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Mono-isotopic beams of exotic nuclei produced by a universal on-line laser ion source

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Abstract

We report on recent experiments proving the high efficiency and selectivity of a universal and fast on-line laser ion source based on resonance laser ionization in a gas cell. The application for the production of neutron-rich nickel isotopes is discussed, including the first observation of γ-transitions from the decay of ^{71}Ni. We also discuss current efforts to still increase both efficiency and selectivity.

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1. Introduction

For the study of weakly produced exotic nuclei at on-line mass separators, efficient and selective ion sources are needed to create sufficiently intense beams of the isotope to be studied without too large contributions of other, often much more abundantly produced isobars. Ion sources based on resonant laser photoionization can combine high selectivity with high efficiency. Using a laser ion source based on laser ionization in a hot cavity [1], very high efficiencies and selectivities have been obtained for some elements, but both the selectivity and the extraction time are element-dependent. The release time of nickel from the available target materials, for example, is of the order of minutes, which excludes the production of beams of short-lived nickel isotopes with this ion source [2].

We developed a laser ion source based on resonance laser ionization in a gas cell (Ion Guide Laser Ion Source, IGLIS). The principle is shown in Fig. 1. The recoil products from a nuclear reaction in a thin target are stopped in a high-pressure noble gas (helium or argon) and are transported together with the buffer gas to the ionization region. Due to the impact of the primary beam, the thermalized recoil products are for more than 90% neutralized during this transport. Then they are selectively ionized by laser pulses (typically at 200 Hz), transported out of the cell through the exit hole (∅ = 0.5 mm) and accelerated, while the buffer gas is "skimmed off". This ion source was installed at the LISOL separator [3] on-line with the CYCLONE cyclotron.

The principles of the IGLIS source are described in more detail in Refs. [4,5], where also the first applications are reported. In this contribution we concentrate on the recent application of the laser ion source for the production of neutron-rich nickel isotopes and on further developments concerning the improvement of both the efficiency and the selectivity of the source.

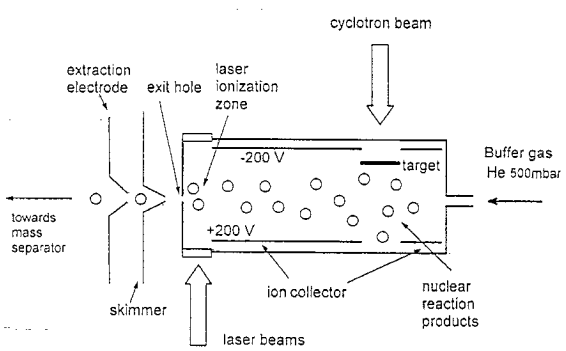

Fig. 1. Principle scheme of the laser ion source.

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2. Neutron-rich nickel isotopes

The first successful tests with the IGLIS were performed using a light-ion induced fusion-evaporation reaction [4,5]: the selective production of ^{54,55}Ni and ^{54}Co after impact of a 27 to 45 MeV ^{3}He beam on a ^{54}Fe target. The selectivity, defined as the enhancement of the ion yield of the selected isotope by resonant laser ionization, was of the order of 300 and an efficiency of about 5% was obtained.

In a later stage, the source was tested for fission reactions: the impact of a 65 MeV proton beam on a uranium foil [5]. We concentrated mainly on the production of neutron-rich rhodium and nickel isotopes. In a first test we obtained a laser enhancement of the $^{113}Rh^{+}$ yield by a factor of 50. The ion source efficiency, corrected for the estimated recoil product stopping efficiency by the noble gas (about 2%), is similar to the efficiency for fusion reactions, but the stopping efficiency is the main loss factor for fission reaction products.

