

THERMAL NEUTRON CAPTURE EXPERIMENTS WITH RADIOACTIVE TARGETS

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ABSTRACT

ISOLDE-prepared targets of neutron deficient $34.5 \text{ d } ^{84}\text{Rb}$, $36.4 \text{ d } ^{127}\text{Xe}$ and $6.5 \text{ d } ^{132}\text{Cs}$ have been used to search for (n_{th}, p) and (n_{th}, α) reactions. Two proton branches, representing a cross-section $\sigma_p = 12 \pm 2 \text{ b}$, were observed with ^{84}Rb . In the other cases only upper cross-section limits for alpha emission were obtained. Possibilities of extending the work to shorter-lived nuclei are discussed.

1. Introduction

Nuclear reaction experiments have in a limited number of cases been performed with long-lived radioactive targets. It may be of interest to mention, however, that already at the first far-off-stability conference (Lysekil 1966) an extended use of such targets was discussed¹. With the improved production capacity² of the ISOLDE on-line isotope separator facility, nuclear reaction studies are now becoming feasible for a large number of nuclides, including more short-lived ones. With the present proton intensity ion beams of nA strengths are available for several isotopes. As an example a 48 hour collection of the most abundant cesium isotopes gives more than 10^{15} atoms. With a typical size of the beam spot of 2 mm diameter this corresponds to the order of $10 \text{ } \mu\text{g}/\text{cm}^2$ of radioactive target material.

In the present investigation the emission of charged particles from compound nuclear states populated in thermal neutron capture have been studied. Both proton^{3,4} and alpha^{5,6,7} emission from such reactions have previously been observed for a small number of stable or very long-lived nuclides.

A process related to (n, p) and (n, α) reactions is the emission of charged particles from highly excited states fed in the β -decay of very neutron deficient nuclides, delayed particle emission, which has been studied extensively during the past few years^{8,9}. The particle emitting states lie in the resonance energy region with high level densities, and the β -decay populates states over the whole excitation spectrum. The particle spectra show smooth intensity distributions, and with the present detector resolution one cannot observe the individual states. The neutron capture reactions, of the type described in this paper, adds to the knowledge of these highly excited states.

2. Target preparation and experimental technique

The radioactive targets were produced at the ISOLDE facility at the CERN SC. The neutron irradiations have been done at the Institut Laue-Langevin in Grenoble, confining us to reactions with long-lived target nuclides. The extracted beam of thermal neutrons used here had an intensity of $10^9 \text{ cm}^{-2} \text{ s}^{-1}$. The charged particles were detected with a singles counter at a distance of about 50 mm from the target position. The resulting spectra always showed an increase in the count rate at low energies caused by the strong target activity and by reactions between scattered neutrons and the material in the surroundings of the detector. Background peaks from reactions with lithium and boron were also seen and used as an internal energy calibration.

Up to now three different radioactive targets, ^{84}Rb , ^{127}Xe and ^{132}Cs , have been irradiated at the ILL.

3. Experimental results

3.1. Irradiation of $34.5 \text{ d } ^{84}\text{Rb}$

The first opportunity to neutron irradiate an ISOLDE-produced radioactive target came in November 1975, when nearly 10^{14} atoms of ^{84}Rb were collected on a $10 \text{ } \mu\text{m}$ foil of ultra-pure aluminium during a 20 hour run. The ^{84}Rb target was subsequently irradiated for 94.5 hours. The charged-particle spectrum obtained with a $220 \text{ } \mu\text{m}$ silicon surface barrier detector (26 KeV FWHM) is given in Fig 1. Well-known peaks due to reactions with boron and lithium, present as impurities, can be identified in the spectrum. The two peaks at 3.41 and 2.54 MeV, however, cannot be ascribed to any impurity, but they correspond well to the expected positions^{10,11} of proton branches from the capturing state in ^{84}Rb to the 0^+ ground state and the 2^+ first excited state of ^{84}Kr (Fig. 2): The Q_p value

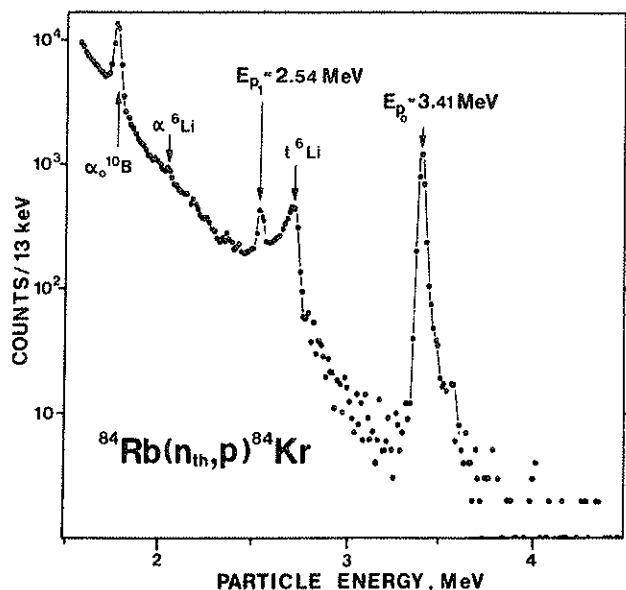


Fig. 1. Energy spectrum of charged particles from a 0.43 mCi ^{84}Rb target irradiated with thermal neutrons. The peaks at 3.41 and 2.54 MeV have been identified as protons from the $^{84}\text{Rb}(n_{\text{th}}, p)^{84}\text{Kr}$ reaction feeding the ground state (0^+) and first excited state (2^+) in ^{84}Kr .

