

Can the waiting-point nucleus ^{78}Ni be studied at an on-line mass-separator?

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Short-lived nickel isotopes have been studied using a chemically selective Ion Guide Laser Ion Source (IGLIS) based on resonance ionisation of atoms at the Leuven Isotope Separator On-Line (LISOL) separator. The decay properties of different Ni isotopes have been studied using β - γ -coincidences. Experimental production rates of proton induced fission of ^{238}U are obtained for $^{69,71}\text{Ni}$. These numbers are in a strong disagreement with Silberg-Tsao calculations.

1. Introduction

Since decades neutron- and proton-rich nuclei are studied at on-line mass separators [1], revealing many interesting nuclear physics phenomena. One of the most interesting nuclei is the doubly magic nucleus ^{78}Ni . Its level and decay properties at the doubly-closed shell and of the nuclei in its neighborhood form well defined test cases for various nuclear structure models and can be used to calculate e.g. residual interactions in a shell model picture. Also from astrophysics point of view, these nuclei are of interest as the neutron-capture probabilities and β -decay properties influence the mass flow in the r-process path and thus the relative isotope abundances.

The doubly magic nucleus ^{78}Ni is considered as a "waiting-point" nucleus in the region of the $A \simeq 80$ r-abundance peak. This nucleus was since long time looked for and has been identified at GSI-Darmstadt using the fragment separator [2]. At on-line isotope separators (ISOL), various attempts to observe the decay of ^{78}Ni failed. The low production cross section of neutron or light-ion induced fission of ^{238}U or ^{232}Th forms a difficult obstacle but is not a principal problem. Due to their chemical properties Nickel atoms tend to have a rather long delay time in modest temperature plasma ion sources. Due to the short half-life of the nuclei of interest the long delay time induces large losses. Furthermore, the fission reaction is not selective resulting in isobaric contaminations with order of magnitude larger beam intensities.

The solution to these problems is an on-line ion source that ideally fulfills the following requirements: the ionization efficiency should be high ($> 10\%$), the delay time short (< 10 ms) and the element selectivity should be high (> 100). For this purpose a laser ion source to ionize reaction products was developed.

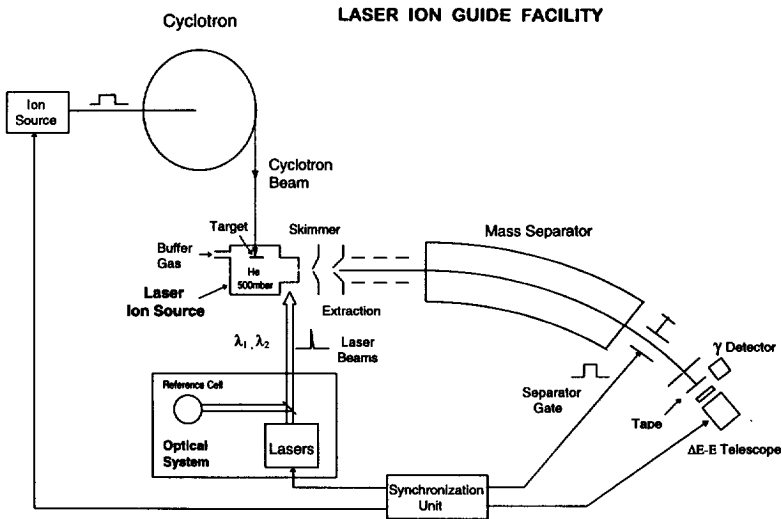


Figure 1. General lay-out of the laser ion guide facility (IGLIS) situated at the LISOL mass separator

2. The Ion Guide Laser Ion Source (IGLIS)

The principle of the IGLIS at LISOL is based on the photoionisation in a gas cell. The reaction products are stopped in a high pressure noble gas (e.g. 500 mbar helium or argon) and transported together with its carrier to the ionization chamber. Due to the plasma created by the primary beam, the reaction products are neutralised. Then they are selectively ionized by pulsed laser light, transported out of the cell, accelerated and mass separated. The pulsed laser system used for the resonant ionization consists of two synchronizable (400 Hz, 60 Watt) XeCl excimer lasers and two pulsed dye lasers with frequency doubling option. Essentially all atoms in the laser beam path are ionized and transported by the buffer gas flow to the exit hole.

Efficient ionization schemes using frequency doubling of one of the dye laser outputs have been found for different elements: nickel, cobalt, rhodium and titanium. In the case of the nickel ionization both transitions could be saturated in both steps with the available laser power. For more details about the IGLIS see e.g. refs. [3–5] an references therein. Figure 1 shows a general layout of the LISOL facility with the IGLIS laser ion source.

3. Results from a feasibility study

The laser ion source and its on-line performance was investigated with ^3He induced fusion evaporation reactions on a ^{54}Fe (3 mg/cm²) target and with proton induced fission

of a set of two ^{238}U (10 mg/cm²) targets. The radioactive ions were mass separated and transported in front of a $\Delta\text{E-E}$ β -telescope (made of plastic scintillators) and a Ge detector (90% and 75% relative efficiency).