Recently we used the IGLIS to produce pure beams of ^{69}Ni and ^{71}Ni. Fig. 2a shows the β-gated γ-spectrum at mass 71, accumulated for 7 h with an average primary beam intensity of 0.7 μA (using a 4s on–4s off macrostructure) with the lasers at resonance; Fig. 2b is the spectrum without lasers, accumulated for 3.5 h. The marked peaks correspond partly to known γ-transitions from the decay of ^{71}Cu (present as a daughter of the produced ^{71}Ni activity). The remaining resonant peaks were attributed to γ-transitions from the decay of ^{71}Ni (of which no γ-lines were previously known). These assignments were confirmed by extracting the lifetime from the macro time structure (growing in-decay) of the events in each line. We observed γ-transitions at 471.6(0.5) keV, 534.1(0.5) keV, 980.9(0.5) keV, 1251.7(0.5) keV and 2015.2(0.5) keV with relative intensities of respectively 28(5)%, 100%, 55(8)%, 40(7)% and 32(7)%; to obtain absolute intensities, a scaling factor of 0.50(6) should be applied. The recorded data also allowed us to determine the half-life of ^{71}Ni by fitting the growing-in-decay pattern of the counts in the γ-lines attributed to ^{71}Ni and also using the time structure of the β-counts; the combined analysis yielded a value $T_{1/2}$ = 1.9(2) s. The obtained production for ^{71}Ni was calculated using the number of β-rays detected during the beam-off period; a total of 2403(51) counts were recorded in 25740 s showing a 1.9 s decay time structure (a constant background and the contribution of the longer-lived ^{71}Cu daughter product were fitted from the time structure and subtracted). Taking into account the detector efficiencies (a combined efficiency of 11% for the ΔE–E telescope), the mass separator beam transport efficiency of 85% towards

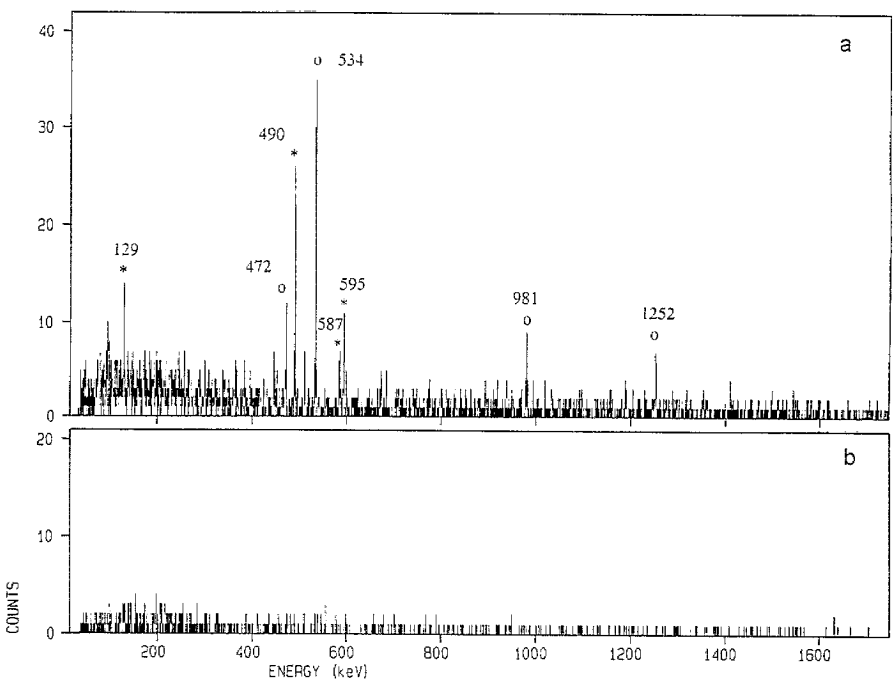

Fig. 2. β-gated γ-spectrum of mass 71, (a) with the lasers tuned for resonant ionization of nickel; (b) without lasers. The peaks labelled * are known lines from the decay of ^{71}Cu [7] (present as a daughter from the produced ^{71}Ni activity); those labelled ○ were assigned as belonging to the decay of ^{71}Ni. The energies of the γ lines are given in keV.

the tape and a calculated fraction of 44% of the nuclei decaying during the beam-off period, finally a ^{71}Ni production of about 3 atoms per μC was obtained. Due to improved beam quality and transmission (see Section 3.1) this production rate was recently increased by a factor of 5.

3. Current improvements on efficiency and selectivity

3.1. Efficiency

As mentioned above, the main loss factor in the efficiency of the IGLIS for reaction products with a high recoil energy is the poor stopping efficiency in the buffer gas. With the set-up described above, the pressure in the cell was limited to about 500 mbar for helium and 150 mbar for argon; above these limits the gas load on the separator leads to a bad beam quality and bad transmission through the separator. Recently the skimmer (see Fig. 1) was replaced by a sextupole ion guide to improve the beam quality and to allow higher pressures to be used [6]. Since pressures up to 1 bar argon can now be dealt with, we expect a drastic increase of the efficiency for fission and heavy-ion induced fusion-evaporation reactions.

