EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/86-128
12 September 1986

RADIOACTIVE ION-BEAMS AVAILABLE AT ON-LINE MASS SEPARATORS

H. L. Ravn
ISOLDE group, CERN, Geneva Switzerland

ABSTRACT

Today new rapid separation methods, based on thermochemical and physical principles, allows radioactive nuclei of almost all elements to be continuously transferred from an accelerator target into an ion beam. These techniques often referred to as target and ion-source systems have in the last 20 years turned on-line mass separators into the most efficient tool for production and study not only of nuclei far from stability but radioactive nuclei in general.

The present paper summarizes the status of this field in terms of elements available as ion beams, overall efficiency, intensity, selectivity and speed. By means of examples selected from the ongoing development work at many on-line separator laboratories the prospects for improving existing systems and extension to further elements are assessed.

To be presented at: Proc. Eleventh Int. Conf. on Electromagnetic Isotope Separators and
Techniques Related to Their Applications
Los Alamos, N. M. 18-22 August, 1986

Geneva, September 4, 1986

1. INTRODUCTION

It is now 35 years since Kofod-Hansen and Nielsen¹⁾ in a pioneering effort at the Niels Bohr Institute started the first on-line mass separator experiment which was aimed at the study of the short-lived neutron rich Krypton nuclei formed in thermal neutron fission of ^{235}U . On-line mass-separation of radioactive ion-beams obtained by irradiation of a target connected to the ion source of a mass separator, of which the principle is shown in fig.1, has since become a standard technique to produce not only very short-lived nuclei far from stability but almost any radioactive nucleus. In fact for most elements it is a faster, continuous and mass dispersive alternative to the well established radiochemical techniques.

The unit in which the target and ion source is combined is the most crucial element of an on-line separators since it determine the elements available as well as their yield and chemical purity. The last years progress in the development of target and ion sources for on-line mass separators has opened up a number of new fields of research which take advantage of the ion-beam form in which the radioactive nuclei are presented to the experiment.

The purpose of this paper is to review the status of the beams that have been developed at the many on-line mass separators that have been taken into use since the Lysekil conference²⁾ that marked the start of the field. This is not an easy job since at the 37 on-line mass separators listed in table 1, ion beams of 82 elements or about 1200 nuclides out of the 1900 artificially produced nuclei are available. I shall attempt to comply with this task by firstly, in chapter 2, shortly to discuss the various techniques that are used in order to exploit the characteristics of the different nuclear reactions used to produce the nuclei and their combination with different types of ion sources and mass separators. In chapter 3, the status of the beams available at the on-line mass separators is given for each group of elements according to the their behaviour in an ion source.

In view of the large number of on-line mass separators in operation today time does not allow to comment on each single machine. I will illustrate the beams available by means of a few selected examples which demonstrate what they have done for physics. A more detailed overview of the physics done with on-line mass separators can be found in the proceedings of several topical conferences³⁹⁻⁴¹⁾. Finally in chapter 4, new developments aimed at further improvement of the ion beams are mentioned.

2. NUCLEAR REACTION AND MASS-SEPARATOR TYPE

As seen in table 1, the existing on-line mass separators can be classified according to two criteria: The source of bombarding particle which determine the nuclear reaction used for production of the nuclei of interest and the type of mass separator coupled to the target and ion

source unit. In particular the projectiles used have directed the technical development in three principal different directions:

- 1) At accelerators of heavy ions or low energy protons ($E < 100 \text{ MeV}$).
- 2) Around thermal neutron sources like nuclear reactors and neutron generators.
- 3) Systems on-line to high energy proton or helion accelerators ($E > 100 \text{ MeV}$).

Three different types of electromagnetic mass-separators have been used:

- 1) Mass spectrometers
- 2) Low intensity isotope separators
- 3) Medium intensity isotope separators

In all the systems the first problem is rapidly to separate the nuclear reaction products from the target bulk and transfer it to the ion source. The second problem is that the production reaction are more or less complex and form many isotopes of different elements so that systems with high selectivity both in A as performed by the mass separator and in Z as obtained by a chemical separation step is the ideal. The basic properties of on-line mass separators is described in terms of the following properties;

1. Maximum current I that the beam optics can handle.
2. Mass range $M = (M_{\text{max}} - M_{\text{min}})/M_{\text{min}}$, where M_{max} is the highest mass and M_{min} the lowest mass present in the focal plane.
3. Resolution $R = (M/\Delta M)$, where ΔM is the full width at half maximum of a beam of ions with mass M in the focal plane.
4. Dispersion $D = d(M/\Delta M)$, where d is the perpendicular displacement in mm between focussed ion beams of mass M and $M + \Delta M$.
5. Enhancement factor $E = (C_{\text{fw}}/C_{\text{iw}}) * (C_{\text{ip}}/C_{\text{fp}})$, where for nuclide collection C_{fw} is the final concentration of the wanted nuclide, C_{iw} its initial concentration, C_{fp} the final concentration of one contaminating nuclide and C_{ip} its initial concentration.
6. Production rate Y , radioactive beam intensity measured in the focal plane and given in atoms per second per unit of bombarding beam intensity.
7. Delay times, the time delay between production of a nuclide and its arrival at the focal plane is quantitatively described by a probability function $p(t)dt$ characterized by a

delay parameter $\mu^{14)}$. Since this figure is strongly element and system dependent the delay half time, T_d , i.e. the time it takes for 50% of the atoms produced at time zero to arrive at the focal plane, is often used as figure of merit for a target and ion-source system.

8. Overall efficiency, ϵ is the production rate Y relative to the production rate in the target. This one can often be broken down into a number of partial efficiencies like the ones of target release, transport to the ion source, ionization efficiency and ion optical transport.

In the following the different approaches are discussed separately.

