RECENT DEVELOPMENTS AT IGISOL-FACILITY*

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The recent developments at the IGISOL-facility in Jyväskylä are reviewed. The spectroscopy of fission products has revealed a new set of beta-delayed neutron emitters and resulted in an identification of new isotopes in the $A = 110$ region. The new results on level structures of even-even refractory fission products imply the population of the two-quasiparticle structures. The spectroscopy of light fission products has lead to the observation of superasymmetric fission. The implementation of the heavy-ion ion guide has opened the possibility to apply the ion guide technique to medium and heavy neutron-deficient nuclei. Its performance in the vicinity of the $N = Z$ line is summarized. The highlights of the research on the light proton-rich nuclei are given as well as the recent results of the collinear laser spectroscopy at IGISOL. The new project of mass-selective cooling and bunching of ion beams from the IGISOL-separator is presented.

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1. Introduction

Ion guide based isotope separation was developed in Jyväskylä in the early 80's. It was first used for light-ion-induced reactions and later this technique was applied for various types of reactions including heavy-ion reactions and charged-particle induced fission. In the ion guide, reaction products are stopped in He-gas and transported out from a gas cell with the He-flow as 1^+ ions. The ion guide technique is characterized by its chemical unselectivity, which allows extraction of ion beams of all elements. It has also proven to be faster than conventional ion sources. However, due to inefficient stopping in gas, it suffers from a low efficiency in some reactions [1, 2].

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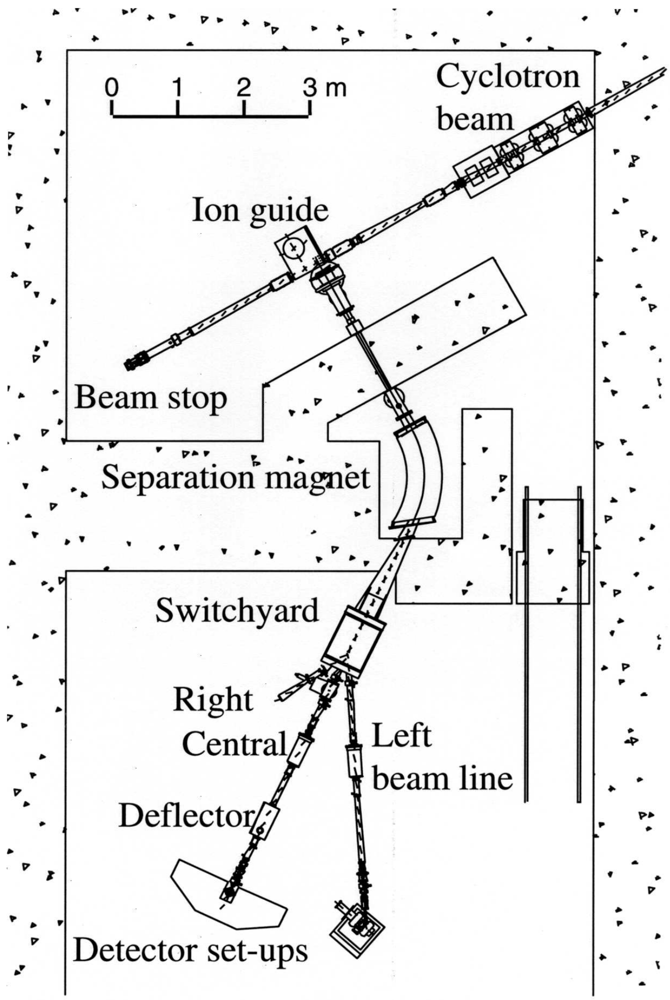

Fig. 1. The present layout of the IGISOL-facility at the Accelerator Laboratory at the University of Jyväskylä.

In the beginning of the nineties, the IGISOL-separator was moved from the old laboratory to the new cyclotron laboratory. In this phase, the facility was upgraded with a better vacuum system and larger Roots-pumps in the front end of the separator. In addition, the focal plane of the dipole magnet was equipped with a three-way switchyard. Beam lines served by the switchyard were devoted to different tasks. The left-most beam line was equipped with the conversion electron spectrometer, ELLI [3]. The central beam line serves as a general-purpose spectroscopy line where different types of detector systems can be installed. The right most beam line seen from the direction of the ion beam can be accommodated, for example, with charged-particle detectors. The central beam line is also equipped with a 90° deflector, which deflects the IGISOL-beam to the second floor through a vertical beam line. On the second floor, a dedicated laser spectroscopy setup was built in collaboration with laser spectroscopists from Birmingham and Manchester. The layout of the IGISOL-facility is shown in Fig. 1.

