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Levels in ^{210}Fr and the decay of a high-spin, multi-particle isomer

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Abstract. The structure of ^{210}Fr has been studied through the ^{197}Au(^{18}O, 5n)^{210}Fr reaction. A high-spin isomeric state has been identified at ~4.4 MeV. It has a lifetime of 686(17) ns and decays by two γ-rays that are very likely to be either $M2$ or $E3$ multipolarity. The measured strengths in the case of $E3$ assignments are approximatively 8 and 21 W.u., respectively. These would be less enhanced than is observed in the decay from the high spin isomers in ^{209}Fr and ^{211}Fr that are believed to be from a related configuration. Possible configuration assignments are discussed.

1 Introduction

The shell model has been used to describe successfully the structure of spherical nuclei. The observation of high spin states in nuclei near the Z=82, N=126 shell closures has been a substantial ground for testing the model and expanding our understanding of the structure of heavy nuclei. In this region, collectivity is an important factor as the 3^- octupole vibration, which is the lowest lying state in ^{208}Pb, and results from coherent motion of nucleons excited across the Fermi surface [1], can couple to particular orbitals. In a semi-empirical shell model, both modes of excitation can be taken into account resulting in a good reproduction of the properties of states that contain a coupling of single particle excitation and collective motion [2, 3].

Francium isotopes (Z=87) are reasonably well known at high spin, with all isotopes from A=208 to A=215 having been investigated to some extent prior to this work [4–8], except for ^{210}Fr. Some states from the α-decay of ^{214}Ac into ^{210}Fr had been investigated [9] and another study (Ref. [10]) reported a set of γ-ray transitions from heavy-ion reactions that were erroneously assigned to ^{210}Fr [4]. More recently, Kanjilal *et al.* [11] reported a level scheme for ^{210}Fr that is in significant disagreement with the present work.

In ^{209}Fr and ^{211}Fr [5, 6], enhanced $E3$ transitions observed to depopulate long-lived isomers with $J^\pi = 45/2^-$ have been explained by the $i_{13/2} \rightarrow f_{7/2}$ proton configuration change and coupling with the 3^- octupole vibration. This report is focussed on the observation of a similar isomer in ^{210}Fr, and its decay. The complete level scheme will be presented in a subsequent report [12].

2 Experimental methods

The structure of ^{210}Fr was investigated using the ^{197}Au(^{18}O, 5n)^{210}Fr reaction, with a beam energy of 97 MeV and a 5mg/cm^2 target. Two experiments were performed at the 14UD Pelletron accelerator at the ANU Heavy-Ion Accelerator facility using different beam pulsing conditions. In the first, 1 ns wide pulses separated by 1712 ns were used and prompt and out-of-beam data were collected in order to conduct time correlated γ-γ spectroscopy and lifetime measurements. The analysis of the data revealed the presence of a long-lived isomer and motivated a second experiment using a beam with pulses of 1 μs width with a 9 μs separation, together with an in-beam veto to allow selection of only delayed γ-rays.

The CAESAR array was used to observe the emitted γ-rays. It consists of nine Compton-suppressed high purity Germanium detectors (HPGe) and two low energy photon spectrometers, or LEPS detectors. Six of the HPGe detectors are positioned in pairs in the vertical plane, forming a set of three angles ±97°, ±148° and ±48° relative to the beam direction. This allows angular distributions to be measured. From the data collected, coincidence matrices were built using appropriate time requirements between both the coincident γ-rays and the beam pulse and the γ-ray arrival times. Different techniques were used to perform lifetime measurements. For example, the short lifetime of the 16^- isomer at 2206 keV was measured by projecting time spectra from γ-γ-ΔT cubes with gates on transitions above and below the isomer. For lifetimes greater than a few hundred nanoseconds, the best results were obtained with the 1/9 μs pulsed data, by measuring the time-dependence of coincidence intensity of de-exciting γ-rays. Contamination by coincidences with γ-rays from long-lived decay activities was eliminated by subtracting events late in the time interval, that is, after the isomer had decayed.

3 The high spin isomer in ^{210}Fr at ~4.4 MeV

By using γ-γ-ΔT coincidences and beam-γ coincidences, a level scheme for ^{210}Fr has been deduced. This report focuses on the states observed above a short lived isomer at 2206 keV which are fed by a long-lived high spin isomer. Figure 1 presents a partial level scheme showing the high spin isomer and its associated intermediate decay. The

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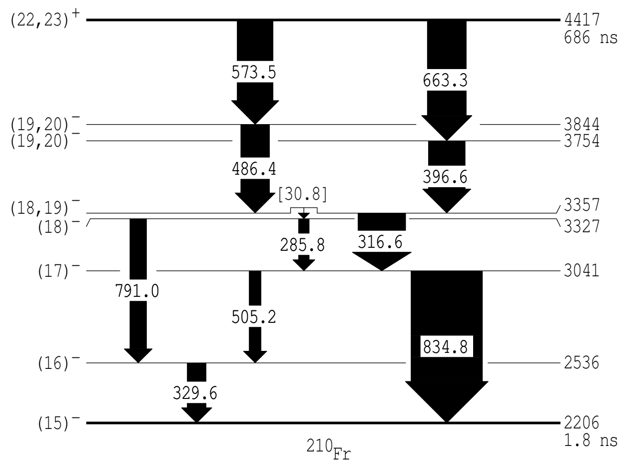

Figure 1. Partial level scheme for ^{210}Fr showing the decay of the isomer at 4417 keV in ^{210}Fr.

