Beta-decay properties of the neutron-rich $^{94-99}\text{Kr}$ and $^{142-147}\text{Xe}$ isotopes

U.C. Bergmann^a C.Aa. Diget^b K. Riisager^b L. Weissman^{a,*}
G. Auböck^c J. Cederkäll^a L.M. Fraile^{a,1} H.O.U. Fynbo^a
H. Gausemel^d H. Jeppesen^b U. Köster^a K.-L. Kratz^e
T. Nilsson^a B. Pfeiffer^e H. Simon^{a,2} K. Van de Vel^f J. Äystö^a
and the ISOLDE collaboration

^a*ISOLDE, CERN, CH-1211 Genève 23, Switzerland*

^b*Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C,
Denmark*

^c*Technical University Graz, A-8010 Graz, Austria*

^d*Kjemisk Institutt, Universitetet i Oslo, Postboks 1033, Blindern, N-0315 Oslo,
Norway*

^e*Institut für Kernchemie, Universität Mainz, D-55128 Mainz, Germany*

^f*IKS, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium*

Abstract

Beta-decay half-lives and delayed-neutron emission probabilities of the neutron-rich noble-gas isotopes $^{94-99}\text{Kr}$ and $^{142-147}\text{Xe}$ have been measured at the PSB-ISOLDE facility at CERN. The results are compared to QRPA shell-model predictions and are used in dynamic calculations of r-process abundances of Kr and Xe isotopes.

Key words: half-lives, P_n values, on-line separation, QRPA calculations, r-process nuclei, $^{94-99}\text{Kr}$, $^{142-147}\text{Xe}$

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* Present address: NSCL, Michigan State University, East Lansing, MI 48824-1321, USA.

Email address: weissman@nscl.msu.edu (L. Weissman).

¹ On leave from Dpto. de Física Atómica, Molecular y Nuclear, Univ. Complutense, E-28040 Madrid, Spain.

² Present address: Institut für Kernphysik, Technische Universität, D-64289 Darmstadt, Germany.

1 Introduction

Fifty years ago, the first isotope separation on-line (ISOL) experiment was carried out at the Institute for Theoretical Physics in Copenhagen, Denmark [1–3]. In that pioneering work the isotopes $^{89-91}\text{Kr}$ were produced and extracted from a uranium containing target installed at a cyclotron, and their β -decay half-lives were measured for the first time ”on-line” after mass separation. Since then there has been surprisingly little progress in the investigation of neutron-rich Kr and Xe nuclei. A number of short-lived Kr and Xe isotopes were measured at various ISOL facilities [4–11], however, these studies were limited to $^{91-94}\text{Kr}$ and $^{139-143}\text{Xe}$. The heaviest noble-gas isotopes known so far, ^{95}Kr and $^{144,145}\text{Xe}$ [12], were in fact obtained in earlier experiments utilising emanation, chemical separation and gas-jet techniques [13–17]. These indirect half-life determinations generally suffered from systematic errors and were not always as reliable as the measurements with mass separation. In contrast to the noble gases, the results from on-line measurements of extended isotope sequences of other elements, such as the alkaline, are much more detailed. For example, the heaviest isotopes of Rb and Cs studied so far are ^{102}Rb and ^{150}Cs [12,18,19], 8 and 7 mass units beyond the corresponding Kr and Xe nuclides. One reason for this situation may be the more difficult analysis of half-lives and rather weak delayed-neutron emission probabilities (P_n values) of the Kr and Xe nuclides in the presence of the much more intense neutron branching ratios of their alkaline daughters. Another complication in studies of noble gas isotopes is associated with their fast diffusion from the implantation material.

On the other hand, the Kr and Xe isotopic chains are of considerable interest for the understanding of the development of nuclear structure in the $N \simeq 56$ and $N \simeq 90$ shape-transitional regions, respectively. Moreover, the $N \geq 58$ and $N \geq 90$ even-neutron isotopes of Kr and Xe are expected to be so-called ”waiting-point” nuclei [20] in rapid neutron-capture (r-process) nucleosynthesis processes.

Noble gases are difficult to ionise, usually requiring chemically non-selective plasma-discharge ion sources that, for a selected mass, ionise the whole isobaric chain. However, the combination with a water-cooled transfer line between target and ion source adds the necessary element selectivity by condensing and depositing all less volatile reaction products. This rather simple target-ion-source system is ideal for production of pure radioactive beams of noble-gas elements with high ionisation efficiencies [21]. The high fission yields of Kr and Xe isotopes, their high ionisation efficiency and isobaric selectivity, together with the simple operation of this type of plasma ion source has made these pure noble-gas radioactive beams very attractive for use in various target tests. In this publication we report on new results for heavy Kr and Xe nuclei obtained at the ISOLDE separator.

2 Experiments and results

2.1 Experimental techniques

In two different experiments, referred to as A and B, neutron-rich Kr and Xe isotopes were produced in fission reactions induced by a pulsed beam of 1 GeV or 1.4 GeV protons (3×10^{13} protons/pulse) from the CERN proton synchrotron booster (PSB) facility impinging on a standard ISOLDE uranium-carbide/graphite target (with 50 g/cm² of U) [22]. The reaction products diffused from the target heated to about 2000 °C and effused through a low-temperature, water-cooled transfer line to an ion-source chamber, where the ionisation by plasma discharge took place [23]. The temperature of the transfer line was kept at about 50°C, providing efficient condensation of all elements except volatile gases. The lighter noble-gas isotopes ^{87–93}Kr and ^{137–142}Xe were mass-separated and implanted into an aluminised mylar tape and transported to a 4π β -detector setup. The implanted isotopes were identified via their half-lives. The counting rates for various delay times after the proton pulse were measured for these longer-lived isotopes to provide full information on the release characteristics from the target. In the context of this paper the release curves for Kr and Xe were only used to determine the total yields of their neutron-rich isotopes which were implanted during restricted time periods for half-life measurements as explained below.

The heavier Kr and Xe isotopes were measured with a different detection system. The radioactive beam was stopped in, A) an aluminium foil, or B) an aluminised mylar tape, situated in the centre of a cylindrical 4π neutron long-counter. This detector consists of 12 parallel-coupled ³He proportional counters embedded in a paraffin moderator [24]. The neutrons emitted after β decay were thus thermalised in a random walk process through the moderator before detection. The time delay introduced by the thermalisation follows an exponential distribution with a mean residence time of $\tau = 89 \pm 1$ μ s [25]. The detected random neutron background was only 0.3 Hz. The detection efficiency, ε_n , has been measured previously to be $19 \pm 1\%$ [26] which was verified in the present experiments using a calibrated Am(Li) neutron source.