3.2. Selectivity

The obtained selectivity of the IGLIS is not limited by the laser ionization process itself, but it results from the small fraction of reaction products that reaches the laser ionization region in an ionic state. In order to check the influence of the presence of the cyclotron beam on the charge state of the atoms of interest, we produced a continuous flow of stable and neutral nickel atoms by resistive heating of a nickel filament mounted in the cell near the gas input. Curve a in Fig. 3 shows the mass-separated $^{58}Ni^{+}$ signal resulting from the impact of a pulsed cyclotron beam (50 ms on, 50 ms off). Right at the beginning of the pulse the ion signal rises sharply: atoms close to the exit hole (about 25 mm from the cyclotron beam path) are immediately ionized, either by fast electrons created by the beam or by uv light from helium atoms that are excited by the beam. After about 20 ms the signal rises steeply again: this corresponds to atoms ionized in the cyclotron beam path for which the evacuation time was measured independently to be 21 ms. During the beam-off period, the signal drops steeply as the source of fast electrons and/or uv light near the exit hole disappears. Later on, the cell is gradually emptied by the helium flow from the rest of the ions on a time scale of 25 ms.

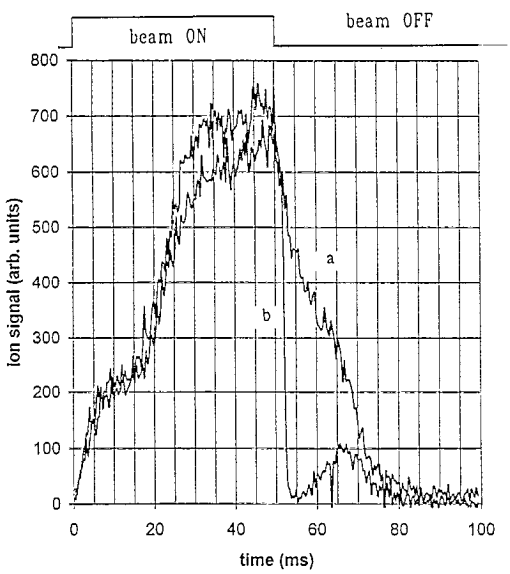

Fig. 3. Stable nickel ion signal, resulting from ionization by a pulsed (50 ms on–50 ms off) cyclotron beam. (a) Without ion collector; (b) with an ion collector pulse (delay 1 ms after the end of the beam-on period; width 2 ms).

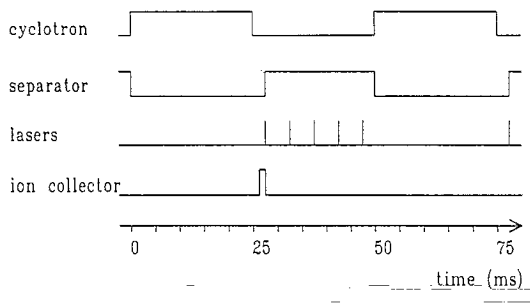

Fig. 4. The time structure used for the selective production of beams of exotic nuclei.

So, the major fraction of the ions ionized by the cyclotron (non-resonantly) leaves the ion source during the beam-on period. On the other hand, the resonant ion signal, which is two orders of magnitude higher than the signals shown in Fig. 3, is reduced drastically during the beam-on period [4]. Consequently, to achieve a high selectivity (and efficiency) for the production of beams of radioactive nuclei, a pulsed cyclotron structure with separator antigating is needed. Moreover, to further reduce the fraction of non-resonantly produced ions, we installed an ion collector in the ion source, consisting of two semi-cylindrical electrodes (see Fig. 1). The idea is to collect the non-resonantly produced ions in the cell by a voltage pulse (typically 2 ms width, ±200 V amplitude) using the time structure presented in Fig. 4. The cyclotron is alternately on during 25 ms and off for the same duration; after the beam is switched off, the remaining ions are collected and only then, the lasers start to fire and the separator gate is opened. The experimentally determined optimum beam on/off time of 25 ms corresponds roughly to the evacuation time of atoms from the region of the cyclotron beam

