ALPHA DECAY OF NEUTRON-DEFICIENT ISOTOPES STUDIED AT "ISOLDE", CERN

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1. Introduction

In the five-year period since the Leysin Conference, the studies of α decay of very neutron-deficient nuclides have been continued at the ISOLDE facility at CERN. As a result of higher proton-beam intensity from the rebuilt 600 MeV cynchro-cyclotron at CERN, spallation reaction yields have been increased. Moreover, progress in target technology has allowed the investigations to be extended to several more elements.

The present paper summarizes the findings made at ISOLDE and presents a survey of some systematic trends in α decay. Three topics have been covered: (i) Mass determinations, (ii) Transition probabilities for α decay, and (iii) Specific spectroscopic information. Existing information from other sources [1-4] has been included in several places to complete the picture of α decay of the elements studied.

2. Experimental Methods

For all the nuclides investigated, the activity was provided by the ISOLDE facility [5,6]. The use of a La-Th alloy at 1400°C has provided francium and radium isotopes in good yields [7]. The light bismuth and lead isotopes have been available from a high-temperature (2000°C) ThO_2 powder target [8], but the yields have been smaller than those from the molten-metal targets. The α-active isotopes of Ra, Fr, Pb, and Hg were investigated, and the relevant target assemblies are described in detail elsewhere [9,10].

The measuring equipment and techniques were largely identical to those applied in earlier investigations [11,12]. Branching ratios were determined by on-line particle counting in cases where the α-decay daughter is α-active and by simultaneous counting of α particles and x rays from the EC branch in decays of the mother nuclei.

In the experiments, the mass-separated ion beam was stopped either directly on the tape of a tape-transport system [13] or on thin carbon foils. In the first case, the activity was brought in front of a silicon surface-barrier detector after a preset collection time. In the second case, the carbon collector foil was stationary in front of the α detector, and an electromagnetic shutter was used to intercept the beam before counting was initiated. Recently, this method has been replaced by electrostatic deflection of the ion beam for termination of the collection periods.

In the calculations of the $\alpha/(\alpha+\beta+EC)$ branching ratios, the growth and decay of daughter lines in the spectra were used [12].

3. Results

3.1 Q values

In recent years, the number of known α-emitting nuclides has been increasing steadily, and the knowledge of their decay has also been improved due to developments of detectors and increased reaction yields. Today, a large number of Q values has been established with a precision of better than 5 keV.

The largest recent extensions of our knowledge of α decay have come from the region $Z \leq 82$. At ISOLDE, very clean conditions have been established via the use of mass-separated samples. Thus it has been possible to measure the decay energies, half-lives, and branching ratios for a large number of short-lived isotopes of Pb, Hg, Au, and Pt [11] and [14]. In fig. 1, the advantages of the mass separation are demonstrated in the α spectrum of ^{204}Fr by the very low contaminations from other francium isotopes produced in yields that are larger by orders of magnitude.

