Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research B 204 (2003) 220–224
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Production yields of noble-gas isotopes from ISOLDE UC_x/graphite targets ☆

U.C. Bergmann [a,*], G. Auböck [b], R. Catherall [a], J. Cederkäll [a], C.Aa. Diget [c], L. Fraile [a,1], S. Franchoo [a], H. Fynbo [a,c], H. Gausemel [d], U. Georg [a], T. Giles [a], H. Jeppesen [c], O.C. Jonsson [a], U. Köster [a], J. Lettry [a], T. Nilsson [a], K. Peräjärvi [a], H. Ravn [a], K. Riisager [c], L. Weissman [a,2], J. Äystö [a], The ISOLDE Collaboration

[a] *ISOLDE, EP Division, CERN, CH-1211 Genève 23, Switzerland*
[b] *Technical University Graz, A-8010 Graz, Austria*
[c] *Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark*
[d] *Kjemisk Institutt, Universitetet i Oslo, Postboks 1033, Blindern, N-0315 Oslo, Norway*

Abstract

Yields of He, Ne, Ar, Kr and Xe isotopic chains were measured from UC_x/graphite and ThC_x/graphite targets at the PSB-ISOLDE facility at CERN using isobaric selectivity achieved by the combination of a plasma-discharge ion source with a water-cooled transfer line.

The delay times measured for a UC_x/graphite target allow for an extrapolation to the expected yields of very neutron-rich noble gas isotopes, in particular for the "NuPECC reference elements" Ar and Kr, at the next-generation radioactive ion-beam facility EURISOL.

PACS: 25.85.Ge; 28.60.+S; 29.25.Rm
Keywords: Radioactive ion beams; Release; Ion yields; Isotope separation on-line; Uranium and thorium carbide targets

1. Introduction

Krypton beams were the first radioactive ion beams produced with the isotope separation on-line (ISOL) method [1]. Already in the earliest ISOLDE experiments [2] ISOL beams of all noble gas elements were produced. In this paper we report on the collected data of yields and release characteristics of the elements He, Ne, Ar, Kr and

☆ Supported by the EU RTD project EURISOL (HPRI-CT-1999-50001).
* Corresponding author. Tel.: +22-767-2563; fax: +22-767-8990.
E-mail address: uffe.bergmann@cern.ch (U.C. Bergmann).
URL: http://www.ifa.au.dk/ucb.
[1] On leave from Dpto. de Física Atómica, Molecular y Nuclear, Univ. Complutense, E-28040 Madrid, Spain.
[2] Present address: NSCL, Michigan State University, East Lansing, MI 48824-1321, USA.

0168-583X/03/$ - see front matter
doi:10.1016/S0168-583X(02)01921-3

Xe performed with actinide targets since the move of ISOLDE to the PS-Booster synchrotron.

2. Experimental technique, analysis and results

Neutron-rich noble-gas isotopes were produced in fission and fragmentation reactions induced by a pulsed beam of 1.0 or 1.4 GeV protons ($2–3 \times 10^{13}$ protons/pulse) impinging on standard ISOLDE UC_x/graphite or ThC_x/graphite targets (50 g/cm^2 U or Th). The reaction products effused from the target heated to about 2100 °C via a low-temperature, water-cooled transfer line to a FEBIAD type [3] plasma ion-source (type MK7 [4]). The temperature of the transfer line was kept at about 50 °C providing "pure" noble-gas beams without isobaric contamination. The transfer line lets pass only atoms and molecules which are gaseous at room temperature and distills out less volatile species. Normally this suppresses isobaric contaminations by many orders of magnitude. However, occasionally a much stronger produced isobar (the neighbouring alkali for neutron-rich noble gases and the halogen for neutron-deficient ones) might "leak" through the line. For the targets reported here no "leaking" was observed. Hence the Kr and Xe beams were indeed very pure. This is not true for all masses of Ne and Ar. They suffer from a background of multiply charged Kr or Xe. Very neutron-rich Ne isotopes are affected by Kr^{3+} and Xe^{5+} and Ar isotopes by Kr^{2+} and Xe^{3+}. Although a FEBIAD is optimised to provide singly-charged ions, it also produces multiply charged ones. Its efficiency drops typically by one order of magnitude for each additional electron to be removed, but the high production of Kr and Xe at the peak of the fission distribution can over-compensate this lower efficiency.

