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Beams of short-lived exotic nuclei produced by laser ionization in a gas cell

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Introduction

Nuclear models to describe isotopes that contain too many nucleons to allow a complete ab initio calculation are strongly based on experimental observations and new developments in nuclear physics are usually triggered by unexpected experimental findings. Since the majority of experimental data refers to stable isotopes or isotopes near the stability line, calculations for isotopes far from stability often fail to predict the nuclear properties correctly. Therefore it is crucial for a better global understanding of the physics of nuclei and for the development of more elaborate theoretical models to get experimental access to properties of nuclei far from stability.

The ion guide laser ion source

In order to study weakly produced nuclei far off stability, on-line isotope separators have been extensively used, suppressing the primary-beam induced background and selecting a single mass-over-charge ratio. Such a system consists of a target, in which the radioactive nuclei are formed, a catcher to stop the nuclei and an ion source to ionize them so that they can be accelerated and mass separated. Although mass selection is guaranteed by such a system, there is no intrinsic element selectivity. Only for specific classes of elements dedicated selective ion sources can be used, e.g., surface-ionization ion sources for alkali elements. For certain elements the delay time of the target catcher - ion source system is often too long to produce efficiently the very short-lived isotopes of interest.

At the Leuven Isotope Separator On Line (LISOL) project, we have developed an on-line ion source which attacks all above mentioned problems: a laser ion source, based on resonant photo-ionization in a gas cell [1,2]. The operation of the source is illustrated in Figure 1. The reaction products recoil out of the target into the buffer gas (typically 500 mbar helium or argon) and thermalize to a 1+ charge state. After a few milliseconds most of the ions are neutralized. Before the atoms leave the gas cell, they are irradiated by pulsed laser beams, ionizing only the atoms of the element of interest. While the buffer gas is pumped away, the ions are accelerated and mass separated. The residence time inside the gas cell depends on the type of buffer gas used and on the size of the exit hole. For the case of helium with an exit hole diameter of 0.5 mm it is about 40 ms. An alternative concept of an on-line laser ion source was developed at CERN [3]. There the reaction products diffuse out of a thick target into a hot tube in which the resonant ionization takes place. Because of the high primary production in the thick target, the obtained yields are generally higher in that case, but for refractory-type elements the delay time is rather long, reducing severely the yields of short-lived reaction products.

Efficiency and selectivity

Resonance photo-ionization by laser light is used to ionize the atoms. Almost all elements can be ionized by a two-step ionization scheme (see Figure 2). Typically a uv laser beam (obtained via frequency doubling of a dye laser beam) excites the atoms to an intermediate energy level via a resonant transition, and a direct dye laser beam transfers the atoms to an autoionizing state from which they decay to an ionic state. Generally, pulsed laser beams are needed to provide sufficient power density for complete ionization. Typical saturation energies in our set-up are of the order of 0.1 mJ per pulse for resonant excitation and 1 mJ per pulse for transitions towards autoionizing states. These energies are routinely obtained with commercial excimer- (or YAG-) pumped dye lasers, so all irradiated atoms can be ionized. Because of the doubly-resonant method the ionization is extremely selective: only atoms of the chosen element will be photo-ionized.

The overall selectivity in our laser ion source is not directly related to the laser ionization selectivity, but it is mainly determined by the fraction of recoiled nuclear reaction products that survives the transport to the exit hole of the gas cell without getting neutralized or that is non-selectively reionized (not by laser interaction, but e.g. by radioactivity from the target). As demonstrated in Figure 3, this fraction is generally small: without resonant laser ionization typically two orders of magnitude less ions are produced.

Many processes occurring in the gas cell contribute to the total efficiency of the laser ion source: the stopping efficiency of the recoil products (which depends on the recoil energy and the...
gas type and pressure), the neutralization efficiency into the atomic ground state that can be addressed by the laser light, the survival efficiency of the atoms against formation of molecules and against diffusion to the wall, the spatial and temporal overlap of the laser beams with the atom flow... For the case of light-ion induced fusion all these factors result in a total efficiency of about 3%; for the heavy-ion induced fusion and fission the efficiencies obtained so far are roughly one or two orders of magnitude lower.