Table 1. Properties of selected transitions in ^{210}Fr including intensities, I_γ (measured in the out of beam data), angular anisotropies (A_2/A_0), and proposed spin assignments.

E_γ	$A_2/A_0^{(a)}$	J_i^π	J_f^π
30.8$^{(b)}$			
285.8	−0.35(2)	(18^-)	(17^-)
316.6	+0.34(3)	(19^-)	(17^-)
329.6	−0.42(4)	(16^-)	(15^-)
396.6	−0.28(3)	$(19,20)^-$	(19^-)
486.4	−0.34(4)	$(19,20)^-$	(19^-)
505.2	−0.69(4)	(17^-)	(16^-)
573.5	$^{(c)}$	$(22,23)^+$	$(19,20)^-$
663.3	$^{(c)}$	$(22,23)^+$	$(19,20)^-$
791.0	+0.25(10)	(18^-)	(16^-)
834.8	+0.36(3)	(17^-)	(15^-)

$^{(a)}$ Three-point anisotropy fitted to a second-order Legendre polynomial.
$^{(b)}$ Unobserved low energy transition inferred from coincidence relationships.
$^{(c)}$ Not yet determined.

properties of the transitions are shown in Table 1. We note that the possible presence of gaps (unobserved low energy transitions) in ^{210}Fr is being investigated [12] and could potentially result in an increase of the spins in the present level scheme.

Spectroscopic information available at this stage of the work provides several strong pieces of evidence regarding the nature of some transitions, while the γ-γ coincidence results, such as the spectrum shown in Figure 3, supports the present level scheme. In this spectrum, only transitions from the decay of the high-spin isomer in ^{210}Fr are observed.

The information extracted strongly supports the assignments of the 834.8 and 791.0 keV γ-rays as being $E2$ transitions, which results in $J^\pi = (17)^-$ and $J^\pi = (18)^-$ assignments for the states at 3041 and 3327 keV, respectively. The conversion coefficient and angular distribution for the 329.6 keV γ-ray are in agreement with an $M1/E2$ multipolarity and therefore a $(16)^-$ assignment for the state at 2536 keV. The current information for the 396.6 and 486.4 keV γ-rays suggests dipole assignments, but mixing with higher order multipolarities could occur. As a result, states between, and including, the 3844 and the 2206 keV states probably all have the same parity. The isomeric nature of the level at 4417 keV is obvious from a study of prompt coincidences in which both the 663.3 and the 573.5 keV γ-rays are absent. The lifetime of the isomer has been measured in the experiment with 9 μs chopping to be 686(17) ns (see Figure 2).

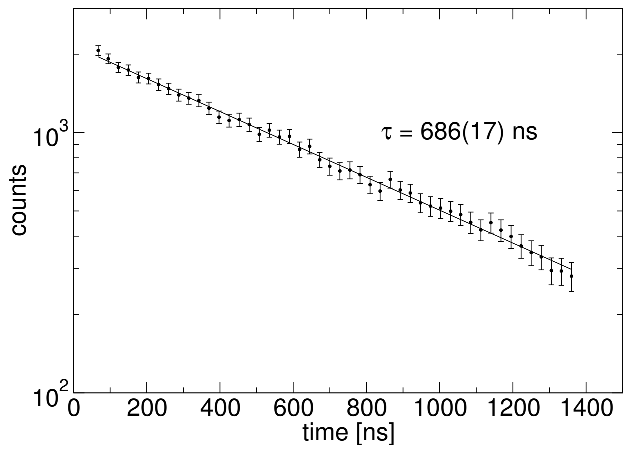

Figure 2. Intensity of γ-ray coincidences below the 4417 keV isomer as a function of time. A lifetime of τ = 686(17) ns is deduced.

4 Discussion

States from the one at 2206 keV up to the state at 3357 keV (see Figure 1) possibly belong to the $\pi(h_{9/2}^4 i_{13/2})\nu(p_{1/2}^{-2} f_{5/2}^{-1})$ multiplet which has a maximum spin of $21\hbar$, while the two states at 3754 and 3844 keV could be either from this multiplet or from the $\pi(h_{9/2}^3 i_{13/2} f_{7/2})\nu(p_{1/2}^{-2} f_{5/2}^{-1})$ configuration for which maximal alignment results in $J^\pi = 23^-$. Higher spin states can only be reached by exciting one more proton to the $i_{13/2}$ shell (or through core excitation) leading to a parity change. Such a configuration change is consistent with the observation of a lifetime for the state at 4417 keV and the presence of enhanced $E3$ transitions.