2.1 Separators on-line to heavy ion accelerators

The short range ($R \leq 200 \text{ mg/cm}^2$) of the projectiles used here demands for thin target technology. The typical nuclear reaction types used are fusion reactions, projectile stripping and occasionally fission. The forward momentum imparted to the reaction products may conveniently be used to separate them from the target material and to recoil through a thin window into the ion source. The small target often allows it to be situated inside the source. A typical example is the GSI integrated target and ion source⁴²⁾ shown in fig. 2. Note the pulsed cooling, applied to the wall of the ion source, that allows to bunch the radioactive ion beam.

With delay half times of 0.3-1 s these systems are among the fastest, resulting in some of the highest production rates of the most neutron deficient nuclei. The maximum rates are limited by target thickness and incident beam intensity to $<10^7$ atoms/s. Together with the few heavy-ion reaction-channels this gives a very high sensitivity because the overall contamination level is determined by the most abundantly produced nuclei. Since the target may be outside the ion source almost any solid element can be used as target.

2.2 Systems which uses thermal neutrons as projectile

Thermal neutrons were the first projectiles to be used at an on-line mass separator¹⁾. These systems which are limited to produce neutron rich nuclei of the elements within the ^{235}U thermal neutron fission yield distribution, may typically use of the order of 5g of ^{235}U . The target material which in most cases consists of porous or fibrous graphite²⁰⁾ impregnated with uraniumcarbide is situated inside an surface ionization source²⁶⁾ or most often an plasma discharge ion-source. A typical example of an integrated high-temperature target and plasma type ion-source taken from the TRISTAN II separator at Brookhaven⁴³⁾ is shown in fig. 3. In the most favourable cases the available neutron flux is about 10^{11} neutron/cm² s which results in maximum production rates of

10^8 atoms/s²⁰⁾. The delay half time⁴⁴⁾ is of the order of seconds but the systems have usually no chemical selectivity. A particular advantage of a reactor based on-line separator is the large amount of beam time available per year.

2.3 Systems which use high energy proton or helion reactions

These particles are particularly useful as projectiles for on-line mass separators since their long range permits the use of very thick targets, up to 300 g/cm^2 for 600 MeV protons. This leads to production yields which often exceeds that of all other methods and for the most abundant products reaches 10^{11} atoms per second per μA incident proton beam for a target thickness of 100 g/cm^2 . The upper limit of proton beam intensity which may be supported by the present target technology is $100\text{ }\mu\text{A}$ ⁴⁵⁾. Furthermore the three nuclear reaction types: spallation, fragmentation and high energy fission of natural Uranium and Thorium produces almost all known nuclei. In the ISOLDE beam-catalogue⁴⁶⁾ the measured intensities of ~ 600 beams of 66 elements are listed.

Due to the large amount of target material the target proper is usually situated in a separate container connected to the ion source by means of a tube as done in the typical ISOLDE target unit⁴⁷⁾ shown in fig.4. The major problem for these systems is the frequent lack of chemical selectivity. Many different techniques have been developed which achieve this selectivity, excellent yields and delay half times down to 1 s. When unselective systems are used the nuclear spectroscopy study of rare species produced in sufficient amounts have often been abandoned due to the presence of much more abundantly produced isobaric masses. The large amount of radioactivity produced in the target unit places the mass separators on-line to high-energy beams in the class of heavy nuclear industry where robotics is needed for target handling.

2.4 On-line mass spectrometers

The mass spectrometer is a precision apparatus where resolving power is achieved by means of slits, the maximum ion current out of the ion source is of the order of $1\text{ }\mu\text{A}$ and the acceleration voltage is 5-10 KeV. The ion source for on line use is for intensity reasons limited to positive surface-ionizers and the resolving power achieved is 400. The yields reaches 10^8 atoms/s for a proton beam of $1\text{ }\mu\text{A}$. The measured delay half-times for alkalis are as short as 30 ms which allows the ion beam to be pulsed in synchronization with the accelerator beam as used by the Orsay group⁵⁾. Despite the element limitations these compact and mobile instruments have at an early stage made decisive contributions to on-line mass separator physics. Their role has today been taken over by the low current mass-separator.

2.5 Low current mass separators for on line use

This type of separator is the most frequently used on-line mass separator its origin is the Scandinavian laboratory separator and it typically allows the use of ion sources which delivers a beam of up to 300 μA . It features fringe field vertical focusing to give spot image in the focal plane where the mass range may be up to $\pm 15\%$ of the central mass. The mass resolution is 500-1500 dependent on the type of ion source used. The resulting enhancement factor is at best 10^4 . These separators have often been equipped with elaborate beam transport systems that allows simultaneous study of up to 4 different masses. The largest facility of this kind is the SC-ISOLDE with one such machine out of two mass separators³⁷⁾.

2.6 Medium current on-line mass separators

Medium current mass separators with maximum current capability of 1 - 20 mA present a number of advantages for on-line use. The slit geometry ion sources best suited for this current range may have a higher outlet area which shortens the delays for elements which are limited by the surface lingering time. The beam optics can handle the intense stable ion beams that result from the use of volatile target materials, helium jets and reactive gases added to the source in order to volatilize elements with low vapour pressure. Furthermore the slit geometry combined with higher order correction fields allows the resolution to be raised to more than 20 000 which result in enhancement factors of larger than 10^6 as seen from the mass spectrum in fig. 5, taken at the first separator of this new generation the Chalk River machine³²⁾ developed in Orsay.

3. RADIOACTIVE ION-BEAMS AVAILABLE AT ON-LINE MASS SEPARATORS

The status of the target and ion source techniques which delivers continuous ion-beams of radioactive nuclei for subsequent mass-separation is obtained from the periodic table of the elements shown in fig. 6 As result of systematic development made around in the many laboratories isotopes of 83 chemical elements are today available at on-line mass separators.