Sextupole ion guide and chemistry

To transport the ions from the ion source to the mass separator and at the same time pump away most of the buffer gas, traditionally a "skimmer" was used: a metallic plate with conical shape around the axis with a small hole at the center, which was negatively biased relative to the ion source. With this set-up the gas throughput to the separator was relatively high, limiting the allowed pressure inside the gas cell. Moreover the resulting beam quality was rather poor, mainly due to energy-changing collisions in the regions between the ion source and the skimmer.

We replaced the skimmer by a "sextupole ion guide" (SPIG)[4], a system consisting of six rods mounted parallel to each other in a hexagonal structure, on which an rf voltage was applied with each rod in antiphase with its neighbours (see Figure 1). This configuration provides a net axial focusing force, guiding the ions to the mass separator, while the gas can be efficiently pumped away through the open structure. So higher gas cell pressures can be used than with the skimmer, and the resulting beam quality is excellent. For optimal production conditions, eventual molecular ions formed in the ion source can be dissociated by applying a negative dc offset potential on all rods relative to the source. However, this potential is not essential for a good transmission; thus the SPIG also provides the possibility to study the chemistry inside the gas cell by monitoring the intensity of the mass-separated molecular ion signals and their evolution as a function of time elapsed after the laser pulse. This can be done in on-line conditions (with cyclotron beam on the target) or off-line using atoms evaporated from a resistively heated filament.

An example of this application is illustrated in Figure 4. Cobalt atoms are evaporated in the gas cell with helium with purity 99.9999 % as a buffer gas. The mass spectrum (Figure 4a,c) shows that the cobalt ions are pushed to a large extent into molecular side bands. All observed molecular ions

![Figure 2. Schematic atomic level scheme showing different paths for resonant laser ionization.](image)

![Figure 3. Partial γ spectrum at mass 73 obtained (a) with and (b) without laser light irradiating the gas cell. The integrated primary beam dose was 1.6 \times 10^4 and 5.7 \times 10^4 μC, respectively. The time evolution of the intensity attributed to the decay of ^{73}\text{Ni} is shown in the inset.](image)
are formed inside the gas cell in reactions of the laser produced cobalt ions with impurities, which are present at ppm level in the buffer gas. Figure 4b shows that the molecular ions can be efficiently converted again to atomic ions (at mass 59) by applying a 250 V acceleration voltage between the gas cell and the SPIG rods.

Extensive tests using also a gas purifier to purify noble gases down to the ppb level and a gas mixing system to prepare well-controlled foreign gas admixtures in the ppb range show that with this system we are able to detect impurities in noble gases even below 1 ppb. On the other hand we are also sensitive to the very low rate reactions involving noble gases themselves. Of particular interest for our project is the reaction of e.g. nickel, cobalt and rhodium ions with argon to form XAr⁺, XAr₂⁺, XAr(H₂O)⁺,... (X=Ni,Co,Rh,...). These molecular ions can easily be dissociated again (see above), but still they influence the efficiency of the ion source, since the molecular ions neutralize in a few ms, i.e. before they leave the ion source. This makes argon less suitable than helium as a buffer gas. This is however partly compensated by the higher atomic mass of argon resulting in a higher recoil product stopping efficiency and in smaller diffusion losses.

Conclusion and outlook:

We constructed a laser ion source for creating pure beams of short-lived radioactive isotopes. It was successfully tested for light- and heavy-ion-induced fusion reactions as well as for proton-induced fission of uranium. Further tests are needed to investigate the influence of chemical reactions and of the primary-beam-induced plasma on the efficiency and the selectivity of the ion source and to find ways to optimize the ion source parameters for all these reactions. However, already now detailed decay studies have been performed on the $^{54}\text{Ni}$ [5], $^{55}\text{Ni}$ [1], $^{68-74}\text{Ni}$ [6] and $^{67-70}\text{Co}$ isotopes, some of which have half-lives down to 200 ms. As an example the γ-ray spectra obtained at mass 73 are shown in Figure 3. The extracted information on the latter two series (half-lives, branching ratios, single-particle energies) shed light on the importance of the $N=40$ subshell closure and on theoretical predictions towards the doubly-magic closed shell nucleus $^{78}\text{Ni}$.