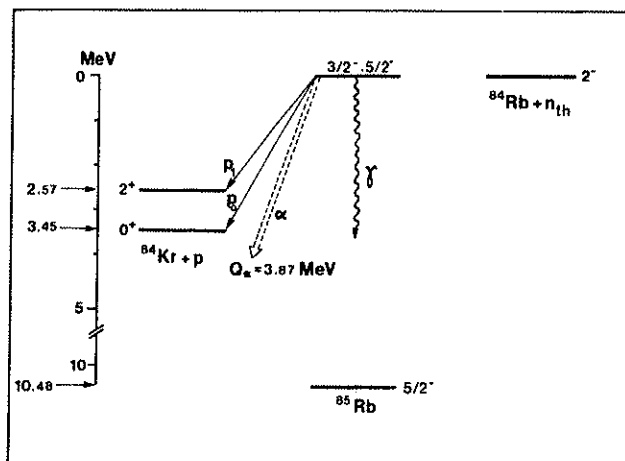


Fig. 2. Level scheme of the $^{84}\text{Rb}(n_{\text{th}}, p)^{84}\text{Kr}$ reaction. The neutron separation energy is known to be 10.48 MeV¹¹⁾, and the Q value for proton emission to the 0^+ state has been determined as 3.45 ± 0.01 MeV. The Q value for alpha-emission is calculated from literature¹¹⁾ to be 3.87 MeV.

determined as 3.45 ± 0.01 MeV is consistent with the value 3.461 ± 0.003 MeV obtained by adding the neutron-proton mass difference to the Q_β value of ^{84}Rb ¹²⁾.

The number of counts in the two proton peaks, 3300 ± 100 and 700 ± 100 , gives the ratio of the level widths as $\Gamma_p(0^+)/\Gamma_p(2^+) = 4.7 \pm 0.7$. One cannot, however, make an unambiguous spin assignment of the capturing state based on this ratio^{8, 13)}.

The product of neutron flux and detec-

tor efficiency was determined with an accurately weighed amount of lithium using the well-known reaction $^6\text{Li}(n_{\text{th}}, \alpha)^3\text{H}$. The average number of ^{84}Rb atoms present during the irradiation was determined to be $(6.8 \pm 0.7) \times 10^{13}$, and the (n_{th}, p) cross-section could be calculated as $\sigma_p = 12 \pm 2$ b.

The $^{84}\text{Rb}(n_{\text{th}}, \alpha)^{81}\text{Br}$ reaction is also energetically allowed and would give alpha particles with the main peak at 3.69 MeV energy. No peak at this position in the spectrum was found, giving an upper limit to the (n_{th}, α) cross-section of 60 mb.

A more detailed account of the ^{84}Rb experiment has recently been published¹³⁾.

3.2. Irradiation of 36.4 d ^{127}Xe

The capturing state in ^{128}Xe has a Q_p value of 1.45 MeV and a Q_α value of 7.84 MeV¹¹⁾. The (n_{th}, α) reaction was therefore expected to be more probable than the (n_{th}, p) reaction for this nuclide (Fig. 3).

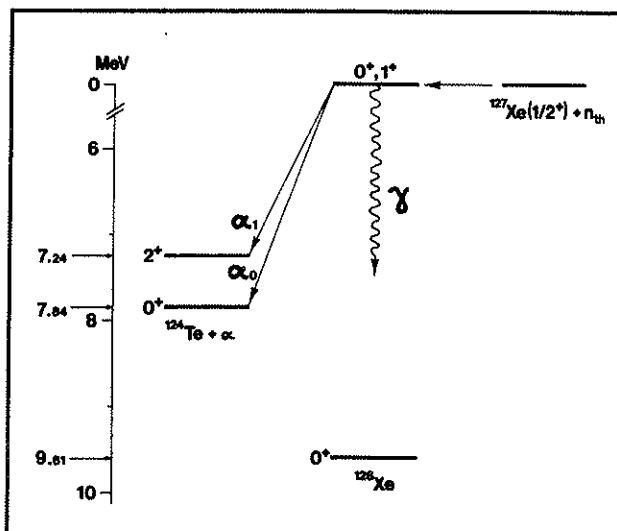


Fig. 3. Level scheme of the $^{127}\text{Xe}(n_{\text{th}}, \alpha)^{124}\text{Te}$ reaction. The neutron separation energy, 9.61 MeV, and the Q value for alpha-emission to the 0^+ state, 7.84 MeV, are calculated from literature¹¹⁾.