They can roughly be divided into two groups:

1. About 23 elements that successfully are separated with chemical selectivity and in overall yields above 10 %.
2. Another 60 elements that are observed as on-line beams but do still leave room for improvements in yield, selectivity, delay time and range of nuclei that can be produced.

It follows from this that the further developments should be concentrated on the detailed improvements of the procedures for the above mentioned group of 60 elements and to find procedures for the remaining 20 elements not yet available on-line.

It is possible to classify the elements broadly according to their behaviour in the target and

the ion source even though each one presents specific problems. Of major practical importance is the temperature required in the target and ion source in order to keep the element or a suitable compound in the gas phase so that it can be transferred and ionized efficiently. The general physical and chemical properties must also be considered so in the following I have found it useful to discuss the elements in groups which are roughly those of the periodical system.

3.1 The Alkali elements Li, Na, K, Rb, Cs, and Fr

Due to their high vapour pressure and simple chemical behaviour these elements are the easiest elements to handle in an on-line mass separator. Their low ionization potential has permitted many laboratories efficiently to produce element selective beams. In fig. 7 is shown the Na yields obtained by the ORSAY group⁴⁸⁾ who has pioneered the production of the light alkali beams. By means of this system they have reached the 1.5 ms ^{35}Na ⁴⁹⁾ which is considered to be the heaviest bound isotope of Na and represent the fastest beta decay observed in a nuclear system. The mass yield curve of cesium produced at ISOLDE¹⁴⁾ is shown in fig. 8. Note that that all 38 known Cs-isotopes are available. On the proton rich side, ^{114}Cs was shown by D'Auria et al.⁵⁰⁾ that it is situated at the proton drip line. This was confirmed by Faesterman et al.⁵¹⁾ who observed the proton unstable $1\mu\text{s}$ ^{113}Cs .

3.2 The alkaline earth metals Be, Mg, Ca, Sr, Ba and Ra

Only beams of the three heavy and most volatile elements of this group are produced efficiently on-line, the lighter ones still may be improved. Despite low production yields the RAMA group²¹⁾ could identify the heaviest and lightest nuclei with isospin projection $T_Z = -2$ the ^{36}Ca and ^{20}Mg respectively. The Ra-beam intensities of 10^9 atoms/s at ISOLDE⁵³⁾ allowed the identification of 2 more cases of ^{14}C emission⁵⁴⁾.

3.3 The trivalent metals Al, Sc, Y and The Rare earths

The two lightest members of this group are only available in low yields. Many groups successfully produce the rare earths. In fig. 9. a comparison of lanthanide yields of several groups is made. The yields obtained at ISOLDE⁴⁸⁾ have mainly been used in an extensive laser spectroscopy programme by the Mainz group⁵⁵⁾ the displayed yields correspond to an overall efficiency of 10 - 50 %. The reason for not using these beams for nuclear spectroscopy purposes is the lack of element selectivity. The limits of stability in this region has been probed by the GSI group⁵⁶⁾. In the reaction $^{58}\text{Ni}(5\text{MeV/u}) + ^{92}\text{Mo}$ the ground state proton emitter ^{147}Tm with a half life of 0.56 s was produced at a rate of 0.1 atom/s. Similar production rates of other rare earths have been obtained by the SARA group²⁸⁾ who elegantly used the high gas throughput of a medium intensity mass-separator to obtain 2% overall efficiency of an He-jet coupled ion source.

3.4 The Actinides Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No and Lw

The heavy members of this group only can be produced in heavy ion fusion reactions and the cross sections for their formation are quite low since the preferred de-excitation mode of the compound nucleus is fission. At the OASIS separator at Berkeley they have succeeded to make an ^{250}Fm beam of 150 atoms/h¹⁹⁾. The overall efficiency of the separator in the case of Fm formed in the reaction $^{238}\text{U}(^{16}\text{O},4\text{n})\text{Fm}$ was 10%.

3.5 The iron group Cr, Mn, Fe, Co and Cu

The proton rich isotopes of this series of elements are difficult to produce by means of spallation reactions on thick targets since no refractory target material with high reaction cross-section have been found. The neutron rich nuclei falls in the minimum region of the cross-section curve for production by means of high energy fission and fragmentation.

These elements have mainly been studied in heavy ion reactions. The part of the chart of nuclei shown in fig. 10 illustrates the region of the neutron rich nuclei produced at GSI⁵⁷⁾ by means of multinucleon transfer reactions induced by irradiating a ^{nat}W target with 9 MeV/u ^{76}Ge ions. The obtained beam intensities allowed to establish the decay schemes of a number of new nuclides.

3.6 Refractory metals Ti, V, Zr, Nb, Mo, Hf, Ta and W

The very low vapour pressure of these transition metals and many of their compounds has for a long time prevented their on-line study. In order to solve this problem several groups have taken up the chemical evaporation technique introduced by Sidenius and Skilbreid⁵⁸⁾ for stable beam production. In this method reactive gas is introduced into the target and ion source so that volatile compounds of the elements in question are synthesized. These molecules serve to transport the nuclear reaction products to the ion source and keep them in the gas phase. The ISOCELE group has made radioactive ion beams of the elements Nb, Zr, Hf, Ta and W⁵⁹⁾ by introducing CF_4 in the ion source. Since this method gives rise to high gas pressures in the ion source and consequently high beam intensities, their use of a medium current mass-separator was a necessary condition for the success. A typical example of the obtained beam intensities are shown in fig. 11. Note that the Hf is separated in the form of HfF_3^+ ions which in addition assured the isobaric separation so that the group could extend our knowledge to 7 new Hf and Ta nuclei.