In Experiment A the β particles were measured with a detector consisting of two plastic scintillators of 50 mm diameter placed directly behind the aluminium foil. A Bicron BC-444 scintillator, of 1 mm thickness with a decay time of 160 ns, was optically cemented to a 25 mm thick Bicron BC0420 scintillator with a 2 ns decay time. A gated integrator, set to integrate the signal between 50 and 150 ns, followed by a low-level discriminator detected the slow component of the light signal. This allowed to discriminate γ -rays from neutrons which do not produce a signal in the thin scintillator. With this setup

data were collected for the isotopes ^8He , $^{94-98}\text{Kr}$ and $^{142-147}\text{Xe}$. The former served as a test beam. The efficiency of the β detector, ε_β , was determined in fits of the Kr and Xe decays (as explained in Subsection 2.2) and was always in the range of 20–25%, but varied from one isotope to another due to slight changes in the position and shape of the implantation spot. A cross check was made by calculating the efficiency from the ratio of the number of time correlated β -n pairs to the number of detected neutrons [27], and agreement was found. The detection rate of long-lived β background was 100–400 Hz. During these measurements only one proton pulse per the PSB cycle (14.4 s) was used, allowing detailed analysis of the daughter decays. The total number of proton pulses taken for each measurement was in the range of 25–70.

For Experiment B improvements were made to the detector setup which allowed better signal-to-background conditions. The isotopes $^{94,96-98}\text{Kr}$ were re-measured with longer measuring times (100–500 proton pulses) and the data were extended to include also ^{99}Kr . Again data were taken with a beam of ^8He to make cross checks of the analysis. After each implantation and subsequent decay, and before the arrival of the next proton pulse, long-lived daughter activities were removed from the detection region by moving the aluminised tape. Consequently, the detection rate of long-lived β activity was always in the range of 3–10 Hz. The implantation point was situated close to a 125 μm mylar window transparent to high-energy β particles. A 1.5 mm thick plastic detector was positioned close to the mylar window inside the neutron long-counter for detection of β particles. The scintillation light from the plastic detectors was guided outside the neutron counter using optical fibres to two photo-multipliers per detector. The signals from the photo-multipliers were amplified and fast time signals generated. Only coincidences between time signals from two photo-multipliers detector were considered as a true detection of a β particle. This allows for a reduction of random electronic noise to a level of 1 Hz [28]. The detector efficiency was determined by the fits of the Kr decays and was always 4–5%. Again this agreed with the results from studies of β n time correlations. In this experiment the target was bombarded by the PSB proton pulses each 8.4 s. After the measurements it was discovered that the aluminised tape had been installed upside down which meant that the ions were implanted into the mylar side of the tape. It is well-known that a significant fraction of Kr ions implanted into mylar diffuses rapidly [29]. This fast diffusion affects dramatically the measured half-lives for longer-lived isotopes, leaving the P_n values unchanged to first order. Being very unfortunate this effect can, however, be analysed and proper half-lives extracted as shown in the following two subsections.

Using an electrostatic deflector (“beam-gate”) the ion beam was directed to the implantation point only in designated time intervals shortly after the impact of the proton beam. The collection time was chosen for each case to optimise the activity of the noble-gas isotope after implantation and at the

same time to minimise the fraction of daughter nuclei created during collection. For strong activities, the start of implantation was delayed in order to reduce dead-time effects. For the isobaric background (of Br, Rb and I, Cs respectively) possibly leaking through the water-cooled transfer line an upper limit of 1% was determined by measurements on masses where only stable Kr and Xe isotopes occur (80, 86, 130 and 136). Hence it is negligible for this analysis.

The detection times of β particles and thermalised neutrons were recorded by a precise time-stamping module based on a 10 MHz clock with 32 bits time resolution. Each registered event consisted of the time relative to the proton pulse, and a pattern word to indicate whether the event was triggered by a β particle or a neutron. This allowed to produce both "singles" time spectra relative to proton beam impact of neutrons and betas independently, referred to as "decay spectra" below, as well as β -neutron time correlations on the μ s scale.

2.2 Analysis procedure

A standard description of chain decay is given in text books (such as [30]). However, when considering nuclei with non-negligible β -delayed neutron branches one arrives at a situation where most isotopes involved in the chain decay are fed by more than one precursor and decay to several daughter nuclei. Below, an iterative method to solve this problem is outlined.

For all nuclei in question the multi-neutron emission probabilities can be neglected, i.e. $P_{1n} = P_n$ and $P_{xn} = 0$ for $x > 1$. To find the β and neutron decay-activities at any time t after proton impact on target, we need to know the concentration in the sample at time t of all decaying isotopes. Let us assume that we know the isotopic concentrations for the element with proton number $Z-1$ and we want to determine the amounts of nuclei at the level Z of proton number. Let us consider the nucleus A_ZX_3 which is fed in βn and β decay by the nuclei ${}^{A+1}_{Z-1}X_1$ and ${}^A_{Z-1}X_2$. If these nuclei have decay constants λ_1 , λ_2 and λ_3 and P_n values of P_1 , P_2 and P_3 , the number of X_3 nuclei is given by the differential equation

$$\frac{dN_3}{dt} = -\lambda_3 N_3(t) + P_1 \lambda_1 N_1(t) + (1 - P_2) \lambda_2 N_2(t) \quad (1)$$

which is valid after the implantation has finished, i.e. at times $t > t_0 + \Delta t_0$ where t_0 denotes the start of implantation and Δt_0 the collection time. To simplify the notation let us introduce the time variable $t' = t - (t_0 + \Delta t_0)$. If N_1 and N_2 are on exponential form, that is

$$N_1(t') = \sum_{i=1}^{n_1} a_i \exp(-\alpha_i t') \quad (2)$$

$$N_2(t') = \sum_{j=1}^{n_2} b_j \exp(-\beta_j t') , \quad (3)$$

a complete solution to Eq. 1 is

$$N_3(t') = \sum_{i=1}^{n_1} A_i \exp(-\alpha_i t') + \sum_{j=1}^{n_2} B_j \exp(-\beta_j t') + C \exp(-\lambda_3 t') , \quad (4)$$

where $A_i = a_i P_1 \lambda_1 (\lambda_3 - \alpha_i)^{-1}$, $B_j = b_j (1 - P_2) \lambda_2 (\lambda_3 - \beta_j)^{-1}$ and $C = N_3(t'=0) - \sum_{i=1}^{n_1} A_i - \sum_{j=1}^{n_2} B_j$. In Eqs. 2 and 3 the arbitrary parameters a_i , b_j , α_i , β_j , n_1 and n_2 should be determined iteratively from the initial conditions (Eq. 5 below).