In the near future, a study of the medium-mass isotopes near the $N=Z$ line, produced with the laser ion source, will be initiated. Furthermore we will test the use of circularly polarized light for the excitation-ionization scheme to obtain atomic polarization and via hyperfine interaction also nuclear polarization. Assuming that collisional depolarization is small, high degrees of polarization can be expected. Another line of development is formed by the use of the SPIG as a buncher and cooler: the ions can be accumulated and

Figure 4. Mass spectra of laser ionized stable cobalt atoms: (a) $V_{dc} = V_{ac} = 0$; (b) $V_{dc} = 250$ V; (c) the same as (a), but enlarged 100 times.
trapped in the SPIG during typically 1 s (by applying a positive potential at the exit) and then released as a bunch with a well-defined time structure could be exploited in half-life measurements. It would lead to a background reduction in many types of experiments and it could be efficiently injected into another trap for high precision experiments.

References

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In memory of Bjørn Wiik

On Friday, February 26, an incomprehensible message threw the physics community into misery and mourning: Bjørn Wiik, the Director General of DESY in Hamburg, had passed away. An accident took him out of the middle of his most creative phase. We have lost a great scientist, who has opened new avenues of research at DESY and supported the progress of science in a broad scope on an international scale.

Bjørn Wiik was born in 1937 in Brøvik, Norway, and received his higher education in Bergen, Norway. In 1956 he began a physics study at the Technische Hochschule Darmstadt, Germany. There I learnt to know this very exceptional young Norwegian student, when he just received his Diplom degree in 1963 and I became professor in the Institut für Technische Kernphysik, founded and directed by Peter Brix. For his PhD in 1965, he studied (γt)-reactions on silver nuclei using a high energy Bremsstrahlung photon beam from the Darmstadt linear electron accelerator, which had been taken into operation during his stay at the institute of Peter Brix. Bjørn and I became very good friends, lived at the same place and shared many things in our daily work and life, especially our enthusiasm for everything new in physics and the world around us. During this time he also began studies on a microtron recirculation accelerator principle, which we named "Wiiktron," and on which he carried on to work later in Stanford, using superconducting cavities.

In 1965 our ways separated: he left Darmstadt for California to start a career in particle physics in the High Energy Laboratory of the Stanford University, and I returned to Munich to wind up in heavy ion physics. However, we never lost track of each other and tried to keep in contact by communicating the progress in our respective fields. From 1968 to 1972 Bjørn joined the staff of the Stanford Linear Accelerator Laboratory, SLAC, as a research associate. His main physics interest focused on photoproduction of mesons, especially pions from hydrogen, a field which was recently revived and became an interesting domain of nuclear physics in context with the chiral perturbation approach to low energy QCD. In 1972 Bjørn Wiik returned to Germany and joined the scientific staff of DESY in Hamburg. He was promoted to a senior scientist in 1976, became HERA project leader in 1981 and in the same year professor for physics at the II. Institut für Experimentalphysik der Universität Hamburg. Since March 1st 1993, Bjørn Wiik was Director General of DESY.

Bjørn Wiik’s scientific contribution to the progress of particle physics through his work at DESY is outstanding in many respects. As an outsider of the field, I can only sketch it exemplarily and hope that it receives the appropriate comprehensive acknowledgement from more competent circles. Bjørn has made unique contributions to the DESY R&D programme, especially to all phases of the development of its collider projects from DORIS to PETRA to HERA and to a future linear collider, his last grand vision.

As a member of the DASP collaboration at the DORIS e+e- collider, he participated in the first observation of the two photon cascade in 1975 connecting the υ' and the J/ψ charmonium states, which led to the discovery of P-resolution in charmonium, the spectroscopy of which is still of current interest in context with non-perturbative effects in QCD.

During this period, in fact a bit earlier (1973), Bjørn Wiik developed his first ideas to realise electron-proton collisions at high centre-of-mass ener-