3.7 Platinum like metals Tc, Ru, Rh, Pd, Re, Os, Ir and Pt

Like the refractory elements discussed in sect. 3.6 it is difficult to make beams of these noble metals since very high temperatures are required to keep them in the gas phase. It has often been claimed that He-jet systems may do the job in such cases. Maybe they do until the ion source where these elements unfortunately are ionized in very low yields due to condensation. An elegant way to avoid this problem has been devised by the Jyväskylä group¹⁵⁾. In their He-jet ion guide system shown in fig.12 they make use of the primary recoil ions produced in a heavy ion reaction. After charge equilibration in the He gas the 1+ ions are injected via a He skimmer into the separator without the use of a conventional ion source. The element-dependent overall-efficiency of the process is 0.03 -10 % and the delay half time is below 1ms. With this technique they have made beams of a number of refractory elements including Tc. In a recent experiment with proton induced fission the 1 s ^{116}Rh was identified⁶⁰⁾.

3.8 Group 2B elements Zn, Cd and Hg

The volatility of these elements allowed to make intense beams at an early stage of the on-line mass separation era. The high yields of Hg opened up the studies of the nuclear ground states by techniques of atomic physics. The pioneering experiment by the Mainz group⁶¹⁾ on the nuclear radii of the Hg isotopes revealed an unexpected sharp change between ^{187}Hg and ^{185}Hg . This started off many groups in the study of the level structure of the light Hg nuclei and the discovery of shape coexistence in this region.

3.9 Group 3A elements Ga, In and Tl

The low ionization potential and the relatively high vapour pressure has allowed a number of groups to make selective and intense beams of these elements. Recently the element In has been extensively studied since the undiscovered but presumably doubly magic ^{100}Sn decays to it and the doubly magic ^{132}Sn can be studied via the decay of ^{132}In ⁶²⁾. In this context Helium refrigerators for on-line nuclear orientation have been placed on-line with isotope separators at Leuven and Daresbury. This technique has been applied to spin and nuclear moment measurements in $^{105-108}\text{In}$ ⁶³⁾.

The studies of the decay of 184,186 and 188 Tl at UNISOR⁶⁴⁾ revealed two coexisting bands in the even Hg isotopes, the strongly deformed one being build on a low lying 0^+ state.

3.10 Elements which form refractory compounds B, C, N, O, Si, S and P

Although fig. 1 shows beams of several of these element the overall efficiencies are typically 0.01% and they need still much development work before more efficient beam production methods are available. The recent interest in post acceleration of these elements for nuclear astrophysics purposes has renewed the interest in high efficiency methods as discussed in ref. 65.

3.11 Group 4A,5A and 6A elements Ge, Se,Te, Sn, As, Sb, Pb, Bi and Po

The neutron deficient nuclei of the 6 lightest members are at present best produced in heavy ion fusion reactions. The GSI mass separated beams of Te, Sn and other elements⁶⁶⁻⁶⁷⁾ allowed the discovery of a new island of alpha emission. The lightest alpha emitter known so far ^{106}Te -- ^{102}Sn give insight into the $Z = 50$ shell strength through Q-value and mass measurements⁶⁸⁾.

The heavy members and the neutron rich isotopes of the lighter ones are best produced in spallation and fission of U or Th respectively. The Studsvik⁴⁴⁾ group have used their integrated target and ion source containing 3g ^{235}U and situated near the core of the reactor at a flux of $4 \cdot 10^{11}$ n/cm² s in a particular careful study of the cross-sections of products from thermal-neutron induced fission of ^{235}U . They not only give the production yields of about 170 nuclides but also the delay-time distribution and ion-source efficiency of each element separated. They have recently introduced a new system⁶⁹⁾ in which they have raised their target temperature from 1500°C to 2500°C. The resulting shorter delays give the improved overall efficiencies shown in fig. 13.

3.12 The Halogens F, Cl, Br, I, and At

Characterized by their volatility and their high electron affinity the halogens heavier than F may be produced almost as intense and selective as the alkalis. The chemical selectivity has at ISOLDE been obtained by means of negative surface ionization a typical example^{46,70)} is the At yields shown in fig. 14. The new isotopes $^{226-228}\text{At}$ has at present only been identified as radioactive ion-beams their decay properties will be studied later⁴⁷⁾. The ^{72}Br beam at the Chalk River high resolution mass separator was used to demonstrate feasibility of the on-line separator itself for direct mass measurements⁷¹⁾.

3.13 The rare gases He, Ne, Ar, Kr, Xe and Rn

These noble gases are the most easy elements to bring on-line since they form no chemical bindings and diffuse out of a number of target materials for some even at room temperatures. One of the first targets⁷²⁾ used at ISOLDE in 1967 was $\text{ThO}_2 \cdot \text{XH}_2\text{O}$, which emanated Rn at room temperature. Since then all known isotopes of these elements are available at ISOLDE in high yields and chemical selectivity and the beams are continuously being improved. Recently new targets consisting of alkaline earths oxides have been taken into use for the production of the neutron deficient isotopes of Ne, Ar and Kr⁵³⁾. They have been found to be the fastest ISOLDE targets with delay half times of ~ 0.5 s. As an example the Ar yields are shown in fig. 15. The three orders of magnitude increase in ^{32}Ar yield allowed⁷³⁾ to carry out, via its dominant beta-delayed proton decay mode, a precise evaluation of the axial-vector (Gamow-Teller) strength relative to its

free-nucleon value. The ^{31}Ar which according to most updated mass formulas is stable or nearly stable against direct two proton emission was not observed in this experiment but was recently observed⁷⁴⁾ at the LISE recoil spectrometer at GANIL.

4. CONCLUDING REMARKS

In this short review I have tried to give the status and illustrate recent progress in the techniques for making ion beams of unstable nuclei. It only remains to include some comments on the future development of radioactive ion-beams.