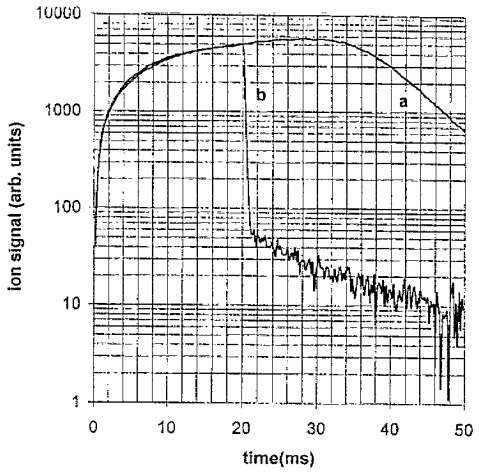

Fig. 5. Off-line test of the ion collector: laser ionized mass 112 signal. (a) Without ion collector pulse; (b) with a 10 ms ion collector pulse 20 ms after the laser pulse.

path. So the complete cell is first filled with radioactive atoms (during the beam-on period) and then all atoms are ionized and evacuated within the beam-off period.

For the measurement of the half-life of radioactive nuclei, a macro time structure (usually in the range of seconds) is superimposed on the 25 ms structure described above: implantation of activity during typically three half-lives followed by a similar beam-off period (to observe the decay of the prepared source).

For off-line testing of the ion collector, stable nickel atoms were ionized by a laser pulse entering on the axis of the cell. The nickel ions have an appreciable cross section for associative reaction with water molecules, so a considerable fraction of the nickel ions leaves the ion source as $^{58}Ni(H_2O)_3$ (mass 112) [5,6]. We used this ion signal for off-line tests since in that way we select the ions that stayed in the cell for the longest period and that are consequently the most homogeneously distributed over the cell (by diffusion). Curve a in Fig. 5 shows the evacuation time profile of mass 112 ions after the laser pulse. Next a 10 ms wide voltage pulse (-230 V on one of the electrodes) was applied 20 ms after the laser pulse. The signal is cut sharply: it reaches the 1% level in less than 2 ms. Only the ions that were very near the exit hole at the moment the pulse was applied, can escape from the cell.

Fig. 3b shows the effect on the cyclotron-ionized stable nickel signal of a 2 ms wide ion collector pulse with a delay of 1 ms after the 50 ms cyclotron-on period. The signal disappears immediately but shows a remaining peak about 15 ms later. This peak probably stems from ions that were near the cyclotron beam path during the ion collector pulse; apparently the cyclotron-induced after-glow plasma at that place shields the ions somewhat from the applied electrical field. Still the integral under the curve in the beam-off period is reduced by a factor of 6 when the voltage pulse is applied.

When using the ion collector for the selective production of radioactive beams according to the scheme of Fig. 3, a typical additional reduction of the isobaric background by only a factor of 3 was obtained. To increase this reduction factor the plasma conditions should be manipulated so as to have the plasma dying out on a shorter time scale.

In this respect the purity of the gas is of crucial importance. We experienced that a high gas purity (impurity concentration $< 10^{-6}$) has to be used and that the gas lines have to be conditioned carefully to obtain a high efficiency and selectivity. We are planning to install a gas purifier to purify the gas to the 10^{-8} level and to make use of well-controlled small gas admixtures to find the optimum buffer gas conditions for the IGLIS source.

References

[1] V.I. Mishin et al., Nucl. Instr. and Meth. B 73 (1993) 550.
[2] A. Jokinen et al., these Proceedings (EMIS-13), Nucl. Instr. and Meth. B 126 (1997) 95.
[3] M. Huyse et al., Nucl. Instr. and Meth. B 70 (1992) 50.
[4] L. Vermeeren et al., Phys. Rev. Lett. 73 (1994) 1937.
[5] Y. Kudryavtsev et al., Nucl. Instr. and Meth. B 114 (1996) 350.
[6] P. Van den Bergh et al., these Proceedings (EMIS-13), Nucl. Instr. and Meth. B 126 (1997) 194.
[7] R.B. Firestone, Table of Isotopes (Wiley, New York, 1996).