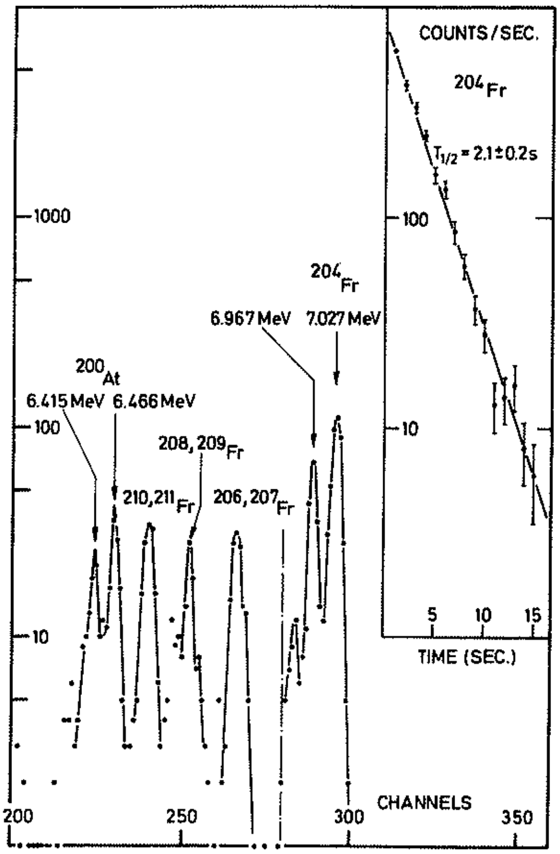

Fig. 1: Singles α-spectrum for ^{204}Fr. The left and right side correspond to counting intervals of 16 and 6 sec, respectively. Collection time was for both parts 3 sec. The inset shows a decay curve for the 7.027 MeV ^{204}Fr α-group.

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The improvements of the experimental conditions obtained by the reconstructed synchro-cyclotron and the rebuilt ISOLDE-2 have already in the first runs allowed the identification of several new α emitters (see table 1). As an example, fig. 2 shows the α spectrum of the lightest mercury isotope observed so far, i.e., ^{177}Hg.

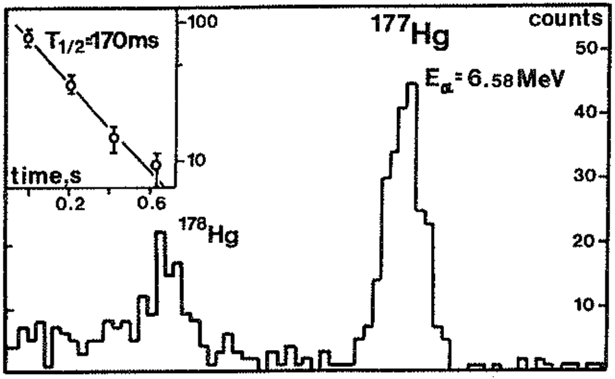

Fig. 2. Singles α-spectrum for ^{177}Hg. In addition to the 6.58 MeV ^{177}Hg α-line, contamination from ^{178}Hg is observed at 6,43 MeV. The inset shows a decay curve for the 6.58 MeV α-group.

However, in spite of these achievements, Q values have not yet been extensively used in the tests of different mass formulae. This is due to the fact that the linkage to the known masses closer to the line of α stability is established only in a few cases. Also, the fact that the symmetry term (N-Z) does not change in the α decay makes these cases less interesting as tests of predictions.

Table 1. Experimental Results

Isotope	$T_{1/2}$ (sec)	E_α (MeV)	α/dis
^{202}Fr	Not measured	7.25 ± 0.02	Not measured
^{177}Hg	0.17 ± 0.05	6.58 ± 0.01	" "
^{178}Hg	0.26 ± 0.03	6.425 ± 0.015	" "
^{175}Pt	2.52 ± 0.08 [1]	5.96 ± 0.01 [1]	0.55 ± 0.05
^{174}Pt	0.7 ± 0.2 [2]	6.035 ± 0.01 [1]	0.88 ± 0.10
^{173}Pt	Not measured	6.19 ± 0.01 [1]	$0.95^{+0.05}_{-0.25}$
^{171}Os	8.2 ± 0.08 [3]	5.25 ± 0.01 [3]	(1.3 ± 0.2) x 10^{-2}

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3.2 Transition probabilities

The transition probability for α decay is often expressed in terms of a reduced width, W_α. This parameter is derived from the experimental half-life data by removal of trivial factors depending on decay energy and the branching ratio for α decay in such a way that the widths alone reflect the specific nuclear-structure features of the α decay [12,15].

The experiments at ISOLDE have yielded results for the α decay of several trans-lead elements (Z = 84-88, refs. [12,14]). These results are in very good agreement with the general trends observed in the actinide region.