The chemical selectivity can be improved by means of a number of techniques. Ideally it can be achieved by increasing the resolution of the mass separator towards 30000 where isobar separation may be obtained. By means of higher order correction elements and a very careful beam optical design the new ISOLDE separator^{75,76)} presently under construction and the planned TRIUMF on-line mass-separator⁷⁷⁾ opens up for this possibility. The recent advances in laser techniques now allows selective photoionization⁷⁸⁾. The atoms in the molecular flow of nuclear reaction products which leaves the on-line target is ideally suited for this process. By subjecting them to resonant excitation by radiation from two or three dye lasers they may be brought into the auto ionization or Rydberg states. By irradiation of Sr atoms inside a hot cavity Andreev et al.⁷⁹⁾ has achieved 17% ionization efficiency. Thermochromatographic element separation in the focal plane of an on-line mass separator has been pioneered by the OSIRIS group⁸⁰⁾. At this conference the GSI group⁸¹⁾ showed the first example of thermochromatographic separation performed inside the ion source. The same technique also allows a bunching of the radioactive beam. Chemical reactions inside the ion source have in a few cases been used to volatilize refractory elements and to obtain selectivity via the formed molecular ions⁸²⁾. And this technique holds much promise for future developments. Radiofrequency ion sources of the single stage ECR type is receiving attention in several laboratories⁸³⁾ because of its long lifetime and its high efficiency for producing singly charged ions of the light gaseous elements⁸⁴⁾. The use of proton beam intensities of the order of $100\text{ }\mu\text{A}$ ⁴⁵⁾ and the postacceleration of the resulting intense radioactive beams, which has been a technical possibility since long, is now being planned⁷⁷⁾.

As so clearly seen in the past developments of this kind will open up new domains of elements, intensity, purity and energy, and will serve many research fields, including nuclear science, atomic physics, astrophysics, solid state physics and medical research.

Table 1 On-line mass separators from which examples have been taken

<u>At heavy ion acc.</u>	<u>At Reactors or Neutron generators</u>	<u>At high energy acc.</u>
Montreal ³⁾ + Orsay ⁶⁾ + Tokyo ⁸⁾	Mass spectrometers GODIVA-Los Alamos ⁴⁾ SOLAR-Richland ⁷⁾ OSTIS-Grenoble ⁹⁾	Orsay -CERN ⁵⁾ +
Daresbury ¹⁰⁾ GSI-Darmstadt ¹²⁾ Juväskulä ¹⁵⁾ LISOL- Leuven ¹⁷⁾ OASIS-Berkeley ¹⁹⁾ PINGIS-Stockholm ²¹⁾ + Stockholm ²³⁾ + POLARIS-Princeton ²⁵⁾ + RAMA-Berkeley ²⁷⁾ SARA-Grenoble ²⁸⁾ Tohoku ²⁹⁾ Tokai ³⁰⁾ UNISOR-Oak Ridge ³¹⁾	Low current separator type Copenhagen ¹⁾ + ARIEL-Grenoble ¹³⁾ + HELIOS-Mainz ¹⁶⁾ Kyoto ¹⁸⁾ OSIRIS-Studsvik ²⁰⁾ SOLIS-Soreq ²²⁾ + TRISTAN I-Ames ²⁴⁾ + TRISTAN II-Brookhaven ²⁶⁾	IRIS-Leningrad ¹¹⁾ ISOLDE 2-CERN ¹⁴⁾
Chalk River ³²⁾ BEMS 2 Dubna ³⁵⁾ EMSONHIB Dubna ³⁸⁾ + + Separators no longer in operation	Medium current type separators IAELE-Buens Aires ³³⁾ Strasbourg ³⁶⁾	ISOCELE-Orsay ³⁴⁾ ISOLDE 3-CERN ³⁷⁾

Figure captions

1. The principle of on-line mass separation.
2. The GSI integrated target and ion source with the bunching system mounted in the colder position (A) of the ion source. By inverting the anode cylinder the ports come to the hot position (C). Bottom: Configuration with target/catchers in a holder on the entry side, with cooler decoupled and extra heater. Top: Configuration with heat-shielded window and the target/catcher stack in the pocket and with coupled cooler. (1) heavy-ion beam, (2) mass-separator beam, (3) target/catcher stack, (4) tungsten window, (5) Heat shields, (6) anode, (7) cathode, (8) outlet plate, (9) accumulation pocket, (10) extra heater, (11) weak cooler, (12) strong cooler, (13) oven line, (14) gas line.
3. The TRISTAN-2 high-temperature integrated target and ion source
4. Typical ISOLDE target and ion source unit.
5. The resolution of 20000 obtained at the Chalk River on-line mass separator allowed to resolve the CO-N₂ doublet at mass 28.
6. Elements of which beams have been produced at on-line mass separators.
7. Intensities of sodium beams observed in the Orsay mass spectrometer obtained by irradiation of an 35 g/cm² iridium-carbon target with 20 GeV protons.
8. Intensities of neutron rich caesium beams obtained at ISOLDE by irradiation of a 16.4 g/cm² uraniumcarbide target irradiated with 600 MeV protons and 910 MeV helions. Also shown are the intensities of the neutron deficient beams obtained from a proton irradiation of a 140 g/cm² lanthanum target.
9. Rare-earth beam-intensities obtained at the mass separators at GSI, SARA and ISOLDE.
10. Beams produced at GSI in ⁷⁶Ge-induced multinucleon transfer reactions.
11. Isotopic beam-intensities of the refractory element Hafnium produced at ISOCELE in the reaction Yb(³He,xn)Hf. The target material was 3 g/cm² YbF₃ irradiated with a 1 μA 280 MeV ³He beam. The collected ions were HfF₃⁺.
12. The Jyväskylä ion guide and its coupling to the separator. The primary recoils are thermalized in He where they reach the 1+ ionization, after skimming of the excess He they are injected into the extraction electrode gap.
13. The overall efficiency of the OSIRIS target and ion-source as function of atomic number of fission product nuclei. The upper curve is measured at a target temperature of 2400°C. For comparison the lower curve shows the efficiencies of the previously used system at 1500°C.
14. Intensities of Astatine beams obtained at ISOLDE by irradiation of a 47 g/cm² thoriumoxide target irradiated with a beam of 1 μA 600 MeV protons.
15. Comparison of intensities of Argon beams obtained at ISOLDE by irradiation of vanadiumcarbide and calciumoxide targets irradiated with a beam of 1 μA 600 MeV protons.

