions. The main difference from the previous case consists in the much higher recoil energy of the reaction products. The fission of uranium atoms gives two ~90 MeV fragments and an isotropic distribution. Nuclei with this energy cannot be stopped by the maximum gas pressure (500 mbar He or 150 mbar Ar) and hence have to be slowed down in the target.

Two uranium targets were placed in a way to avoid direct view from the exit hole region in order to exclude thermalization in this region (Fig. 1). In this way the fission fragments are stopped further inside the cell. We concentrated our tests on ^{113}Rh which has a half life of 2.72 s and which is produced with a cross section of 30 mbarn. The rhodium atoms were ionized by laser beams entering the cell transversely. A calculation of the energy distribution of the rhodium atoms coming out of the target shows that only 1.5% of atoms can be stopped within a distance of 2.5 cm in 500 mbar He and 2.6% in 150 mbar Ar.

In conclusion, a new laser ion source has been successfully tested with light-ion-induced fusion and proton-induced fission reactions. Table II summarizes the achieved results. The obtained efficiencies are typically ten times higher than those of the standard ion guide, both for fission and fusion reactions. Additionally, selectivities around 300 for fusion and 50 for fission were reached. Although an improvement of these numbers can be expected with some modifications, already this ion source allows to extend the study of many isotopes far from stability,[19] especially in cases where isobaric contamination is the limiting factor for those experiments.

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