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OBSERVATION OF PROTON EMISSION FOLLOWING
THERMAL NEUTRON CAPTURE IN 34.5 d ^{84}Rb

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ABSTRACT

Using a target prepared by on-line isotope separation, thermal neutron capture in ^{84}Rb ($I^\pi = 2^-$) has been shown to induce proton emission to the ground state (0^+) and first excited state (2^+) of ^{84}Kr . The branching ratio was measured as $\Gamma_p(0^+)/\Gamma_p(2^+) = 4.7 \pm 0.7$, favouring a $3/2^-$ assignment of the capturing state without excluding $5/2^-$, and the total (n_{th}, p) cross-section as 12 ± 2 b. The energy available for the process was determined to be 3.45 ± 0.01 MeV, in agreement with other mass data in the region.

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Irradiation with thermal neutrons is known [1,2] to induce (n_{th},p) reactions in a limited number of low-mass nuclides. Higher up in the periodic system the difference between the neutron and proton separation energies of the compound nucleus is, if not negative, too small compared to the height of the Coulomb barrier for this process to be observed. This statement, however, is no longer valid if neutron deficient target nuclides are taken into consideration. Within a series of even-mass or odd-mass isotopes the separation energies of charged particles tend to decrease with decreasing neutron number and that of neutrons (and hence the excitation energy of the compound nucleus) to increase [3]. Both effects contribute to make proton-emissive (as well as alpha-emissive) thermal neutron capture, in general, increasingly energy-favoured.

The prospect of widening the field of research, in this way, has recently become of more than academic interest, due to the improved production capacity of the ISOLDE isotope separator facility [4], attached on line with the reconstructed CERN Synchro-cyclotron [5]. With separated radioactive ion beams reaching in some cases nA strengths, it is possible to collect samples of up to about 10^{16} atoms in runs of normal length (1-2 days).

In order to select suitable targets for (n_{th},p) and/or (n_{th},α) reactions, a systematic search [6] has been made among neutron-deficient medium-weight and heavy nuclides, using statistical-model calculated level densities and partial level widths to obtain rough estimates of off-resonance cross-sections. With the additional condition of a reasonably long half-life, 34.5 d ^{84}Rb turned out to be one of the most promising candidates for proton emission.

During a 20 hour run of the ISOLDE facility (700 nA proton current on target of molten Y-La alloy, 63 g Y/cm²), nearly 10^{14} atoms of ^{84}Rb were deposited within an area of 0.5 cm² in a 10 μm foil of ultra-pure Al. The sample was subsequently placed in a thermal neutron flux of $10^9 \text{ cm}^{-2} \text{ sec}^{-1}$ at the high-flux reactor of the Institute Laue-Langevin in Grenoble, and a 220 μm silicon surface barrier detector, subtending a solid angle of 2% of 4π , was set to detect charged particles of energy below 6 MeV. The experimental set-up was essentially the one used in studies of (n_{th},α) reactions with stable target nuclides [7].

In the spectrum from a 94.5 hour irradiation (Fig. 1), well-known peaks due to reactions with boron and lithium, present as impurities, can be identified. Contrary to these, the peaks at 3.41 and 2.54 MeV did not show up in runs with a blank Al backing. However, they correspond well to the expected positions [3,8] of proton branches from the capturing state in ^{85}Rb to the 0^+ ground state and first excited 2^+ state of ^{84}Kr (Fig. 2). The energy difference after recoil correction is found to be 878 ± 4 keV, in satisfactory agreement with the adopted [8] level energy 881.5 keV. This is taken as a confirmation of the interpretation made here.

Because of a slow change in the peak positions towards lower channel numbers during the run, the absolute proton energies could not be determined with an accuracy representative of the detector characteristics (26 keV FWHM of alpha calibration peaks). The Q_p value obtained after correction for the drift, 3.45 ± 0.01 MeV, is still consistent with 3.462 ± 0.007 MeV, as derived from nucleon separation energies [3]. It should be remarked that the implantation into Al of the Rb ions accelerated to 60 keV is equivalent to an absorbing layer of about 4×10^{-2} μm , which gives an average energy degradation of ≤ 1 keV for the protons concerned. The peaks due to reactions in impurity atoms homogeneously distributed throughout the backing, on the other hand, are expected to be significantly broadened and shifted in energy.