References

1. O. Kofoed-Hansen and K.O. Nielsen, Danske Vidensk. Selsk. Mat.-Fys. Medd. **26**(1951) No. 7
2. Proc. Internat. Symposium on Why and How should we investigate Nuclides Far Off the Stability Line, Lysekiel, 1966, eds. W. Forsling, C.J. Herrlander, and H. Ryde, Ark. Fys. **36**(1967)1
3. J.K.P. Lee, G. Pilar, B.L. Tracy and L. Yaffe, J. Inorg. Nucl. Chem. **37** (1975) 2035
4. S.J. Balestrini and L. Forman, Proc. Internat. EMIS Conf. on Low Energy Accelerators and Mass Separators, Skövde, 1973, Eds. G. Anderson and G. Holmén, (Chalmers University of Technology and University of Gothenburg) p. 359(1973)
5. M de Saint Simon, R. Ferreau, M. Jacotin, J.F. Kepinski, R. Klapisch, C. Thibault, F. Touchard, Nucl. Instr. and Methods **186**(1981)87
6. R. Klapisch and R. Bernas, Nucl. Instr. and Methods **38**(1965)291
7. J.J. Stoffels, Nucl. Instr. and Methods **119**(1974)251
8. Y. Yoshizawa, H. Noma, T. Horiguchi, T. Katoh, S. Amemiya, M. Itoh, K. 6.Hisatake, M. Sekikawa and K. Chida, Nucl. Instr. and Methods **134**(1976)93
9. Klaus-Dieter Wünsch, Nucl. Instr. and Methods **155**(1978)347
10. W. Gelletly, Nucl. Instr. and Methods **211**(1983)89
11. E.Ye. Berlovich, E.I. Ignatenko and Yu.N Novikov, Proc. Internat. EMIS Conf. on Low Energy Accelerators and Mass Separators, Skövde, 1973, Eds. G. Anderson and G. Holmén, (Chalmers University of Technology and University of Gothenburg), p.349(1973)
12. C. Bruske, K.H. Burkhard, W. Hüller, R. Kirchner, O. Klepper and E. Roeckl, Nucl. Instr. and Methods **186**(1981)61
13. J.P. Bocquet, R. Brissot, J. Crancon, C. Ristori and A. Moussa, Nucl. Instr. and Method **88**(1970)51
14. H.L. Ravn, Physics Reports **54**(1979)203
15. J. Ärje, J. Äystö, H. Hyvönen, P. Taskinen, V. Koponen, J. Honkanen, K. Valli, A. Hautojärvi and K. Vierinen, Nucl. Instr. and Methods **A247**(1986)431
16. M. Brügger, N. Hildebrand, T. Karlewski, N. Trautmann, A.K. Mazumdar and G. Herrmann, Nucl. Instr. and Methods **A234**(1985)218
17. J. Verplancke, B. Brijs, K. Cornelis, J. Gentens, M. Huyse and G. Lhersonneau, Nucl. Instr. and Methods **186**(1981)99
18. K. Okano, Y. Kawase, K. Kawade, H. Yamamoto, M. Hanada, T. Katoh and I. Fujiwara, Nucl. instr. and Methods **186**(1981)115
19. J. Michael Nitschke, Nucl. Instr. and Methods **206**(1983)341
20. G. Rudstam, Nucl. Instr. and Methods **139**(1976)239
21. K. Fransson, M. af Ugglas and Å. Engström, Proc. Internat. EMIS Conf. on Low Energy Accelerators and Mass Separators, Skövde, 1973, Eds. G. Anderson and G. Holmén, (Chalmers University of Technology and University of Gothenburg), p.330(1973)
22. M. Oron and S. Amiel, Proc. Int. Conf. on Electromagnetic Isotope Separators and the Techniques of their Application, Marburg, (Bundesministerium für Technologie und Wissenschaft), rep. **K 70-28**, p.87 (1970)
23. S. Borg, U. Fägerquist, G. Holm and F. Kropff, Nucl. Instr. and Methods **38**(1965)296
24. W.L. Talbert, Jr., F.K. Wohn, A.R. Landin, J.C. Pacer, R.L. Gill, M.A. Cullison, G.A. Sheppard, K.A. Burke, K.L. Malaby and A.F. Voigt, Nucl. Instr. and Methods **139**(1976)257
25. E.J. Anasaldo, G.T. Garvey, J.M. Lind, F.W. Loeser and F.A. Naumann, Nucl. Instr. and Methods **125**(1975)429
26. W.L. Talbert, Jr., F.K. Wohn, John C. Hill, A.R. Landin, M.A. Cullison and R.L. Gill, Nucl. Instr. and Methods **161**(1979)431
27. D.M. Moltz, J. Äystö, M.D. Cable, R.F. Parry, P.E. Haustein, J.M. Wouters and Joseph Cerny, Nucl. Instr. and Methods **186**(1981)141