More than 10^{15} atoms of 6.2 h ^{127}Cs were collected in a 3 day run. After a waiting time of 23 days, 8.2×10^{14} atoms of ^{127}Xe were irradiated for 170 hours at the ILL. No clearly discernible peak for alphas from the capturing state to the 0^+ ground state (7.58 MeV alphas) or the 2^+ first excited state (7.00 MeV alphas) was seen in the spectrum, giving an upper limit to the (n_{th}, α) cross-section of 10 mb. The $1/2^+$ ground state of ^{127}Xe permits a capturing state of either 0^+ or 1^+ . Note that alpha de-excitation of the 1^+ state to the ground state of ^{124}Te is parity forbidden.

3.3 Irradiation of 6.5 d ^{132}Cs

Nearly 10^{15} atoms of ^{132}Cs were collected in a 36 hour run and subsequently irradiated for 130 hours. Due to the lack

of a surface barrier detector of suitable thickness the intense activity of the target (≈ 30 mCi) resulted in a strong background. No significant amount of 6.74 MeV alphas¹¹ from the $^{132}\text{Cs}(n_{\text{th}},\alpha)^{129}\text{I}$ reaction was detected and on account of the strong background the upper limit of the (n_{th},α) cross-section was determined to have the high value 150 mb.

4. Future possibilities

Several other targets are on our waiting list for neutron capture experiments. However, all these except one belong to the region close to stability. The exception is 16.1 h ^{76}Br which can be obtained from 14.6 h ^{76}Kr produced at ISOLDE. Due to the similarity in the half-lives, the amount of ^{76}Br will continue to increase during the transportation to the irradiation facility in Grenoble and remain nearly constant for several half-lives. The de-excitation of the capturing state in ^{77}Br should proceed to almost 100% by proton emission, making this nuclide a most promising candidate for proton emission. The (n_{th},p) cross-section is estimated to be of the order of 100 barns.

Other very neutron deficient nuclides cannot be investigated with the present experimental technique, because their short half-lives will not permit them to survive the long transportation time. Any attempt to extend (n_{th},p) and (n_{th},α) reaction studies away from stability must therefore incorporate an on-line neutron facility, that is a possibility to neutron irradiate the produced nuclei during their collection. Such a neutron generator is bound to have a much weaker flux than the facility in Grenoble. A feasibility study¹⁴ has been made in order to see to what extent the increasing (n_{th},p) and (n_{th},α) cross-sections with increasing neutron deficiency can compensate for the weaker neutron flux. In this study a radioactive target is produced in a 48 hour run with the present ISOLDE intensities. In the off-line case the target is transported during a time of 8 hours, before it is exposed to a thermal neutron flux of $10^9 \text{ cm}^{-2} \text{ s}^{-1}$ for 100 hours. In the on-line case the target is irradiated with $10^7 \text{ neutrons cm}^{-2} \text{ s}^{-1}$ during the 48 hour long collection. The result of this investigation for (n_{th},p) reactions in a number of Rb isotopes is shown in Fig. 4. Off-line irradiation is seen to be the favourable mode of operation for the long-lived isotopes close to stability. On-line irradiation becomes the only possibility for neutron deficient nuclides and results in an appreciable number of detected protons from a surprisingly large number of isotopes, including isotopes very far from the stability line.

The result from the investigation of other elements (Cs, Eu, Hg) also show this trend.

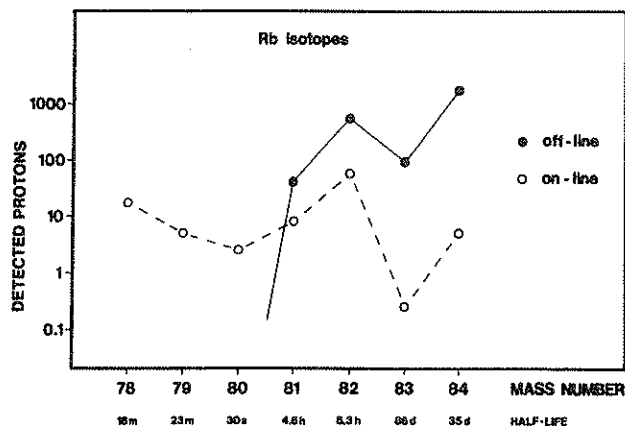


Fig. 4. The estimated number of protons to be detected from (n_{th},p) reactions in radioactive Rb isotopes using either a 48 hour irradiation of the collecting position with $10^7 \text{ neutrons cm}^{-2} \text{ s}^{-1}$ (on-line), or a 48 hour collection, 8 hour transportation and 100 hour irradiation of the collected sample with $10^9 \text{ neutrons cm}^{-2} \text{ s}^{-1}$ (off-line).

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