We note that N_3 is again on exponential form and can be used, along with similar results for the other isotopes with proton number Z , as input equations in the next step of the iteration, to calculate the amounts of isotopes with proton number $Z+1$. This procedure continues until one reaches isotopes which are stable on the time scale of the measurement.

To start the iteration one needs to know the amount of mother nuclei in the sample, $N(t')$. Since the mother nucleus is an isotope of a noble gas it is subject to diffusion and depending on its atomic size, the implantation depth, the implantation material, and its half-life it may leave the collection point before decaying and disappear from the detection region, through the vacuum tube of the beam line, with thermal velocity ($\sim 270A^{-1/2}$ cm/ms). From decay data on ^8He ($T_{1/2} = 119$ ms) it is apparent that a significant part of the implanted ^8He atoms diffuse out of both aluminium and mylar with a diffusion “half-life” of around 32 ms. Further analysis shows that the diffusion process can be described with an additional exponential component in the time evolution of implanted ^8He atoms,

$$N(t') = N_{\text{nd}} \exp(-\frac{\ln 2}{T_{1/2}} t') + N_{\text{d}} \exp(-\frac{\ln 2}{T_{\text{eff}}} t') . \quad (5)$$

Thus, at time $t'=0$ the implanted sample consists of N_{nd} noble-gas atoms which are stuck at the implantation site and cannot diffuse (denoted *non-diffusible*) and N_{d} atoms which are subject to diffusion (denoted *diffusible*). Both groups of atoms undergo radioactive decay which for the latter gives rise to an effective half-life of $T_{\text{eff}} = T_{1/2} T_{\text{d}} / (T_{1/2} + T_{\text{d}})$, T_{d} being the diffusion half-life.

The relevant isotopes of the decay chain are shown in Fig. 1. On the experiment time scale of 14 s we need, apart from the mother decay, to consider the decays of the β , βn , $\beta\beta$, $\beta\beta\text{n}$, and $\beta\beta\beta$ daughters. For the nuclei studied here one can

neglect the P_n values of the $\beta\beta$, $\beta\beta n$, and $\beta\beta\beta$ daughters. Having determined the concentration of all these isotopes, using the procedure described above, the measured β and neutron activities are given as

$$R_\beta(t') = \varepsilon_\beta \ln 2 \left(\frac{N(t')}{T_{1/2}} + \frac{N_\beta(t')}{T_\beta} + \frac{N_{\beta n}(t')}{T_{\beta n}} + \frac{N_{\beta\beta}(t')}{T_{\beta\beta}} + \frac{N_{\beta\beta n}(t')}{T_{\beta\beta n}} + \frac{N_{\beta\beta\beta}(t')}{T_{\beta\beta\beta}} \right) + R_\beta^{\text{back}} \quad (6)$$

$$R_n(t') = \varepsilon_n \ln 2 \left(\frac{P_n N(t')}{T_{1/2}} + \frac{P_\beta N_\beta(t')}{T_\beta} + \frac{P_{\beta n} N_{\beta n}(t')}{T_{\beta n}} \right) + R_n^{\text{back}}, \quad (7)$$

where the amount of isotopes, half-life and P_n value of the βx daughter are denoted $N_{\beta x}(t')$, $T_{\beta x}$ and $P_{\beta x}$. The parameters R_β^{back} and R_n^{back} describe the long-lived background components which were not included in the decay chain. Due to the decay of mother nuclei during the finite collection time Δt_0 , in principle all $N_{\beta x}(t'=0)$ are non-zero. However, since short collection times were used (see Tables 1 and 2) only $N_\beta(t'=0)$ and $N_{\beta n}(t'=0)$ were treated as non-zero. These numbers were estimated to lowest order from the in-growth of activity in the region $t_0 < t < t_0 + \Delta t_0$ of the β decay-spectrum.

The fitting procedure was carried out as follows: The β and neutron decay-spectra were fitted simultaneously, as histograms with 2 ms channel width, using the ‘‘Poisson likelihood χ^2 ’’ statistic ³ with theoretical functions

$$N_\beta^{\text{bin}} = \int_{\text{bin}} dt' N_{\text{pulse}} R_\beta(t') [1 - \tau_{\text{eff}}(R_\beta(t') + R_n(t'))] \quad \text{and} \quad (8)$$

$$N_n^{\text{bin}} = \int_{\text{bin}} dt' N_{\text{pulse}} R_n(t') [1 - \tau_{\text{eff}}(R_\beta(t') + R_n(t'))], \quad (9)$$

respectively. Here N_{pulse} is the number of proton pulses taken and τ_{eff} ($\sim 2\mu\text{s}$) is an effective dead time parameter for the electronics and data acquisition [27]. For the purpose of determining the half-life and P_n value of the implanted nucleus, and their statistical uncertainties, the following 9 parameters were varied freely while fitting: $N_{\text{nd}} + N_{\text{d}}$, $N_\beta(t'=0)$, $T_{1/2}$, P_n , R_β^{back} , R_n^{back} , ε_β , $N_{\text{d}}/(N_{\text{nd}} + N_{\text{d}})$, and T_{d} . The parameter minimisation and error analysis were performed with MINUIT [32]. The decay parameters of the noble-gas daughters are well-known in literature, they were fixed at the values given in [33]. Varying these parameters within the uncertainty quoted in the literature had a negligible effect on the fit [34]. For the cases with low count numbers the 9-parameter fit showed strong parameter correlations. This is an undesirable

³ As discussed in [31] this method, which is based on the maximum-likelihood principle, gives more reliable results than the classical chi-square method in the cases of poor statistics and histogram binning.

situation in which one can no longer trust the resulting error bars. Therefore, for such cases, the diffusion parameter T_d was fixed at an averaged value determined from fits of lighter Kr and Xe isotopes, respectively, which restored a normal fit situation. This procedure is justified by the fact that different isotopes of the same noble-gas element were implanted at nearly the same depth and should therefore have similar diffusion times. The decay spectra were fitted in the time region from the end of implantation to the onset of the next proton pulse. (For Experiment B the fit was made only as far as 7.5 s, the time where the tape was moved).