The noble-gas isotopes closest to stability were implanted into an aluminised tape and transported to a 4π β-detector setup. The implanted isotopes were identified via their half-lives. The counting rates for various delay, collection and measuring times after the impact of the proton beam were measured for the longer-lived isotopes to provide full information on the release from the target. These data were then fitted using a 4-parameter release function,

$$p(t) = \left(1 - \exp\left(-\frac{\ln 2t}{t_r}\right)\right)\left(\alpha \exp\left(-\frac{\ln 2t}{t_f}\right) + (1-\alpha)\exp\left(-\frac{\ln 2t}{t_s}\right)\right), \quad (1)$$

as defined in [5]. The time constants t_r, t_f and t_s govern the rise, fast fall and slow fall of the function, respectively. The rise time is mainly determined by the speed of effusion from the target to the ion source whereas effusion and diffusion within the target material influences the fall of the function. The "fast" fraction α ($0 < \alpha < 1$) determines the relative weight of the fast and slow fall components. We are aware of the fact that this parameterisation does not exactly describe the release as shown in [6]. However, it fits sufficiently well the release data to be used to determine yields and release efficiencies. It was adapted to periodic proton pulse conditions and was convoluted with the radioactive decay of the implanted ions and, whenever needed, with the decay of daughter and grand-daughter nuclei fed in pure β decay or via β-delayed neutron emission. The exponential nature of the parameterisation allowed the fit function to be calculated analytically which ensured a fast fit performance.

The much lower yields of the very neutron-rich isotopes were measured with a combined setup of a neutron long-counter and a set of β detectors [7]. With this setup the previously unknown half-lives and P_n values of the most neutron-rich Kr and Xe isotopes were determined by simultaneously fitting the recorded time spectra for β particles and neutrons as reported in [7]. After determination of the half-lives, as well as the release parameters and ionisation efficiencies, the obtained yields could be corrected for losses inside the target and ion-source system (by integrating Eq. (1) with an exponential decay factor [5]) to give the in-target production yields. To obtain reliable results for the latter quantity, it is essential to have measured good quality release data for a longer-lived isotope of the same element (e.g. ^{6}He, ^{23}Ne, ^{43}Ar, ^{90}Kr and ^{139}Xe).

Release curves may vary slightly from target to target or when targets are aged, even if the

operation conditions are kept the same. However, it is useful to consider some typical release curves obtained at a given target temperature. The left panel of Fig. 1 shows such release curves for the elements He, Ne, Ar, Kr and Xe produced in UC_x/graphite targets at 2100–2200 °C, their release parameters are given in Table 1. The effusion and diffusion processes slow down as the mass and size of the atom increases which gives rise to longer time constants and a more dominating tail of the release function.

For ^{6}He even the unselective "hot" plasma ion-source of type MK5 [4] provides clean beams since no other radioactive isobar exists on mass 6 and possible multiply-charged ions of mass 12, 18 or higher have far too low yields to become disturbing. In Fig. 1 (right) release profiles from measurements of ^{6}He with "cold" and "hot" plasma ion-sources are compared. The cooled transfer line (longer and colder than the transfer line of a hot plasma source) introduces an additional delay which results in a slightly slower release.

Based on a large collection of data obtained with UC and ThC targets during the last 10 years of operation at the PS-Booster reference yields have been evaluated for the isobaric chains of noble gases as shown in Fig. 2. Also the in-target production yields are given. They represent the yields from an ideal target/ion-source system with no decay losses during extraction and 100%

