Alpha decay of ^{198}Rn

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(Received 9 July 1984)

The intensities of mass-separated radon beams have been improved by means of a new high temperature thorium spallation target. The production yields of the selectively produced radon ions were determined. The new nuclide ^{198}Rn was found to have an α -decay energy of 7196 ± 10 keV and a half-life of 50 ± 9 ms. Decay energies and half-lives for $^{199}\text{Rn}^m$, ^{199}Rn , and ^{200}Rn were remeasured.

I. INTRODUCTION

The element radon was discovered by Rutherford as early as 1899.¹ It was its chemical nature as a noble gas which permitted this finding. By means of modern on-line mass separators² the whole chain of almost 30 isotopes of the element radon has been made available for studies. However, the chemical selectivity has been of lasting importance in this research.

Because of recent improvements in the understanding of targets and ion sources, as will be outlined in Sec. II, the extension of this series of isotopes to the hitherto unknown species ^{198}Rn became feasible. In Sec. III we discuss the α spectroscopy and the half-life measurements performed on the very neutron-deficient radon isotopes ^{200}Rn — ^{198}Rn and compare them with the existing data.^{3,4}

II. RADON YIELDS

Ion beams of the heaviest known gaseous element radon were among the first to be produced by the spallation of thorium at the ISOLDE mass separator⁵ on line to the CERN 600 MeV synchrocyclotron. Neutron deficient radon isotopes as light as $A=200$ (Ref. 2) have been studied using targets of partially dehydrated thoriumhydroxide.⁶ Although this material has excellent release properties and selectivity, its use is limited to intensities of a few tenths of a μA of 600 MeV protons because of radiation-induced dehydration. Later it was demonstrated⁷ that porous ceramic ThO_2 at high temperatures allows the use of much more intense proton currents and also releases a large variety of elements, including radon. In the present study a newly designed high temperature ThO_2 target and ion-source system has been employed, which was dedicated to the selective production of radon. The combined effect of target development and increased proton currents leads to radon ion-beam intensities 7000 times higher than that obtained earlier.

The radon nuclei are formed by spallation in the ThO_2 material, which is kept at a temperature of 1700°C . Subsequently they are brought into a plasma discharge ion source which has a measured ionization efficiency for Xe^+ of 10%. The ionization efficiency for Rn^+ is estimated to be 40%. This figure has been obtained by relating the radon yields and the francium yields⁸ from thorium-induced spallation. It is furthermore based on the assumption of a surface ionization efficiency for Fr^+ of 100%.

The yield of a given isotope is then measured as follows: The magnetically deflected ions are directed through a slit arrangement. The width of the slit is chosen such that only ions of a preselected mass number will pass. They are guided by an electrostatic beam transport system to the measuring ports.

Ions with mass numbers 202–212 are implanted into a $60\text{ }\mu\text{m}$ thick aluminized Mylar tape which transports them into a 4π plastic scintillation detector. The neutron deficient isotopes ^{198}Rn — ^{200}Rn are stopped in a $20\text{ }\mu\text{g}/\text{cm}^2$ thin carbon foil which is viewed from behind by a silicon surface barrier detector.

From the measured decay rates, the beam-line transmissions, and the solid angles involved, the production yields are readily calculated. They are normalized to $1\text{ }\mu\text{A}$ of 600 MeV protons and to $40\text{ g}/\text{cm}^2$ thorium target material.

It should be noted that no correction for decay losses has been applied, i.e., the quoted yields are as observed at the collection position. The results obtained are subject to various statistical and systematic uncertainties which are discussed in Ref. 9. The accuracy is conservatively estimated to be better than a factor of 2 near the peak yields and to gradually increase to a factor of 10 at the $A=198$ position.

The results are summarized graphically in Fig. 1. The steep decrease of yield at the wings of the distribution is due to a combined effect of a decreasing production cross section and the decay losses of the more short-lived

FIG. 1. Production yield of radon nuclei formed by spallation of a 40 g/cm² Th target with a 1 μ A 600 MeV proton beam. For details on the running conditions of the ion source, see the text. The solid line is a guide for the eye. The open circles are the yields given in Ref. 6 and normalized to our improved conditions.

species.⁵ Therefore, an extension of this research to much more neutron deficient (hence shorter lived) nuclei is difficult, although the operating conditions of the target and ion source can be modified in order to significantly

shorten the involved delay times. Conceivably, the future observation of ¹⁹⁷Rn might be feasible.

III. α SPECTROSCOPY

The radon isotopes with mass numbers less than 201 are observed by their α disintegrations. We utilized a surface barrier detector with FWHM resolution of 24 keV to observe the α decay of the radon isotopes, which are implanted into a thin carbon foil. The solid angle is 35% of 4π . From the observed α spectra we derive the α -decay energies which are shown in Table I, where we also compare the α -decay energies with the existing data on $A=199$ and 200.^{3,4} The integrated proton current, Q , used in the respective part of our experiment, is given in Table I. It should be noted that for α energies below the peaks of interest several contaminant α lines are visible. They arise partly from daughter activities of the selected species. Another contribution, however, is due to a general background created by scattering of the much more copiously produced heavier isotopes.