28. A. Plantier, R. Beraud, T. Olliver, A. Charvet, R. Duffait, A. Emsallem, N. Redon, V. Boninchi, S. Vanzetto, A. Gizon, J. Treherne, N. Idrissi, J. Genevey and J.L.Vieux-Rochaz, Connection of a He-Jet to the medium-current source of the SARA on-line separator. To be published in these proceedings
29. M. Fujioka, T. Shinozuka, E. Tanaka, Y. Arai, S. Hayashibe and T.Ishimatsu, Nucl. Instr. and Methods**186**(1981)121
30. T. Tamura Private communication
31. E.H. Spejewski, R.L. Mlekodaj and H.K. Carter, Nucl Instr and Methods**186**(1981)71
32. H. Schmeing, J.C. Hardy, E. Hagberg, W.L. Perry, J.S. Wills, Nucl. Instr. and Methods**186**(1981)47
33. E.O.Achterberg et.al. Proc. Int. Conf. on Electromagnetic Isotope Separators and the Techniques of their Application, Marburg,1970 (Bundesministerium fur Technologie und Wissenschaft,rep. K 70-28), p.108 (1970)
34. P. Paris,C.F. Liang,D. Lecouturier,M. Arianer,J. Obert,A. Caruette,A. Ferro, J. Fournet,J.C. Putaux,J.L. Sarrouy and the ISOCELE Collaboration, Nucl Instr and Methods**186**(1981)91
35. V.A. Karnaukhov,D.D. Bogdanov,A.V. Demyanov,G.I. Koval and L.A. Petrov, Nucl. Instr. and Methods**120**(1974)69
36. J.P. Zirnheld and L. Schutz, Proc. Internat. EMIS Conf. on Low Energy Accelerators and Mass Separators, Skövde,1973, Eds. G. Anderson and G. Holmén, (Chalmers University of Technology and University of Gothenburg), p.469(1973)
37. B. Allardyce and H.L. Ravn, To be published in these proceedings
38. N.I. Tarantin, A.P. Kabachenko, I.V. Kuznetsov, Yu.A. Dyachihin, N.S. Ivanov and Om Zai Khun, Proc. Int. Conf. on Electromagnetic Isotope Separators and the Techniques of their Application, Marburg, (Bundesministerium fur Technologie und Wissenschaft),rep. K 70-28, p.59 (1970)
39. Proc. Internat. Conf. on the Properties of Nuclei Far from the Region of Beta Stability, Leysin,1970 CERN 70-30 2 Vols
40. Proc. 3rd. Internat. Conf. on Nuclei Far from Stability, Cargèse, 1976, CERN 76-13 (1976)
41. Proc. 4th.Internat.Conf on Nuclei Far from Stability, Helsingør Denmark (1981), CERN 81-09 (1981)
42. R. Kirchner, O. Klepper, D. Marx, G.-E. Rathke and B. Sherrill, Submitted to Nucl. Instr. and Methods
43. R.L. Gill, Proc. of the TRIUMF-ISOL Workshop, Mount Gabriel, Quebec Eds. J. Crawford and J.M. D'Auria Triumf Report TRI-84-1,p. 32
44. G. Rudstam, P. Aagard and H. -U. Zwicky, Studsvik Science Research Laboratory, Sweden, Rept. NFL-42 (1985)
45. T. Eaton And H.L. Ravn, Beam heating of thick targets for on-line mass separators, to be published in these proceedings
46. The ISOLDE users manual Ed. J. Kluge to be published as CERN report
47. T. Bjørnstad, E. Hagebø, P. Hoff, O.C. Jonsson, E. Kugler, H.L. Ravn, S. Sundell, B. Vosicki and The ISOLDE Collaboration, To be published in these proceedings
48. F. Touchard, J. Biderman, M. de Saint Simon, C. Thibault G. Huber, M. Epherre, and R. Klapisch, Nucl. Instrum. Meth. **186**(1981)329
49. M. Langevin, C. Detraz, D. Guillemaud-Müller, A.C. Mueller, C. Thibault, F. Touchard, F. Klotz, G. Miche, G. Walther, M. Epherre, and C. Richard-Serre, Phys. Lett. **130B**(1983)251
50. J.M. D'Auria, J.w. Grüter, E. Hagberg, P.G. Hansen, J.C. Hardy, P. Hornshøj, B. Jonson, S. Mattsson, H.L. Ravn and P. Tidemand-Petersson Nucl. Phys. A**301**(1978) 397
51. T. Faesterman, A. Gillitzer, K. Hartel, P. Kienle and E. Nolte, Phys. Letts. **137B**(1984)23
52. J. Äystö, M.D. Cable, R.F. Parry, J.M. Wouters, D.M. Moltz and J. Cerny,