3.1. Light ion-induced fusion evaporation reactions

To test the on-line features of the IGLIS laser ion source a fusion evaporation reaction was chosen in order to have a "simple" system and not too many unknown parameters. The ^{55}Ni isotopes were produced with a 27 MeV ^3He beam on an enriched ^{54}Fe target, via the 2n channel. The normalized production rate was 1650 atoms/ μC . A total efficiency (stopping in 500 mbar helium, neutralization and mass-separation) of 4.6 % and a selectivity, defined as the number of ^{55}Ni ions observed when the lasers were tuned on-resonance relative to when the lasers were tuned off-resonance, 280 was reached. The half-life measured was (204 ± 3) ms which is in agreement with the half-life from Äystö et al. [6].

A beam of ^3He at beam energies of 45 MeV were used to produce ^{54}Ni via the 3n channel. The decay of ^{54}Ni isotope was detected via the 937.4 keV γ -transition in ^{54}Co that is populated via a Gamow-Teller transition. When tuning the lasers off-resonance the 937.4 γ -line was not observed. The half-life obtained is (143 ± 23) ms [7].

3.2. Proton-induced fission reactions of ^{238}U

We have produced neutron-rich Rh isotopes in the proton ($E_p = 65$ MeV) induced fission reaction on ^{238}U to check the performance of the laser ion source in the case of a fission reaction. A production yield of 4206 At/ μC for ^{113}Rh was reached resulting in a total efficiency of 0.22%. This low value is mainly due to the stopping efficiency of the ^{113}Rh atoms in the 500 mbar helium gas pressure: 1.5%. The selectivity for the production of Rh reached 50. It is for the moment not clear what the reason for this lower selectivity is but from the several experiments performed so far we can conclude that while the efficiency is very reproducible, the selectivity isn't. Impurities in the He gas are the most probable cause for these fluctuations.

Very recently we have been able to produce the neutron-rich $^{69,71}\text{Ni}$ isotopes at the LISOL separator applying the IGLIS laser ion source. These isotopes were produced by a proton ($E_p = 65$ MeV) induced fission of ^{238}U . From ^{69}Ni the decay-properties and the level scheme are known [8]. From $^{71,73}\text{Ni}$ only the half-lives are known up to now from studies of thermal fission [9]. In the present experiment it was possible to observe for the first time γ -rays for ^{71}Ni , even in the case of mass 73 there is some evidence for one possible γ -line that might belong to ^{73}Ni β -decay. Comparing the spectra on-resonance and off-resonance in it can be seen that the observed Cu activity is only produced by the decay of ^{71}Ni . However, the experiment was not performed to obtain a good spectroscopic information on these isotopes, its main purpose was to get information on production yields, and fission cross-sections. In the case of $^{69,71}\text{Ni}$ the production-rates were determined on the basis of β - and γ -measurements the data obtained for ^{73}Ni are only based on β -measurements and can only be considered as an upper limit. For ^{69}Ni we obtain a production of 5 atoms/ μC and for ^{71}Ni we obtain 10 atoms/ μC . Cross section calculations were performed according to Silberberg and Tsao [10] for a minimal proton energy of 110 MeV, we obtain 146 μbarn for ^{61}Ni and 15 μbarn for ^{71}Ni respectively. The results are in disagreement with

the experimental data. However the maximum of the cross-section distribution is shifted one mass unit. This disagreement underlines the unreliability of production- and cross section estimates made on the basis of Silberberg and Tsao calculations. These facts show, that reliable cross-section calculations for proton-induced fission cross-sections are needed to prepare future experiments.

4. Expectations for ^{78}Ni and future outlook

The production cross section for ^{78}Ni from proton induced fission is not known experimentally. However one can take a conservative value of 1 nbarn based on Silberberg and Tsao-calculations [10]. This estimated value leads to ca. one ^{78}Ni atom per hour that recoils out of two 10 mg/cm^2 ^{238}U targets bombarded with $10\ \mu\text{A}$ of proton beam.

Presently we suffer still from some difficulties which have to be solved (i) the low stopping efficiency in the buffer gas for the fission products and (ii) the selectivity of the laser ion source which have to be improved. One way to overcome the low stopping efficiency is to use 1 bar of Ar gas – assuming an efficiency of 2.4% – this would yield about 100 ^{78}Ni ions per hour after mass separation. Parallel to the first nuclear physics experiments development of the IGLIS is still continuing.

In order to detect these atoms one might use neutron counters. This method will further enhance the selectivity as the β -delayed neutron branching of ^{78}Zn is much lower than for ^{78}Ni (^{78}Ga does not decay via β -delayed neutrons). However there might be a problem with the neutron background.

The use of efficient Ge-detector arrays like the Ge-mini-ball array – being presently under consideration [11] – might be an alternative. The efficiency of such a device will approach 19% for a 1.33 MeV γ -ray. Together with an efficient β -counter (50%) one would observe about 10 γ /hour. Based on these estimations it looks feasible to study the decay properties of ^{78}Ni and its neighboring isotopes.

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