In the assignment of α peaks to the isomeric and ground state transitions of ¹⁹⁹Rn^m and ¹⁹⁹Rn, respectively, we followed the reasoning of Enge *et al.*⁴ In order to measure the half-life the radon ion beam was periodically switched off by an electrostatic shutter. The lengths of the time intervals "beam on," t_1 , and "beam off," t_2 , respectively, are given in the fourth column of Table I. Alpha-energy signals were observed during both periods. At the opening of the shutter (start of the beam on period) an analog ramp generator was also started. This module

FIG. 2. Time distributions for the α -decaying isotopes ¹⁹⁸Rn^m and ¹⁹⁹Rn^m. The number of counts in the respective α peaks per time bin $\Delta\tau$ is plotted as a function of time. During negative times the Rn⁺ beam from the separator reached the detector; for positive times it was intercepted by a shutter. For ¹⁹⁸Rn $\Delta\tau=19.23$ ms, for ¹⁹⁹Rn^m $\Delta\tau=190.1$ ms. The curves are calculated with our half-lives from Table I. A small background has not been subtracted from the experimental data.

TABLE I. Experimental results for the α -decaying isotopes $^{A}_{86}\text{Rn}$.

A	Q (mC)	E_{α} (keV)	Beam on t_1 (s)	Beam off t_2 (s)	$T_{1/2}$ (ms)	Reference
198	8.6	7196 ± 10	0.1	0.4	50 ± 9	This work
199, m	1.3	7059 ± 10	1	4	325 ± 25	This work
199, m		7060 ± 15			290 ± 50	3 and 4
199, g	1.3	6995 ± 10	1	4	620 ± 25	This work
199, g		6990 ± 15			500 ± 200	3 and 4
200	1.3	6900 ± 10	1	4	1055 ± 70	This work
200	0.04		2	10	1060 ± 20	This work
200		6909 ± 8			1000 ± 200	2

produces pulses with an amplitude proportional to the time elapsed (since the start of the ramp). The unit has been calibrated with a precision pulser and has a linearity better than 1%.

For each α disintegration the energy and the time signal are written onto magnetic tape. For the α peaks in the spectrum (as well as for the background) the time distribution can then be obtained by a subsequent off-line analysis.

For the two isotopes ^{198}Rn and $^{199}\text{Rn}^m$ these distributions are shown in Fig. 2. Negative times correspond to the growth curve, positive times correspond to the decay part of it. The background has been analyzed independently and was found to be small and long-lived.

The time distributions were evaluated by comparing with a theoretical function (also shown in Fig. 2 as the dashed curve), taking into account the growth and decay of a single half-life, allowing for a small constant background. These half-life values are given in Table I. For comparison we also evaluated only the decay region and for ^{198}Rn we obtained $t_{1/2} = 49 \pm 9$ ms, which is in good agreement with the above value.

Because of the very low statistics the maximum likelihood method was used.¹⁰ Although this statistical approach is expected to be superior in the case of very low count rates, the numerical results of a least squares analysis give very similar values to those quoted for ^{198}Rn — ^{200}Rn in Table I.

IV. DISCUSSION

For radon isotopes in the range of $A = 200$ – 222 , Hornshøj *et al.*² have analyzed the systematics of partial half-lives for α decay. This work can now be extended to the neutron number $N = 112$. The α -branching ratio for radon isotopes lighter than 201 can be expected to be close to unity. In fact, by using information about the beta-decay strength the α -branching ratio could be evaluated.

For an estimate we use the beta half-life of Takahashi *et al.*,¹¹ and obtain for the α -branching ratio, $\Gamma_{\alpha}/\Gamma_{\text{tot}}$, 0.7, 0.93, and 0.99 for ^{200}Rn , ^{199}Rn , and ^{198}Rn , respectively. Partial α half-lives based on these figures agree perfectly with the fit given in Ref. 2 (their Fig. 10) for an α width 1.06 times the one of ^{212}Po (which is set to unity for normalization). This confirms the smooth behavior of the α widths expected far away from the magic neutron number $N = 126$.

The high yields found in these experiments suggest the feasibility of measurements with nuclear spin oriented radon nuclei. Spin orientation of rare gas atoms, notably xenon nuclei, has been achieved by spin exchange with optically pumped alkali atoms.^{12,13} This technique has recently been applied to align the radioactive isotopes ^{133}Xe , $^{133}\text{Xe}^m$, and $^{131}\text{Xe}^m$; detection of nuclear orientation was achieved by observing gamma ray anisotropies, and measurements of the nuclear magnetic dipole moments were made by observing nuclear magnetic resonances (NMR's) in the anisotropy.¹⁴ The spin exchange cross section for rubidium on radon should be larger than that for xenon, owing to a stronger van der Waals potential, and we therefore expect that similar orientation experiments should be possible with the radioactive radon isotopes.

The improved yields of radon and the optical pumping technique should enable measurements of the nuclear magnetic dipole moments of the odd- A radon isotopes. It is also hoped that measurements of the nuclear electric dipole moments of radon isotopes will be possible along lines suggested by Schiff¹⁵ for ^3He . Measurements of the electric dipole moments of nuclei provide fundamental information on P - and T -violation phenomena which is complementary to that for the free neutron.^{16,17} A preliminary experiment has already been performed on polarized ^{19}Ne .¹⁸ However, heavy atoms appear to be most favorable from atomic and nuclear considerations and radon would appear to be very suitable for such studies.

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