- Phys. Rev. **C23**(1981)879
53. T. Bjørnstad, P. Hoff O.C. Jonsson, E. Kugler, H.L. Ravn S. Sundell and B. Vosciki, Use of refractory oxides and carbides as targets for on-line mass separation, To be published in these proceedings
 54. P.B. Price, J.D. Stevenson and S.W. Barwik, Phys. Rev. Lett. **54**(1985)297
 56. R. Neugart, Proc. Conf. on Lasers in Nuclear Physics, 1982 Oak Ridge
 56. P.O. Larsson, T. Batch, R. Kirchner, O. Klepper, W. Kurchewics, E. Roeckl, D. Schart, W.F. Feix, G. Nymand and P. Tidemand-Petersson, Z. Phys. **A314**(1983)9
 57. E. Runte, W.-D. Schmitt-Ott, P. Tidemand-Petersson, R. Kirchner, O. Klepper, W. Kurchewics, E. Roeckl, N. Kafrell, P. Peuser, K. Rykaczewski, M. Bernas, P. Dessagne and M. Langevin, Nucl. Phys. **A339**(1982)163
 58. G. Sidenius and O. Skilbreid, Proc. Internat. Symposium on Electromagnetic separation of radioactive isotopes, Vienna, 1960 (Springer Verlag, Vienna 1961)
 59. J. Sauvage, C. Bourgeois, A. Caruette, P. Kilcher, J. Obert, J. Oms, J.C. Puteaux, B. Roussire, A. Ferro, J. Fournet, L. Kotfila, C.F. Liang, P. Paris, M.G. Porquet and G. Cornudet, Proc. of the TRIUMF-ISOL Workshop, Mount Gabriel, Quebec Eds. J. Crawford and J.M. D'Auria Triumf Report TRI-84-1, p. 161
 60. J. yst private communication
 61. J. Bonn, G. Huber H.J. Kluge, L. Kugler and E.W. Otten, Phys. Lett. **38B**(1972)308
 62. T. Bjørnstad, M.J.G. Borge, J. Blomquist, R.D. von Dincklage, G.T. Ewan, P. Hoff, B. Jonson, K. Kawade, A. Kerek, O. Klepper, G. Lvhiden, S. Mattsson, G. Nyman H. L. Ravn, G. Rudstam K. Sistemich and O. Tengblad, To be published in Nucl. Phys. A
 63. D. Vandenplassche, E. van Walle, C. Nuytten and L. Vanneste, Phys. Rev. Lett. **49**(1982)1390
 64. J.L. Wood, Proc. of the TRIUMF-ISOL Workshop, Mount Gabriel, Quebec Eds. J. Crawford and J.M. D'Auria Triumf Report TRI-84-1, p. 87
 65. H.L. Ravn, J.M. D'Auria, M.J.G. Borge, Y. Huang, O.C. Jonsson, L. Nikkinen and S. Sundell, Proc. Accelerated Beams Workshop, Parksville B.C. 1985, Eds. L. Buchmann and J.M. D'Auria Triumf Report TRI-85-1, P.94
 66. R. Kirchner, O. Klepper, G. Nyman, W. Reisdorf, E. Roeckl, D. Schardt, N. Kafrell, P. Peuser and K. Schneeweiss, Phys. Lett. **70B**(1977)150
 67. P. Tidemand-Petersson, R. Kirchner, O. Klepper, W. Kurchewicz, E. Roeckl and E.F. Zganjar, GSI-81-19
 68. D. Schardt, T. Batsch, R. Kirchner, O. Klepper, W. Kurchewicz, E. Roeckl and P. Tidemand-Petersson, Nucl. Phys. **A368**(1981)153
 69. L. Jacobson, B. Fogelberg, B. Ekstrm and G. Rudstam, An Unconventional Bi-Mode Ion Source for The OSIRIS Facility. To be published in these Proceedings.
 70. B. Vosicki, T. Bjrnstad, L.C. Carraz, J. Heinemeyer and H.L. Ravn, Nucl. Instr. and Methods, **186**(1981) 307
 71. K.S. Sharma, H. Schmeing, H.C. Evans, E. Hagberg, J.C. Hardy and V.T. Koslowsky, Proc. of the TRIUMF-ISOL Workshop, Mount Gabriel, Quebec Eds. J. Crawford and J.M. D'Auria, Triumf Report TRI-84-1, p. 70
 72. P. Patzelt, Proc. Int. Conf. on Electromagnetic Isotope Separators and the Techniques of their Application, Marburg, (Bundesministerium fur Technologie und Wissenschaft), rep. **K 70-28**, p.158 (1970)
 73. T. Bjrnstad, M.G.J. Borge, P. Dessagne, R.-D. von Dincklage, G.T. Ewan, P.G. Hansen, A. Huck, B. Jonson, G. Klotz, A. Knipper, P.O. Larsson, G. Nyman, H.L. Ravn, C. Richard-Serre, K. Riisager, D. Schardt and G. Walther, Nucl. Phys. **A443**(1985)283
 74. F. Pougheon, R. Anne, M. Bernas, C. Detraz, J. Galin, D. Guerreau, S. Hoath, D. Guillemaud-Mueller, J.C. Jacmart, M. Langevin, A.C. Mueller, F. Naulin, M.G. Saint-Laurent and E. Quiniou, IPNO DRE 86-01
 75. C. Geisse, H. Wollnick, B. Allardyce and E. Kugler, The Optics of ISOLDE-3- The New On-line Mass Separator At CERN, to be published in these proceedings

76. B. W. Allardyce and H. Ravn, The Status OF The ISOLDE-3 Prproject, to be published in these proceedings
77. K. Oxhorn, L. Buchmann, J. Crawford, J. M. D'Auria, H. Dautet, R. Kokke, J. K. P. Lee, R. B. Moore, V. L. Nikkinen, A. Otter, H. Sprenger and J. Vincent, A Radioactive Beam Facility At TRIUMF, to be published in these proceedings
78. H. -J. Kluge, F. Ames, W. Ruster, and K. Wallmeroth, Proc. of the TRIUMF-ISOL Workshop, Mount Gabriel, Quebec Eds. J. Crawford and J.M. D'Auria, Triumf Report TRI-84-1, p 196
79. S. V. Andreev, V. I. Mishin and V. S. Letokov, Optics Comm. **57**(1986)317
80. B. Grapengiesser and G. Rudstam, Radiochim. Acta **20**(1973)85
81. R. Kirchner, A Discharge Ion Sourche With Bunched Beam Release for Various Elements, to be published in these proceedings
82. P. Hoff, L. Jacobsson, B. Johansson P. Aagard, G. Rudstam, and H. -U. Zwicky, Nucl. Instrum. and Meth. **186**(1981)381
83. L. Buchmann, J. L. D'Auria, M. Dombosky, P. Schmor and J. Vincent, Concepts of an ECR Source for an ISOL, to be published in these proceedings
84. V. Bechtold and S. Shiekh, Proc. Accelerated Beams Workshop, Parksville B.C. 1985, Eds. L. Buchmann and J.M. D'Auria Triumf Report TRI-85-1, p.110

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

PERIODIC TABLE OF THE ELEMENTS

GROUP IA																	VIIIA
H												B	C	N	O	F	He
Li	Be											Al	Si	P	S	Cl	Ne
Na	Mg											Ga	Ge	As	Se	Br	Kr
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	In	Sn	Sb	Te	I	Xe
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	Tl	Pb	Bi	Po	At	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
LANTHANIDES—			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
ACTINIDES—			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Elements available as beams at on-line mass separators

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 13

Figure 14

Figure 15