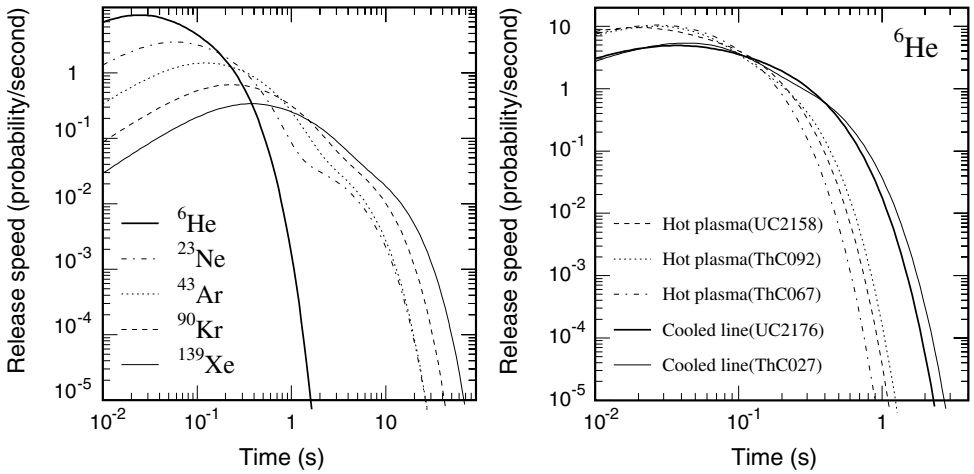

Fig. 1. Left: representative release curves for He, Ne, Ar, Kr and Xe obtained from UC_x/graphite targets. The slower diffusion of heavier nuclei is evident. The release parameters for the five curves are given in Table 1. Right: release curves fitted for ^{6}He ionised with a "hot" plasma source (type MK5) or a plasma source connected to the target by a cooled transfer line (type MK7). The additional delay introduced by the cold transfer line is evident.

Table 1
Typical on-line conditions: target temperature, ionisation efficiency and release parameters

Element	Target (UC_x/graphite)		Ionisation efficiency (%)	Release			
	g/cm^2	°C		α	t_r (ms)	t_f (ms)	t_s (ms)
He	52	2100	0.14	0.38	10	20	81
Ne	52	2100	0.36	0.99	18	150	2100
Ar	52	2100	2.0	0.96	38	300	2030
Kr	52	2100	4.3	0.91	73	530	3190
Xe	52	2200	11	0.86	107	950	5290

The corresponding release curves are shown in Fig. 1 (left).

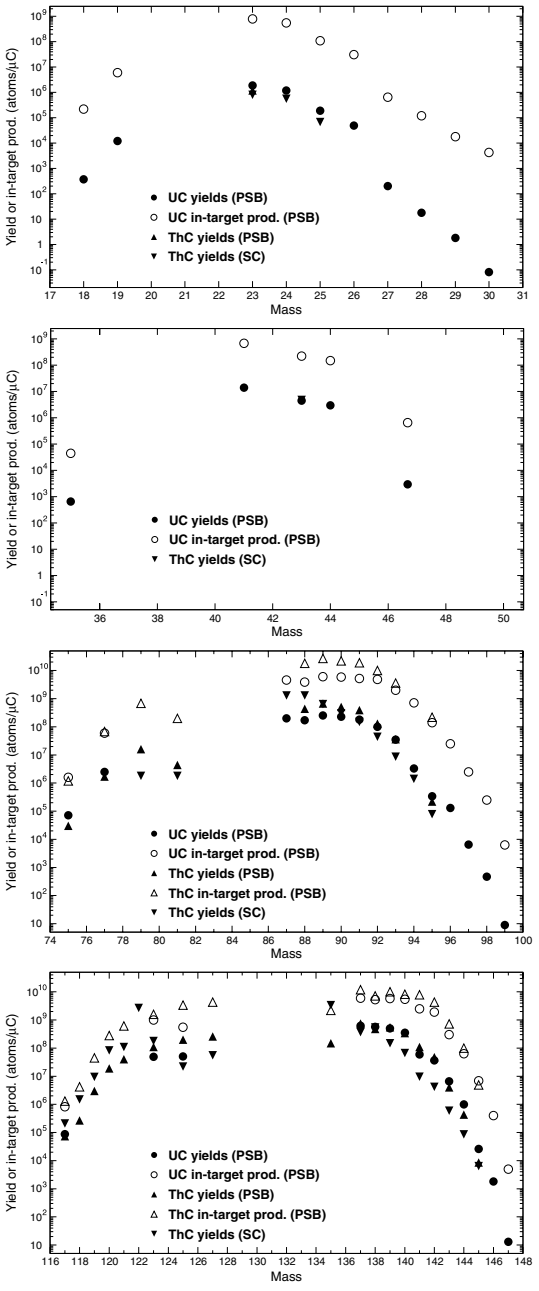

Fig. 2. Reference ion yields (all in units of atoms per μC of protons on target) of Ne, Ar, Kr and Xe isotopes measured from UC_x/graphite and ThC_x/graphite targets at PSB-ISOLDE. Also the corresponding in-target production yields, obtained from the ion yields by correcting for decay losses and ionisation efficiencies, are given for each isotope. The yields of ^{6,8}He are discussed in the text. Yields obtained at the former SC-ISOLDE facility are quoted from [8].