2.3 Results

The measured decay spectra and the fitted decay components are shown in Figs. 2-4. The resulting fit parameters and their estimated uncertainties are given in Tables 1 and 2 for Experiment A and B, respectively. All resulting χ^2 values are acceptable. Similar diffusion half-lives were obtained for aluminium and mylar, about 32 ms for ^8He and 75 ms for Kr atoms, whereas an average diffusion half-life of 38 ms resulted for Xe which was only implanted into aluminium. Thus, the atomic size and the implantation depth determine the diffusion time, rather than the material properties. As expected, a large fraction of the Kr atoms, about 80%, were able to diffuse from mylar, whereas a smaller, but measurable, fraction of 20% could diffuse from aluminium. For Xe in aluminium a diffusible fraction about 10% was obtained. Since the fraction of diffusible ^8He atoms was less dependent on the material we conclude that this parameter also depends on the size of the implanted ion. Consistent diffusion times and diffusible fractions were obtained for different Kr isotopes in the same material. The latter should decrease when the collection time is increased (the important parameter being the ratio $\Delta t_0/T_d$) since a part of the ions had already diffused during implantation. Due to the short collection times which did not exceed the diffusion half-life this effect was not detectable for Kr with the obtained precision. In contrast, for Xe the diffusion was sufficiently fast that no measurable fraction of diffusible $^{145,146,147}\text{Xe}$ atoms was left after 100–200 ms collection ($\Delta t_0/T_d > 3$, Table 1). Similarly, the difference in diffusible fraction for ^8He in aluminium and mylar was enhanced by the use of different collection times. For some isotopes the diffusion time is not given in Tables 1 and 2, although the diffusible fraction is quoted. In these cases T_d was fixed in the fit in order to avoid large parameter correlations. For the isotopes with poorest statistics neither of the two diffusion parameters could be determined, i.e. the confidence interval for the diffusible fraction was larger than [0;1]. The results on diffusion of lighter isotopes were then used to fix these parameters at realistic values in the fit, with their uncertainties taken into account in the quoted half-lives and P_n values.

The analyses of the Kr data from Experiments A and B give consistent results for $T_{1/2}$ and P_n . The combined results for Kr are given in Table 3. At first one would expect the latter experiment to give more precise estimates, thanks to the improved signal-to-background ratio and longer data taking, but this is only the case for the most exotic isotopes since the diffusion component dominates the fit. This demonstrates the importance of the right choice of implantation host in investigations of nuclear decay chains that include noble-gas isotopes. There is only partial agreement between the results of the present experiment and the existing data. In particular, the half-lives from the earlier indirect radiochemical measurements [13–17] (quoted by nuclear data evaluators for ^{95}Kr and $^{144,145}\text{Xe}$ [33]) deviate considerably from our results, indicating that these identifications probably were not correct. The half-lives quoted by [33] for ^{94}Kr and $^{142,143}\text{Xe}$ were obtained at on-line separators [5–7,9,10] and are in reasonable agreement with the present experiment, although their P_n values for ^{94}Kr and ^{142}Xe are a factor 3–5 larger ⁴[6,9]. The present data for ^{147}Xe allow only a rough estimate of the half-life and P_n value. If the ^{147}Xe component is removed from the fit χ^2 increases by 7. Since removing the component effectively removes two fit parameters we conclude that ^{147}Xe is present at a 95% confidence level. The results for ^8He implanted into both materials justify the present analysis. Even for this extreme case where $T_d \simeq T_{1/2}/4$ the resulting mother and daughter half-lives are reliable.

In order to test the data for systematic errors the half-life of the alkali daughter, the fit parameter T_β , was released after completion of the 9-parameter fit (which determined $T_{1/2}$ and P_n for the mother nucleus as explained in Subsection 2.2). As can be seen from Tables 1 and 2 the fitted T_β values did not move further away from their starting points, taken from previous measurements [33], than could be expected according to their deduced uncertainties. Note that these uncertainties are in some cases comparable in size with those in the literature. This is a very sensitive cross check for systematic errors which becomes evident if one tries to remove the diffusion component from the analysis: Apart from ^8He , the effects of diffusion are most pronounced for the nucleus ^{94}Kr which has the longest half-life (of the Kr isotopes). When fixing $N_d=0$ one obtains for implantation in aluminium $T_{1/2} = 192.7 \pm 1.1$ ms and $T_\beta = 2580 \pm 30$ ms, and for mylar $T_{1/2} = 78.8 \pm 1.5$ ms and $T_\beta = 1570 \pm 60$ ms. In contrast, the fitted P_n value is not affected by diffusion. Thus, in both cases the mother and daughter half-lives are underestimated (compare with Tables 1 and 2) and in the worse case, the implantation into mylar, the fitted $T_{1/2}$ value gets close to the effective half-life of the diffusion component, $T_{\text{eff}} = 56$ ms. The χ^2 values obtained in the fit of the ^{94}Kr decay were for

⁴ It is interesting to note that the second method of analysis of the neutron spectra used in [9] provided a P_n value of $1.6 \pm 0.9\%$ for ^{94}Kr which is in agreement with our measurement. However, only the P_n value from the first analysis method [9] ($5.7 \pm 2.2\%$) was accepted by nuclear data evaluators [33].

both data sets decreased by more than 100 by introducing the two additional diffusion parameters (notice the two-component nature, cf. Eq. 5, of the fitted β and neutron contributions from ^{94}Kr in Fig. 4). Generally, when diffusion is not included, the fitted $T_{1/2}$ value will lie somewhere in the interval $[T_{\text{eff}} ; T_{1/2}]$, depending on the actual size of $N_d/(N_{\text{nd}} + N_d)$. For ^{99}Kr this interval is [27ms ; 41ms] which shows that for the heavier Kr isotopes the error made by neglecting diffusion is less important. When using aluminium for implantation the fact that the diffusible fraction is small assures a small error for all Kr isotopes.

The fit parameter $N_\beta(t'=0)$, the amount of alkali-daughter nuclei present in the sample when the implantation was stopped, gives an additional cross check of the analysis. In all cases, when diffusion effects were included, this parameter agreed with the number of daughter nuclei expected from decay during implantation. Thus, no neutron-rich Rb or Cs nuclei were present in the noble-gas beams.