For the region Z ≤ 82, it is now possible to assemble sufficient experimental data to display the systematic trends in α-decay widths. In this region, the difficulties arise mainly from the fact that the α decay occurs only for short-lived, very neutron-deficient nuclides, and the complex reactions, (HI,xn) and (p,spall), used for their formation give rise to very large amounts of interfering activity. For example, in the case of ^{174}Pt, the ^{178}Hg mother activity comprises only about 10^{-12} of the total activity in the target. Under such circumstances, isotope separation is mandatory.

As illustrations of data used in the determination of branching ratios from simultaneous K-Xray and α-intensity determinations, fig. 3 displays two sets of spectra obtained for light lead isotopes [15].

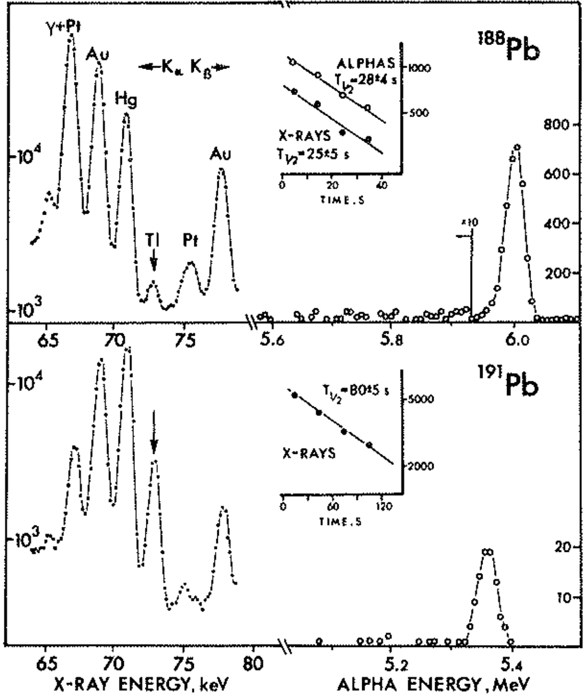

Fig. 3. Energy spectra of K X-rays (left) and α-particles (right) for the nuclides ^{188}Pb and ^{191}Pb. The two examples represent the most difficult cases, i.e., for ^{188}Pb the Tl K_{α_1} is hard to detect, and for ^{191}Pb, the α-count rate is low (0.01 sec^{-1}).

The systematics of reduced s-wave widths is shown in fig. 4 where all available data for even nuclei are included. The widths are large for neutron numbers immediately above the magic numbers, and the trend is a decrease towards the next shell closure. There is a sharp break at N = 126 and a less distinct one at the N = 152 subshell. Only the lead isotopes fall completely outside this general pattern.

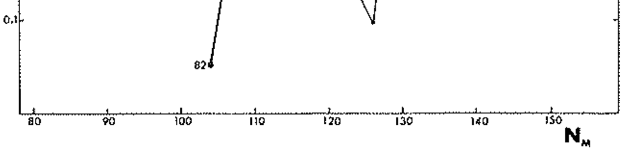

Fig. 4. The systematics of reduced α-widths W_α for ground state to ground-state transitions of even nuclei as a function of the neutron number N_M of the mother nucleus. The curves are labelled with the atomic number of the initial nucleus. The width is defined as the ratio between the theoretical and the experimental α half-life. Note the surprising trend in the lead width.

The interpretation of α-transition probabilities based on single-particle nuclear models has been the topic of several theoretical papers. H. Mang [16] showed that the break at N = 126 is essentially an effect of the nuclear-shell structure: The formation probability for the α particle is large when the single-particle nuclear wave functions are large at the nuclear surface. For the deformed nuclei in the region beyond lead, the decrease in the reduced s-wave width with increasing neutron number can be reproduced in the Nilsson model with pairing included [17]. The theories are rather successful in their description of the relative behaviour of the widths as functions of N and/or Z, whereas the predictions of the absolute widths differ by orders of magnitude. The most recent progress has been made by Kadmenskii and coworkers [18], but the quantitative problem has not yet been completely solved.