ionisation efficiency. The isotopes of He (not shown in the figure) are equally well produced in UC and ThC targets, the yields being about 5×10^7 and 5×10^5/μC for ^{6}He and ^{8}He with three orders of magnitude higher in-target production yields (as a result of low ionisation efficiency, cf. Table 1). The yields of He isotopes have not been corrected for the fraction of implanted He atoms which diffuse quickly out of aluminium (and thereby escape detection). This fraction is, however, known to be only about 20% at 60 keV implantation energy [7]. Although the ionisation efficiencies were influenced, and therefore also the yields, by different settings of the ion source the in-target production yields obtained from targets of the same material bombarded by protons of the same energy were similar (within a factor of 2). Bearing this reproducibility in mind the yields shown in Fig. 2 have been scaled to the same ionisation efficiency for each element (the ones quoted in Table 1). For light neutron-rich nuclei produced by fragmentation (isotopes of He and Ne) the production cross-section may be higher by a factor of 2–5 for 1.4 GeV protons as compared to 1.0 GeV [9]. For such cases the yields at 1.4 GeV were quoted. The yields of the nuclides decaying by isomeric transitions should only be taken as lower limits since the efficiency of the used plastic scintillator for gamma detection was not precisely determined.

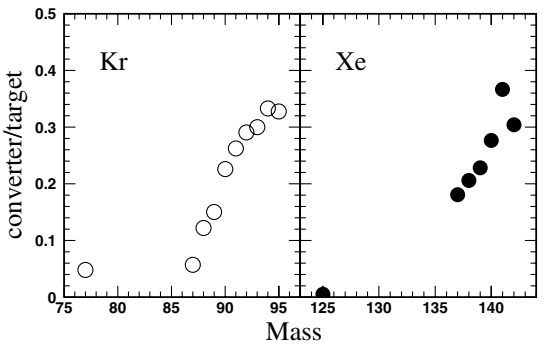

Fig. 3. Ratio of production yields obtained with the proton beam hitting a tungsten neutron-converter positioned next to a UC_x/graphite target and the beam hitting the target directly. As seen, the cross-section for fission induced by spallation neutrons rises relative to the cross-section for fission induced by high-energy protons when moving towards neutron-rich nuclei.

"Neutron converters" in the shape of cylindrical tantalum or tungsten rods have been placed parallel to standard ISOLDE UC_x/graphite targets in order to test their neutron-induced fission yields. In Fig. 3 is shown the ratio of ion yields (or in-target production yields) obtained with the proton beam hitting a tungsten converter and the UC target itself. For the neutron-rich Kr and Xe isotopes this ratio approaches 0.5 which shows the potential of using the converter method to produce very intense beams of fission fragments when using a cylindrical fission target covering most of the solid angle around the converter and raising the proton intensity by several orders of magnitude as suggested for the EURISOL project [10].

References

[1] O. Kofoed-Hansen, K.O. Nielsen, Phys. Rev. 82 (1951) 96.
[2] P.G. Hansen et al., Phys. Lett. 28B (1969) 415.
[3] R. Kirchner, E. Roeckl, Nucl. Instr. and Meth. 133 (1976) 187.
[4] S. Sundell, H. Ravn, Nucl. Instr. and Meth. B 70 (1992) 160.
[5] J. Lettry et al., Nucl. Instr. and Meth. B 126 (1997) 170.
[6] J.R.J. Bennett, Nucl. Instr. and Meth. B, these Proceedings. doi:10.1016/S0168-583X(02)01909-2.
[7] U.C. Bergmann et al., Nucl. Phys. A, in press.
[8] ISOLDE Users Guide, CERN 86-05, H.-J. Kluge (Ed.), Geneva, 1986.
[9] U. Georg et al., Nucl. Phys. A 701 (2002) 137c.
[10] H. Ravn, Nucl. Instr. and Meth. B, these Proceedings. doi:10.1016/S0168-583X(02)01904-3.