The yields of Kr and Xe isotopes at the exit of the mass separator are presented in Table 3. They were obtained from the fitted $N_{\text{nd}} + N_d$ values (Tables 1 and 2) by correcting for the beam transport efficiency and for the fraction of ions not arriving within the implantation period. The latter was deduced from a release curve measured for both target/ion-source systems for long-lived isotopes (as explained in Subsection 2.1) and corrected for decay losses for the case of short-lived isotopes. This yield information is important for the planning of new experiments.

3 Discussion

3.1 Nuclear structure

In general, while the β -decay half-life ($T_{1/2}$) is dominated by the lowest-energy part in the β -strength function, the β -delayed neutron emission probability (P_n) is sensitive to the feeding to the energy region above the neutron separation energy (S_n). The sensitivity of these parameters to the different parts of the β strength is determined by the strong energy dependence of the Fermi function, $(Q_\beta - E)^5$. As the β -strength function depends on nuclear structure, the measured $T_{1/2}$ and P_n do as well. However, the half-life and neutron emission probability probe the structure of low-lying and high-lying levels in the daughter nuclei, respectively.

In order to investigate the sensitivity of the obtained data on deformation we have performed calculations for two sets of parameters. In the first set the

nuclei of interest were assumed to have spherical shapes, and in the second set the shapes were predicted by the finite range droplet (FRDM) [35] and by the extended Thomas Fermi plus Strutinski Integral (ETFSI-1) [36] models. The Q_β and S_n values used for these calculations were taken from [33]. For each case calculations with two types of interactions were performed using the folded Yukawa potential and Lipkin-Nogami microscopic pairing model [37], and the Nilsson model with BCS pairing [38]. For most cases, the calculations corresponding to the two interactions gave close results. An exception are the spherical calculations for the light $^{92-95}\text{Kr}$. It is known that the $\nu g_{7/2}$ single-particle state in the neighboring odd-mass Sr and Zr isotones lies in between the predictions of the two QRPA versions. Since the Gamow-Teller decay to this state determines the half-life of the spherical nuclei in this mass region, we have used the averages of the two calculations for comparison with our Kr data (Fig. 5). The deformations of the ground-state of the mother nucleus and the excitation spectrum of the β -daughter nucleus were assumed to be equal in the calculations. Although this assumption is correct in most cases, it can not be justified in some narrow phase-transition regions. Therefore the results of the calculations can serve only as a qualitative guide, which allows, nevertheless, to draw some important conclusions.

Let us examine first the results for Xe isotopes, shown in Fig. 5a and 5b. As seen the deformed calculations represent better the experimental trend. For the isotopes with 2 $\pi g_{7/2}$ protons-pairs and 3–6 neutron-pairs in the $\nu f_{7/2}$, $p_{3/2}$, $p_{7/2}$ and $h_{9/2}$ shells, all models [35,36] predict a smooth increase in prolate deformation. This can also be observed in the evolution in energy of the first excited 2^+ level with increasing neutron number, where the Xe and all neighbouring nuclei exhibit practically identical behaviour (Fig. 6a). The measured $T_{1/2}$ and P_n values are consistent with the deformed description.

The situation is more complicated in the case of Kr isotopes. The Kr isotopes have 4 proton pairs in the $\pi p_{3/2}$ and $f_{5/2}$ orbitals, and 3–5 neutron pairs in the $\nu d_{5/2}$, $g_{7/2}$ and $s_{1/2}$ orbitals. The neutrons from the down-sloping, deformation driven, $\nu g_{7/2}$ orbital are particularly important for the nuclear structure in this region. It was suggested in the early 1950's that collective effects could be produced by isoscalar residual interactions between protons and neutrons [39]. Such interactions are especially strong between neutrons and protons occupying the spin-orbit “partner” orbitals [40]. In Sr and Zr nuclei ($Z=38$ and $Z=40$) starting with $N=60$, $g_{7/2}$ neutrons become valence particles and cause promotion of valence $p_{1/2}$ protons to the spin-orbit partner $g_{9/2}$ orbital. The strong attractive interaction between $\pi g_{9/2}$ and $\nu g_{7/2}$ nucleons results in a phase transition in nuclear shape, which can be observed as a sudden lowering of the $E(2^+)$ energy in these nuclei (Fig. 6b). On the other hand for even-even nuclei with $Z \geq 40$ the $g_{9/2}$ proton shell is already occupied, thereby blocking a possibility of sudden proton promotion from the lower orbits which is manifested in a gradual shape transition [41]. In the case of the Kr chain

($Z=36$), the lack of protons available for promotion to the $g_{9/2}$ orbital raises a question about the existence of a sharp phase transition. Recent experimental data [42] suggest that no sizeable deformation appears in the Kr chain below $N=60$. G. Lhersonneau and co-workers reached a similar conclusion from a ^{93}Br decay study [43]. Laser-spectroscopy measurements [44] have demonstrated that ^{96}Kr ($N=60$) is only moderately deformed.

The theoretical description of neutron-rich isotopes in this region is somewhat controversial. The earlier potential surface calculation predicted a moderate increase in oblate deformation for neutron-rich Kr nuclei up to $\beta_2=-0.315$ for ^{96}Kr [45,46]. On the other hand the FRD mass model predicts a smooth increase of prolate deformation with increasing neutron number ($\epsilon_2=0.317$ for ^{96}Kr) [35].

Figs. 5c and 5d show that the calculations for prolate deformed nuclei represent the experimental P_n values better than the ones for spherical shapes. The calculations for spherical shapes represent the half-life trend better for the lighter isotopes while for the heavier isotopes the experimental values are in between the results of the two sets of calculations. Since the half-life values probe mostly the lower part of the β -strength function the comparison presented in Figs. 5c and 5d is consistent with the picture of the spherical ground-states of Kr isotopes with $N\leq 60$ and moderate prolate deformation for the heavier nuclei. As P_n values probe the upper part of the β -strength function the better results for calculations with deformed shapes probably reflect the deformation of the highly excited states in the Rb daughter nuclei.

The gross β -decay properties as well as the presented calculations provide only qualitative insight into the structure of heavy Kr isotopes. More detailed experimental information and theoretical efforts are needed for further clarifications in this region.