In addition to improvements of the ion guide isotope separator itself, the IGISOL-facility has gained a lot from the higher beam intensities and energies together with wider selection of primary beams in the new heavy ion laboratory in Jyväskylä.

At the same time, the detection systems have been developed. This means larger solid angles, but also dedicated designs for specific spectroscopic problems. For example, we have developed a $3\pi\beta$-detector, which increases the efficiency of the conventional beta-gamma spectroscopy. Another example is the construction of the novel gas-Si telescope [4]. This has been used successfully in various experiments at IGISOL and elsewhere. Based on the good experience with this detector, a new setup consisting of 15 similar-type gas-Si-telescopes in hemisphere geometry was also developed for multiparticle decays.

In the following I will present results of the new developments in light of the physics program of the IGISOL-facility during the recent years. In all sections I try to connect the technical development to the new results.

2. Spectroscopy of neutron-rich nuclei

Soon after the development of the IGISOL technique, its potential for studying refractory fission products was realized. This and the fact that charged-particle-induced fission results in a symmetric mass distribution directed the research to the spectroscopy of fission products in the mass region $A = 100 - 120$. This project has been extremely successful resulting in an identification of 25 new isotopes and the detailed spectroscopy of neutron-rich medium mass nuclei from Y to Pd.

Recently, altogether 14 new beta-delayed neutron emitters have been found ranging from niobium to technetium [5, 6]. Their beta decay half-lives and beta-delayed neutron branches were measured using a dedicated neutron detection set-up. The obtained half-life and beta-delayed neutron data provide a large set of systematic information on the nuclei far from stability. The comparison to the QRPA predictions [7] indicates the increasing importance of fast beta transitions to high lying states of nuclei with large neutron excess. Comparison of the measured half-lives from Y to Rh with QRPA-calculations and revised gross theory [8] shows only modest agreement, which points to the insufficient treatment of the structure of very neutron-rich nuclei in the region of rapidly changing deformation. Another conclusion drawn from these measurements is that spectroscopic studies at the present IGISOL-system can be extended up to 15 neutrons away from the valley of beta-stability.

The study of collective structures of even-even isotopes has been continued recently by extending the level systematics of Pd-isotopes [9] to ^{118}Pd [10] and performing the first spectroscopic studies on the level structures of ^{110}Mo. The levels in even-even neutron-rich Pd-isotopes are shown in Fig. 2 including preliminary identification of the levels in ^{118}Pd. In the same study, the knowledge of the level structure of ^{110}Ru [11] was extended to higher excitation energies implying that the beta feeding of two quasi-particle states has been observed. The identification of the two-quasiparticle states combined with the known single particle states provides a tool to obtain information on the strength of the pairing interaction [12]. This approach is very interesting since other methods, like extracting the pairing gap from the mass systematics are not possible due to the poor or sometimes even missing mass data. Encouraged by the success of this experiment, similar studies are foreseen in the near future.

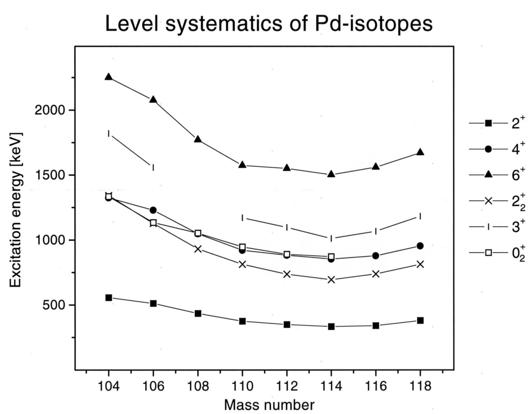

Fig. 2. Level systematics of neutron-rich even Pd-isotopes. The preliminary identification of the levels in ^{118}Pd is from a recent experiment at IGISOL [10].

3. Superasymmetric fission mode

Charged-particle induced fission results in a symmetric mass division leading to an enchancement of yields in the symmetric region of the mass distribution, *i.e.*, around $A = 110 - 120$. Traditionally, thermal fission of ^{235}U has been used to produce nuclei associated with asymmetric mass division. Recently, the yield measurements of n-rich Ni, Cu, Zr, Ga and Ge isotopes have shown increased yields of very light fragments [13]. This indicates an enhancement of the asymmetric mass division at intermediate excitation energy, as shown in Fig. 3. The observation implies the importance of charged-particle induced fission as a complementary reaction for the production of light fission fragments around $N = 28$. Further spectroscopic studies among the light fission products are planned as well as more detailed studies of the observed fission mode, superasymmetric fission, by means of the IGISOL separator and the HENDES-spectrometer [15]. These measurements are crucial to characterize the superasymmetric mode, which may be a potential reaction to approach the region around the doubly magic ^{78}Ni nucleus.