For the d-wave α transitions, the picture is less complete (see fig. 5), but a few features are worth noting: (i) The widths are small to the vibrational 2+ states, (ii) The widths are also small for the L = 2 transitions to the lowest (rotational) 2+ states in platinum and osmium isotopes, and (iii) In the actinide region, the d-wave widths decrease more rapidly than do the d-wave widths, the relative hindrance amounting to a factor of 4 in the californium isotopes compared to the absence of relative hindrance in the decay of the thorium isotopes.

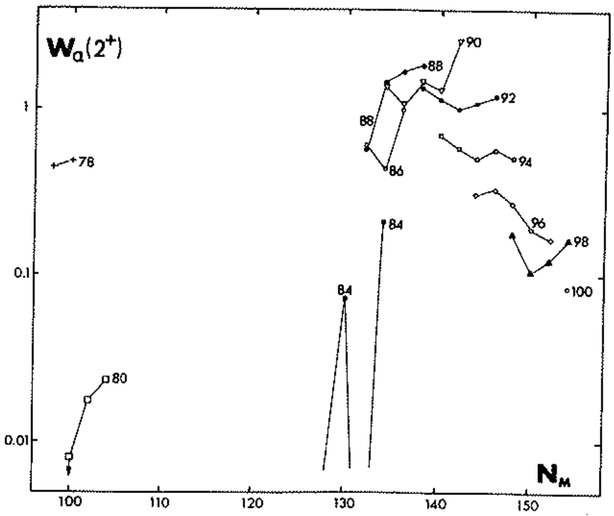

Fig. 5. Reduced α widths $W_\alpha(2^+)$ for $0^+ \rightarrow 2^+$ transitions. The neutron number of the mother nucleus N_M is used as abscissa. The data are from refs. [4] and [15]. No allowance has been made for the centrifugal barrier, thus the unit is the same as in fig. 4.

3.3 Specific spectroscopic information

As a result of the strong energy dependence of the α-transition probability, ground-state-to-ground-state transitions dominate in even nuclei and transitions to low-lying levels dominate in odd nuclei.

This unfortunate property means that, unlike β decay, the α decay does not provide as rich sources of information about nuclear-level schemes. Nevertheless, α-decay "fine structure", i.e., transitions to other levels than that populated by the main (usually "favoured") transition, has been observed in the decay of several mercury and platinum isotopes [11]. The case of ^{185,186m}Hg [19] is particularly interesting in view of the break in optical isotope shifts observed [20] for the mercury isotopes at N = 106. Another experiment aimed at the structure of the light mercury isotopes has been performed with the α decay of ^{188}Pb [21]. Here, a search for α transitions to excited states was made and, in particular, the position of the first-excited 2+ state in ^{184}Hg was of interest. The experiment, however, proved inconclusive as the upper limit (1.5×10^{-4}) set on the α intensity to a rotational 2+ state could not distinguish between two alternatives: (i) The first-excited state has an energy higher than 300 keV, and (ii) The α branch to this state is highly hindered as is the case for neighbouring mercury and platinum isotopes. In later experiments [22], the energy of the 2+ state was determined to be 368 keV.

4. Outlook

The promising results obtained at ISOLDE-2 with the ytterbium target lead us to expect that more detailed studies of some of the rare-earth α emitters may be feasible.

Particular interest is attached to the nuclide ^{153}Yb (N = 83) as α decay has not been observed for any N = 83 nuclides. The preliminary experiments have not been sensitive enough to allow a search for very weak α branches. The influence of the N = 82 closed shell on the α-decay energy may be found for N = 83 isotones closer to stability (from closed energy cycles), and the decrease in the Q_α value is about 1.4 MeV. If this value applies at Z = 70, the expected decay energy is 4.1 MeV, corresponding to an α branch of only 10^{-6}-10^{-7}, which will be extremely difficult to detect.

The investigations of mercury and platinum isotopes have not been completed in all details. Especially deserves the hindrance of the transitions to the excited states in the even nuclei a close study, and among current experiments are systematic α-γ-coincidence studies dedicated to the determination of their intensity.

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