3.2 Astrophysics

Both the heaviest observed Kr ($Z=36$) and Xe ($Z=54$) isotopes lie already in the r-process path(s) in the $A\simeq 100$ and $A\simeq 150$ mass regions for moderate neutron-density conditions. For the modelling of rapid neutron-capture nucleosynthesis (the astrophysical r-process), several nuclear-physics quantities of very neutron-rich isotopes are required, the most important being nuclear masses (in particular neutron separation energies, S_n) and β -decay properties ($T_{1/2}$ and P_n values). The majority of these nuclear data is inaccessible to experiments at present and has to be taken from model predictions. Therefore any new information about so-called r-process waiting-point nuclei is highly important for replacing the theoretical model predictions, testing and improv-

ing the theoretical results and providing more reliable predictions for the more exotic nuclei close to the neutron drip-line. The experimental $T_{1/2}$ and P_n values of the Kr and Xe nuclei as well as improved QRPA predictions of the next heavier isotopes can now be incorporated into dynamic (time-dependent) multicomponent r-process calculations to replace the theoretical predictions.

Figs. 7a and 7b show dynamic calculations of the relative r-abundances of neutron-rich even-even Kr and Xe isotopes under freeze-out conditions at a stellar temperature of $T_9=1.35$ ($1.35 \cdot 10^9$ K) as a function of the neutron density (n_n). The abundances are normalised to the abundance of Si equal to 10^6 . In these calculations, the “quenched” ETFSI mass model has been used [47]. As odd-neutron isotopes have a smaller neutron separation energy and, hence, higher neutron-capture cross-sections than the neighbouring even-even isotopes, they do not build high progenitor abundances before the “freeze out”. Therefore only the even-even Kr and Xe isotopes will act as classical “r-process nuclei” carrying the main r-abundances in both isotopic chains. As can be seen from Fig. 7a at modest neutron densities in the range $n_n \simeq 3 \cdot 10^{19} - 3 \cdot 10^{22}$ n/cm³, representative of the r-matter flow between the classical iron seed and the low wing of the $A \simeq 130$ solar-system r-abundance peak, ⁹⁶Kr and ⁹⁸Kr are the main waiting-point nuclei with high relative isotopic abundances. For higher neutron densities of $n_n \geq 3 \cdot 10^{22}$ n/cm³ corresponding to the conditions for building up and passing the $A \approx 130$ r-abundance peak region, the still unknown isotopes ¹⁰⁰Kr and ¹⁰²Kr become the main waiting-point nuclei. In the Kr chain the ¹⁰⁰Kr isotope has the highest r-abundance at neutron density of 10^{23} n/cm³. A comparison of the solar abundances of the $A \approx 100$ stable isotopes, which have exclusively r-process origin, with the calculated r-abundances of neutron-rich Kr isotopes also indicates that the latter are the dominant progenitors in this region. Indeed, the sum of the abundances of the stable “r-only” isotopes ⁹⁸Mo, ¹⁰⁰Mo and ¹⁰²Ru is 0.976 [48] in units of Si= 10^6 , whereas the corresponding calculated sum for the Kr r-progenitors is 1.097.

Fig. 7b indicates that the abundances of ^{146–148}Xe are rather low for moderate neutron densities. The main r-process progenitors in the Xe chain are the still unknown nuclei ^{150–158}Xe. They represent the waiting-point isotopes for neutron-density conditions in the range $n_n \approx 3 \cdot 10^{23} - 3 \cdot 10^{26}$ n/cm³, where the r-matter flow has already passed the $A \approx 130$ peak to form the rare-earth region and to start the “climb up the staircases” [20] towards the N=126 neutron shell closure. The sum of abundances of the stable ¹⁵²Sm, ¹⁵⁴Sm and ¹⁶⁰Gd isotopes that have dominantly r-process origin is 0.167 [48], while the corresponding sum of the calculated r-abundances for the Xe chain is equal to 0.215, indicating that the ^{152–158}Xe are the main progenitors of these stable isotopes.

4 Conclusion

Gross decay properties of the neutron-rich noble-gas isotopes $^{94-99}\text{Kr}$ and $^{142-147}\text{Xe}$ have been studied at the PSB-ISOLDE facility at CERN using isobaric selectivity achieved by combining a plasma ion-source with a water-cooled transfer line. The β -decay half-lives and delayed-neutron emission probabilities were measured with a β -neutron detector setup. The obtained data were compared to QRPA shell-model predictions. For the Kr chain the obtained data are consistent with the picture of spherical ground-states of Kr isotopes with $N \leq 60$ and moderate prolate deformation for the heavier nuclei. The P_n values indicate deformation of the highly excited states in Rb isotopes. The results for Xe isotopes are consistent with a prolate deformation description of these nuclei. The obtained data and improved model prediction for heavier nuclei were used in dynamic calculations of r-process abundances of Kr and Xe isotopes. The investigated $^{96,98}\text{Kr}$ are shown to be r-process waiting-point nuclei under moderate neutron-density conditions of $n_n \sim 3 \times 10^{19} - 3 \times 10^{22} \text{ n/cm}^3$. The waiting-points in the Xe chain lie in the region of unknown $^{152-158}\text{Xe}$ isotopes.

The present data represent a significant step forward for our knowledge on decay properties of the neutron-rich Kr and Xe isotopes. The half-lives for the most neutron-rich nuclei known previously were shown to be wrong by factors of 5, and 2–4 new isotopes were added for each case, thereby demonstrating the power of the ISOL technique. Although for the neutron-rich Kr nuclides we now cover a mass range twice as large as before [1,2] (^{99}Kr lies 13 mass units away from the heaviest stable isotope ^{86}Kr), it is worth to remember that we still have to go another 20 mass units in order to reach the neutron drip-line around $N=82$. In the analysis it is of course important to take several steps in the decay chains into account, but we stress that when noble-gas atoms are involved their fast diffusion out of the experimental set-up is a key feature that must be taken seriously. We have demonstrated this here for the case where noble-gas atoms were collected as primary species, but similar effects will occur whenever they appear as part of the decay chain. Nevertheless, the technique used here is quite efficient and should in dedicated experiments allow us to go one or two isotopes further out even at the present ISOLDE facility.