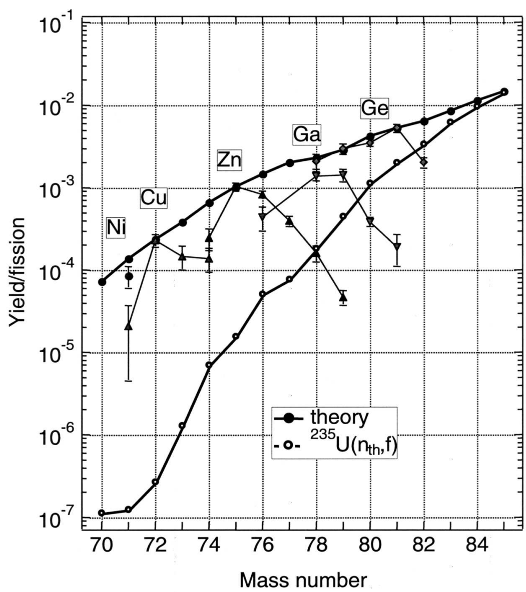

Fig. 3. Measured independent yields of fission product in the superasymmetric region in 25 MeV proton induced fission of ^{238}U. The calculated mass yield for the ^{238}U$(p,\ f)$ reaction is according to [13] and mass yields in thermal neutron induced fission of ^{235}U are taken from [14].

4. Beta-delayed decay of ^{23}Al applying the light ion fusion ion guide

Recently a light ion fusion ion guide was newly designed to improve the collection of recoil ions with a more efficient flow pattern inside the ion guide. It was applied in the decay study of ^{23}Al. The beta-delayed proton decay of ^{23}Al has been studied earlier in Berkeley [16] resulting in a surprisingly high beta-delayed proton branch from the Isobaric Analog State (IAS) in ^{23}Mg. This result, which corresponds to an unusually high isospin mixing of the IAS, has also severe influence on the leakage from the NeNa-cycle in astrophysical calculations. Due to the importance of the beta-delayed proton branch of the IAS we have remeasured the beta-delayed proton decay of ^{23}Al [17].

In our study, a mass separated source of ^{23}Al was used. This fact together with the selection provided by the reaction channel resulted in a very pure source of ^{23}Al in contrary to the previous work in Berkeley, where the He-jet technique was used. Another advantage compared to the previous work is that for the first time both gamma-rays and protons de-exciting the IAS could be observed at the same time. The relative efficiency of gamma and proton decays could be calibrated using online sources of ^{24}Al and ^{20}Na. Our preliminary results give a proton branch from the IAS about eight times lower compared to [16]. This results implies a much smaller isospin mixing, but still remarkably high compared to theoretical estimates. The transition strength $\omega\gamma$ for the $^{22}\mathrm{Na}_{\mathrm{g.s.}}(p\gamma)^{23}\mathrm{Mg}^*$ reaction extracted from our data compares well with the recent reaction studies [18].

5. Development of the heavy-ion guide, HIGISOL

In connection with a move to the new heavy ion cyclotron laboratory the IGISOL technique was also adapted to heavy ion reactions. The heavy ion guide was originally developed for the SARA-facility in Grenoble [19] and has been installed in the Jyväskalä–IGISOL [20]. The heavy ion IGISOL (HIGISOL) is based on the fact that the recoil products are scattered to larger angles than the primary beam in heavy ion reactions. Thus it is possible to stop recoils within the solid angle determined by two cones: the inner cone is defined by the maximum scattering angle of the primary beam and the outer cone is defined by the maximum usable scattering angle of the recoils. The principle of the HIGISOL is illustrated in Fig. 4.

HIGISOL has been used for spectroscopic studies of neutron-deficient isotopes around $A = 125$, which immediately led to the identification of a short-lived isomer in ^{125}La [21]. Recently HIGISOL has been applied for spectroscopy of $N = Z$ nuclei in the vicinity of ^{80}Zr [22]. Fig. 5 compiles the yield information for $^{\mathrm{nat}}\mathrm{Ni}(^{32}\mathrm{S}X\alpha Yp\mathrm{Zn})$ reactions in the vicinity of the $N = Z$ line. Based on these yields, it is obvious that decay spectroscopy of nuclei along the $M_T = +1$ line is feasible and the research on that line is planned, especially for refractory elements. Large decay energies associated with these nuclei allow the observation of a large part of the Gamow Teller sum rule.