The number of counts in the two proton peaks, 3300 ± 100 and 700 ± 100 , gives the ratio of the level widths as $\Gamma_p(0^+)/\Gamma_p(2^+) = 4.7 \pm 0.7$. Since the ground-state spin and parity of ^{84}Rb is known to be 2^- , the capturing state can be either $3/2^-$ or $5/2^-$. Statistical-model calculations [6] predict $\Gamma_p(0^+)/\Gamma_p(2^+)$ to be 7.9 and 0.36, respectively, for the two alternatives, and thus clearly seem to suggest a $3/2^-$ assignment. The calculated values, however, represent averages over a large number of states with the same spin and parity, whereas the experiment measures the ratio of two individual transition probabilities. These are subject to Porter-Thomas fluctuations, which calls for some care in the interpretation of the result. From a calculation [9] based on the distribution function

of the quantity $\Gamma_p(0^+)/\Gamma_p(2^+)$ one finds an appreciable probability (17%) for a $5/2^-$ state to give a value greater than or equal to the one obtained experimentally. Therefore the $3/2^-$ assignment of the capturing state cannot be considered unambiguous.

In order to determine the (n_{th}, p) cross-section, the ^{84}Rb target was replaced by an accurately weighed amount of Li ($13.4 \pm 1.0 \mu\text{g LiF}$) and the count rate of 2.73 MeV tritons from the $^6\text{Li}(n_{th}, \alpha)^3\text{H}$ reaction recorded as 18959 ± 200 counts/min. Using a cross-section for this process [1] of 941 ± 4 b and knowing from radioassay the average number of target atoms during the ^{84}Rb run to be $(6.8 \pm 0.7) \times 10^{13}$, we calculate the (n_{th}, p) cross-section as $\sigma_p = 12 \pm 2$ b. The error includes a $\pm 2\%$ variation with time of the neutron flux.

The high-energy tail of the 3.41 MeV proton line is seen (Fig. 2) to have a peculiar shape. Although its contribution to the intensity uncertainty is minor, it would still be desirable to be able to explain this part of the spectrum in detail. It is interesting in this context to observe that the $^{84}\text{Rb}(n_{th}, \alpha)$ reaction is energetically allowed and would contribute alpha particles mainly of 3.69 and 3.42 MeV energy, feeding the $3/2^-$ ground state and $5/2^-$ first excited state of ^{81}Br . The indication of a peak at 3.59 MeV cannot, however, be interpreted in this way, the energy being too far from those of the hypothetical alpha lines, even if correction is made for an average energy loss in the backing of 7 keV for alphas of this energy. For the ground state transition, the experiment puts an upper limit to the level width as $\Gamma_\alpha(3/2^-)/\Gamma_p(0^+) \leq 5 \times 10^{-3}$, to be compared with a calculated ratio of 2×10^{-8} . The 3.42 MeV branch is predicted to be still weaker, $\approx 6 \times 10^{-10}$, relative to the ground-state protons. It thus seems most unlikely that it could be responsible for any asymmetry of the 3.41 MeV proton peak.

There is in this case, however, at least one effect that may cause proton counts to fall slightly above a normal-shaped peak: coincidence of a proton with an electron due to the target radioactivity. The distribution of energies deposited in the actual detector by positrons from ^{84}Rb (end points at 0.8 and

1.7 MeV) is expected to peak at about 80 keV. Addition of this amount to the proton energy could account for the irregularity visible at ≈ 3.50 MeV. The structure at higher energies may possibly be ascribed to statistical variations in a combination of summing effects and the general background caused by neutron-induced reactions in various parts of the apparatus. In future studies of this kind it is obviously important to improve further the detection conditions by, for instance, careful choice of construction materials, reduction of resolving times, and magnetic enhancement of charged baryonic particles relative to electrons.

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Figure captions

Fig. 1 : Energy spectrum of charged particles from a 0.43 mCi ^{84}Rb target irradiated with thermal neutrons (flux: $10^9 \text{ n cm}^{-2} \text{ sec}^{-1}$). 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 . In addition, peaks due to impurities of boron (1.78 MeV α) and lithium (2.05 MeV α and 2.73 MeV ^3H) are seen in the spectrum. (The 1.46 MeV α_1 line from the boron reaction was also observed, but is not included in the figure.) The increasing count rate towards lower energies is caused mainly by charged particles from reactions of scattered neutrons with materials in the surroundings of the detector. The radioactivity from the target contributes substantially to the background well below 1 MeV. Summing effects, however, give rise to counts also at higher energies and may account for some distortion of the lines in the spectrum.

Fig. 2 : Level scheme of the $^{84}\text{Rb}(n_{\text{th}},p)^{84}\text{Kr}$ reaction. The neutron separation energy is known [3] to be 10.48 MeV and the Q-value for protons to the 0^+ state has been determined as 3.45 ± 0.01 MeV. The Q-value for α -emission is calculated from literature [3] to be 3.87 MeV.

Fig. 1

Fig. 2