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References

- [1] O. Kofoed-Hansen and K.O. Nielsen, Phys. Rev. **82** (1951) 96.
- [2] O. Kofoed-Hansen and K.O. Nielsen, Mat. Fys. Medd. Vid. Selsk. **26**(7) (1951) 1.
- [3] O. Kofoed-Hansen, CERN report, 1976-13, 65.
- [4] G. Holm, S. Borg, V. Fagerquist and F. Kompff, Ark. Fys. **34** (1967) 447.
- [5] W.L. Talbert, A.B. Tucker and G.M. Day, Phys. Rev. **177** (1969) 1805.
- [6] G.C. Carlson, W.C. Schick, W.L. Talbert and F.K. Wohn, Nucl. Phys. **A125** (1969) 267.
- [7] S. Amiel, H. Feldstein, M. Oron and E. Yellin, Phys. Rev. **C5** (1972) 270.
- [8] G. Rudstam and E. Lund, Phys. Rev. **C13** (1976) 321.
- [9] M. Asghar et al., Nucl. Phys. **A247** (1975) 359.
- [10] S.H. Faller et al., Phys. Rev. **C38** (1988) 905.
- [11] T. Mehren et al., Phys. Rev. Lett. **77** (1996) 458.
- [12] R.B. Firestone and V.S. Shirley, Table of isotopes (John Wiley&Sons, New York, 1996).
- [13] A.C. Wahl, R.L. Ferguson, D.R. Nethaway, D.E. Troutner and K. Wolfsberg, Phys. Rev. **126** (1962) 1112.
- [14] P. Patzelt and G. Herrmann, Physics and chemistry of fission, Vol 2, (1965) 243.
- [15] O.L. Cordes, J.E. Cline and C.W. Reich, Nucl. Instr. and Meth. **48** (1967) 125.
- [16] K. Wolfsberg, J. Inorg. Nucl. Chem. **33** (1971) 587.
- [17] H. Ahrens, P. Patzelt and G. Herrmann, J. Inorg. Nucl. Chem. **38** (1976) 191.
- [18] B. Pfeiffer, K.-L. Kratz and P. Moeller, Prog. Nucl. Energ., in print, <http://www.arXiv.org/nucl-ex/0106020>.
- [19] U. Köster, PhD thesis, Technische Universität München, Germany, 2000.
- [20] E.M. Burbidge, G.R. Burbidge, W.A. Fowler and F. Hoyle, Rev. Mod. Phys. **29** (1957) 54.
- [21] T. Bjørnstad et al., Phys. Scripta **34** (1986) 578.

- [22] H.L. Ravn, Nucl. Instr. and Meth. **B26** (1987) 183.
- [23] S. Sundell and H. Ravn, Nucl. Instr. and Meth. **B70** (1992) 160.
- [24] O. Tengblad, Diploma thesis, Chalmers Tekniska Högskola, Göteborg, 1982, unpublished.
- [25] R.E. Azuma et al., Phys. Lett **B96** (1980) 31.
- [26] U.C. Bergmann et al., Nucl. Phys. **A658** (1999) 129.
- [27] U.C. Bergmann et al., Eur. Phys. J. **A11** (2001) 279.
- [28] L. Weissman et al, Nucl. Instr. and Meth. **A423** (1999) 328.
- [29] G.J. Beyer, H.L. Ravn and Y. Huang, Int. J. Appl. Radiat. Isot. **35** (1984) 1075.
- [30] K. Heyde, Basic Ideas and Concepts in Nuclear Physics (IOP Publishing Ltd, 1994).
- [31] Y. Jading and K. Riisager, Nucl. Instr. and Meth. **A372** (1996) 289.
- [32] F. James and M. Roos, MINUIT, Function Minimization and Error Analysis, CERN D506 (Long Writeup).
- [33] G. Audi, O. Bersillon, J. Blachot and A.H. Wapstra, Nucl. Phys. **A624** (1997) 1.
- [34] C.Aa. Diget, B.Sc. thesis, University of Aarhus, Denmark (2001) unpublished.
- [35] P. Möller et al., At. Data Nucl. Data Tables **59** (1995) 181.
- [36] Y. Aboussir et al., At. Data Nucl. Data Tables **61** (1995) 127.
- [37] P. Möller and J. Randrup, Nucl. Phys. **A514** (1990) 1.
- [38] T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A436** (1985) 14.
- [39] A. DeShalit and M. Goldhaber, Phys. Rev. **92** (1953) 1211.
- [40] I. Talmi, Rev. Mod. Phys. **34** (1962) 704.
- [41] M. Sugita and A. Arima, Nucl. Phys. **A515** (1990) 77.
- [42] T. Rzaca-Urban et al., Eur. Phys. J. **A9** (2000) 165.
- [43] G. Lhersonneau, A. Wöhr, B. Pfeiffer and K.-L. Kratz, Phys. Rev. **C63** (2001) 034316.
- [44] M. Keim et al., Nucl. Phys. **A586** (1995) 219.
- [45] A. Faessler, J.E. Galonska, U. Götz and H.C. Pauli, Nucl. Phys. **A230** (1974) 302.
- [46] D. Bucurescu, G. Constantinescu, D. Cutoiu, M. Ivascu and N.V. Zamfir, J. Phys. **7** (1981) L123.
- [47] J.M. Pearson, R.C. Nayak and S. Goriely, Phys. Lett. **B387** (1996) 455.
- [48] F. Kaepfeler, H. Beer and K. Wisshak, Rep. Prog. Phys. **52** (1989) 945.

Figure captions:

Fig. 1: A general scheme presenting the relevant nuclei participating in the decay chain of a neutron-rich Kr or Xe isotope. The nomenclature used for the various half-lives and delayed-neutron emission probabilities is introduced.

Fig. 2: Simultaneously fitted (using 2 ms channel width) β and neutron decay-spectra for Kr isotopes (and ^8He as a test) implanted into aluminium during Experiment A. The resulting total fit functions (Eqs. 8 and 9) are shown as thick dashed curves on top of the data. Below, the individual mother and β -daughter activities are shown as thin dashed and dotted curves, respectively. In addition, the β activity of $\beta\beta$ daughter and the neutron activity of the βn daughter are drawn, both as dashed-dotted curves. (See Fig. 1 and Eqs. 6 and 7 for nomenclature.)

Fig. 3: As Fig. 2, but presenting the Xe data.

Fig. 4: As Fig. 2, but for Kr (and ^8He) implanted into mylar during Experiment B.