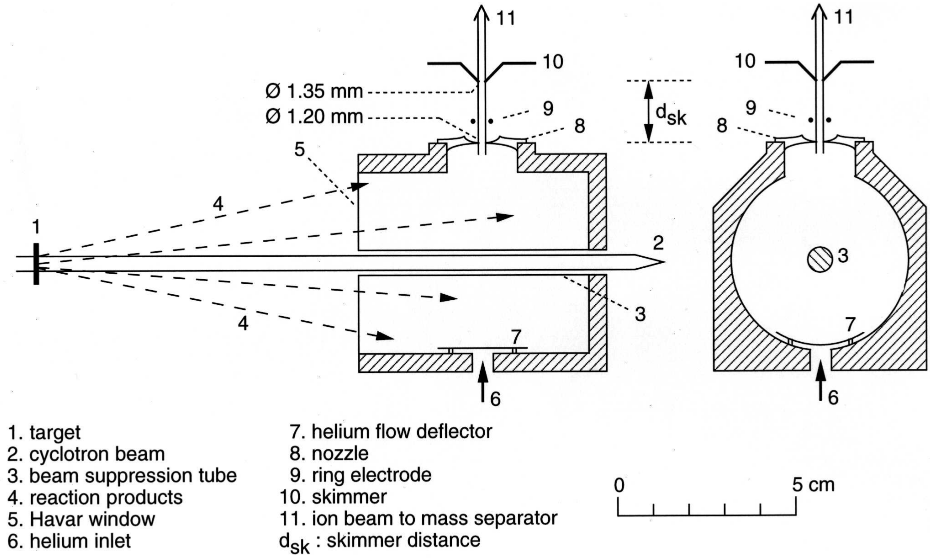

Fig. 4. The principle of the heavy-ion ion guide, HIGISOL.

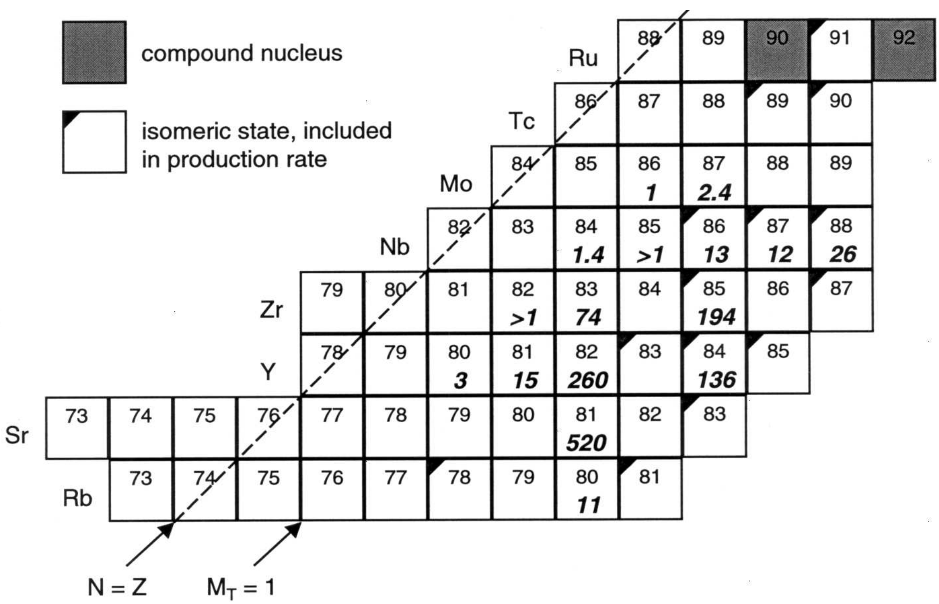

Fig. 5. Production of isotopes in atoms/s produced in the ^{32}S+$^{\rm nat}$Ni reaction at HIGISOL [22].

6. Collinear laser spectroscopy at IGISOL-facility

The unique combination of the ultrasensitive collinear laser spectroscopy with the ion guide technique capable to produce ion beams of all elements allows studies of isotopes and isomers beyond the other presently used techniques. The capability of the set-up has been demonstrated by the spectroscopy of ^{140,142,144}Ba isotopes [23].

The first on-line isotope shift measurements of a refractory element were performed by using the same combination. Collinear laser-induced fluorescence measurements included the radioactive isotopes ^{170,172,173,174}Hf [24]. The obtained charge radii data provide an important reference for theoretical predictions of the deformation along the Hf-isotope chain. However, further studies for the general trend of $\langle r^2 \rangle$ are required, especially for the low and high spin isomeric states in and around ^{178}Hf.

7. Ion cooler and ion trap project at JYFL

When the present ion guide is turned to the maximum yields, the resulting ion beam has a relatively wide energy spread, of the order of 100 eV, but still good emittance, of the order of 3 $\pi\cdot$mm$\cdot$mrad. Thus it is obvious that the quality of the IGISOL-beam deserves improvement. The universality of the ion guide technique, *i.e.* its capability to produce beams of all elements often results in a copious amount of isobaric background preventing the observation of the weakly produced, the most exotic, species. Thus mass purification is also required. However, the speed of ion guide technique should be preserved.

To overcome the problems and retain the nice features of IGISOL-beams, we have decided to manipulate IGISOL-beams in two steps, as shown in Fig. 6. Ions will be first injected into a linear radiofrequency quadrupole structure with gas load. There they will lose energy in collisions with the buffer gas atoms, and the quadrupole field will drive the ion towards the optical axis. A gentle axial field drives the ion towards the end of the rod structure from where they are ejected with an order of magnitude smaller emittance and energy spread compared to the injected beam. In a second step, the ion beam is transported to a Penning-trap, where it is captured by the dynamic capture based on the energy loss in buffer gas collisions. Captured ions excited resonantly so that ions with a certain mass are centered in the trap and other ions are lost.

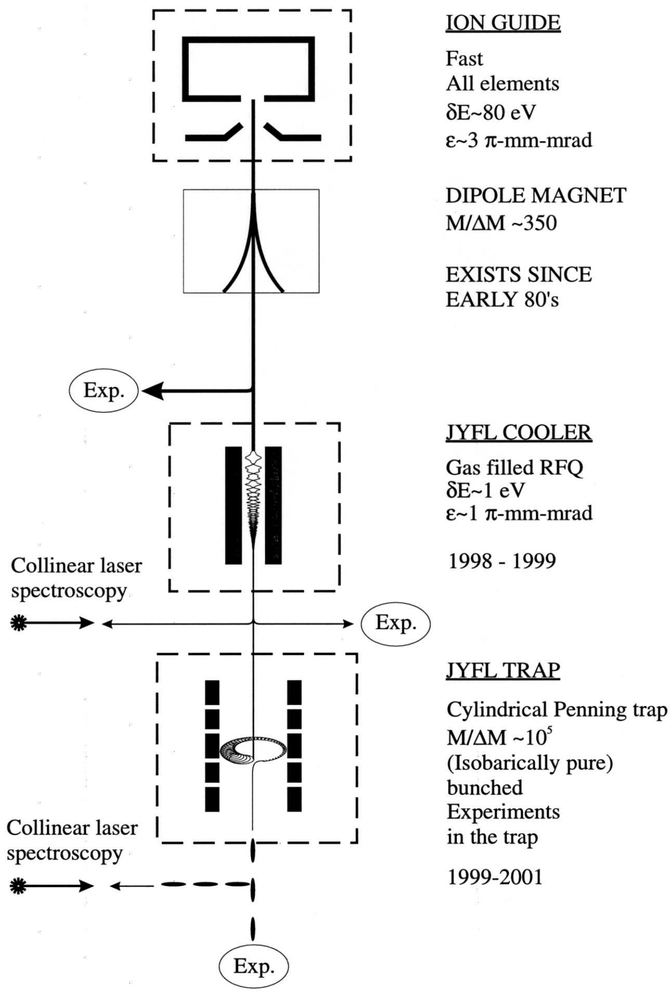

Fig. 6. Schematic layout of the ion cooler and ion trap project at the IGISOL-facility. The mass separated ion beam will be injected through a small aperture into the gas-filled radiofrequency quadrupole (RFQ). The cooled ion beam from the RFQ is then transported to the Penning-trap, where it will be bunched and mass purified.

8. Conclusions

The universality of the ion guide technique and its application for different type of reactions has provided a wealth of new information. The ion guide development is still in progress and further explorations of the nuclei far from stability are expected. The new development of an RFQ-cooler and penning trap to improve the ion optical quality of the IGISOL-beams together with the mass purification will increase the sensitivity of any spectroscopy far from the stability.

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