Fig. 5: Comparison of experimental half-lives and P_n values for Xe (a,b) and Kr (c,d) isotopes with QRPA calculations performed for a spherical and deformed set of parameters. The experimental values for light $^{92,93}\text{Kr}$ and ^{141}Xe are taken from [33].

Fig. 6: Systematics of energies of the first-excited 2^+ levels in even-even isotopes in the $A \simeq 150$ (a) and $A \simeq 100$ (b) mass regions.

Fig. 7: Dynamic calculations for relative r-abundances of neutron-rich even-even Kr (a) and Xe (b) isotopes under freeze-out conditions ($T_9=1.35$) as a function of neutron density (n_n). The abundances are presented in absolute units, following the convention of a Si abundance of 10^6 .

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.

Table 1. Results from the fitting of β and neutron decay-spectra for noble-gas isotopes implanted into aluminium during Experiment A. Different time intervals of implantation after proton beam impact, $[t_0 ; t_0 + \Delta t_0]$, were used. The obtained mother half-lives, $T_{1/2}$, and P_n values, and alkali-daughter half-lives, T_β , are compared to results from previous experiments [33]. The fit functions were constructed by using Eq. 4 iteratively with Eq. 5 as initial input, and inserting the results into Eqs. 6 and 7. In this way, the total number of implanted noble-gas ions per pulse (still present when the implantation was finished), $N_{nd} + N_d$, the diffusible fraction, $\frac{N_d}{N_{nd} + N_d}$, and the diffusion half-life, T_d , were determined. (See text for more details).

Pre-cursor	t_0 (ms)	Δt_0 (ms)	$N_{nd} + N_d$ ($\frac{\text{atoms}}{\text{pulse}}$)	$\frac{N_d}{N_{nd} + N_d}$ (%)	T_d (ms)	$T_{1/2}$		T_β		P_n	
						Present (ms)	Previous (ms)	Present (ms)	Previous (ms)	Present (%)	Previous (%)
^8He	5	100	$1.50(6) \cdot 10^4$	45(4)	32(6)	103(7)	119.0(15)	841(5)	838(6)	15(3)	16(1)
^{94}Kr	100	5	$5.2(2) \cdot 10^4$	20(4)	110(30)	212(5)	200(10)	2670(40)	2702(5)	1.26(10)	5.7(22)
^{95}Kr	100	10	$1.75(8) \cdot 10^4$	13(4)	50(30)	114(3)	780(30)	384(4)	377.5(8)	2.87(18)	
^{96}Kr	5	100	$1.3(1) \cdot 10^4$	22(10)	70(30)	80(8)		189(5)	203(3)	3.8(4)	
^{97}Kr	5	100	1050(50)	18(17)		61(5)		160(5)	169.9(7)	8.2(15)	
^{98}Kr	5	100	36(13)			44(12)		130(17)	114(5)	7(4)	
^{142}Xe	100	2	$5.15(15) \cdot 10^4$	10(2)	100(50)	1250(25)	1220(20)	1650(40)	1689(11)	0.21(6)	0.41(3)
^{143}Xe	100	5	$4.4(2) \cdot 10^4$	9(2)	41(14)	511(6)	300(30)	1770(30)	1791(8)	1.00(15)	
^{144}Xe	100	5	7400(500)	11(3)	31(13)	388(7)	1150(200)	983(20)	993(13)	3.0(3)	
^{145}Xe	100	100	9000(200)	< 3		188(4)	900(300)	558(9)	582(6)	5.0(6)	
^{146}Xe	5	200	800(50)	< 10		146(6)		300(20)	323(6)	6.9(15)	
^{147}Xe	5	100	4.5(20)			$100(^{+100}_{-50})$			225(5)	< 8	

Table 2. As Table 1, but for noble-gas isotopes implanted into mylar during Experiment B.

Pre-cursor	t_0 (ms)	Δt_0 (ms)	$N_{\text{nd}}+N_{\text{d}}$ ($\frac{\text{atoms}}{\text{pulse}}$)	$\frac{N_{\text{d}}}{N_{\text{nd}}+N_{\text{d}}}$	T_{d} (ms)	$T_{1/2}$		T_{β}		P_n	
						Present (ms)	Previous (ms)	Present (ms)	Previous (ms)	Present (%)	Previous (%)
^8He	30	30	$1.11(5) \cdot 10^4$	78(2)	32(2)	100(7)	119.0(15)	834(10)	838(6)	^a	16(1)
^{94}Kr	450	3	8300(1000)	84(3)	79(4)	210(20)	200(10)	2530(300)	2702(5)	0.98(9)	5.7(22)
^{96}Kr	200	7	2000(400)	75(13)	69(9)	80(10)		202(4)	203(3)	3.5(8)	
^{97}Kr	5	80	6000(600)	62(13)	60(12)	68(7)		171.0(15)	169.9(7)	6.5(6)	
^{98}Kr	5	80	450(100)	77(13)		48(10)		126(10)	114(5)	7.0(10)	
^{99}Kr	5	80	9(3)			40(11)		59(12)	50.3(7)	11(7)	

^a Due to parameter correlations the fit did not converge when both P_n and ε_{β} were varied. The β efficiency is not known for the ^8He run since changes had been made to the detector setup. When fixing $P_n=16\%$ the fit gave $\varepsilon_{\beta}=10\%$.

Table 3

Yields of Kr and Xe ions per μC of protons on target (1 pulse $\sim 4.8 \mu\text{C}$) at the exit of the mass separator. The yields of $^{94,96-99}\text{Kr}$ are taken from Experiment B (generally a factor of two larger in Experiment A). Also, the combined results from the two experiments of the Kr half-lives and P_n values are given.

Precursor	Yield (atoms/ μC)	$T_{1/2}$ (ms)	P_n (%)	Precursor	Yield (atoms/ μC)
^{94}Kr	$2.2 \cdot 10^6$	212(5)	1.11(7)	^{142}Xe	$1.7 \cdot 10^7$
^{95}Kr	$1.3 \cdot 10^5$	114(3)	2.87(18)	^{143}Xe	$3.2 \cdot 10^6$
^{96}Kr	$6.8 \cdot 10^4$	80(7)	3.7(4)	^{144}Xe	$4.9 \cdot 10^5$
^{97}Kr	7200	63(4)	6.7(6)	^{145}Xe	$1.7 \cdot 10^4$
^{98}Kr	520	46(8)	7.0(10)	^{146}Xe	890
^{99}Kr	10	40(11)	11(7)	^{147}Xe	7.5