In ^{209}Fr [5] and ^{211}Fr [6], long lived isomers with $J^\pi = 45/2^-$ have been identified at energies of 4660 and 4658 keV, respectively. The configurations assigned to these isomers are $\pi(h_{9/2}^3 i_{13/2}^2)\otimes\nu(p_{1/2}^{-2} f_{5/2}^{-2})$ and $\pi(h_{9/2}^3 i_{13/2}^2)\otimes\nu(j^{-2})$, respectively, in which the neutron-hole pairs are coupled to zero angular momentum. These configurations correspond to the scenario presented above for ^{210}Fr with the addition of an odd neutron hole in the $f_{5/2}$ orbital: $\pi(h_{9/2}^3 i_{13/2}^2)\otimes\nu(p_{1/2}^{-2} f_{5/2}^{-1})$, for which the maximal spin is 25^+. However, the residual interactions do not favour mutual alignment of high-spin protons and neutron-holes. This is reflected in Figure 4 which shows calculations[1] including

[1] These are first order calculations that may be adjusted in the future to obtain better agreement with the low-lying states.

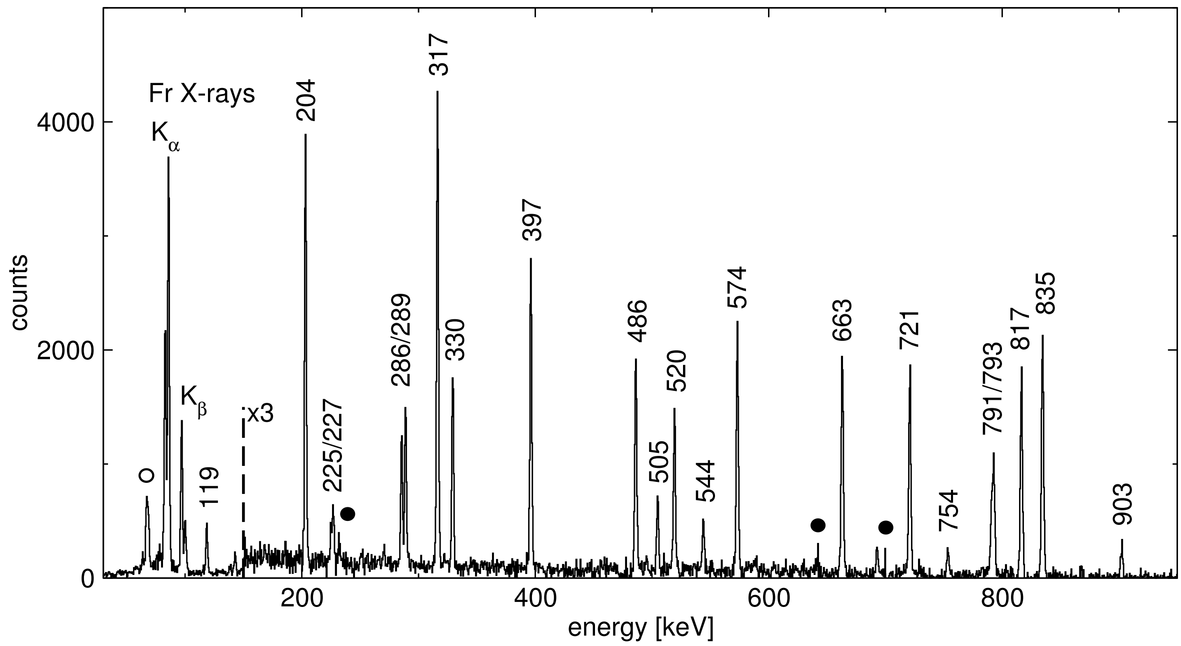

Figure 3. Out of beam γ-ray coincidences for the 256.9 keV transition which is placed lower in the level scheme and follows the decay of the 15^- state (see Figure 1). The open circle denotes known contaminants. Long-lived activities have been subtracted and the filled circles denote subtraction artefacts. The 573.5 and 663.6 keV γ-rays observed here are absent in the in-beam spectrum.

Table 2. Branching ratios and transition strengths for the decay of the 24^+ isomer in ^{210}Fr and comparison with neighbouring odd Fr isotopes.

Nucleus	Initial state τ	Final state J^π	E_γ (keV)	I_γ	$\sigma\lambda$	$\alpha_T{}^a$	Transition strength (W.u.)
^{210}Fr $^{(b)}$	$(22)^+$ 4417 keV						
	686(17) ns	$(19)^-$	663.3	52.9(14)	$E3$	0.0569	8.5(3)
		$(19)^-$	573.5	47.1(12)	$E3$	0.0861	21.0(8)
	$(22)^+$ 4417 keV						
	686(17) ns	$(20)^-$	663.3	52.9(14)	$M2$	0.1980	$6.1(3)\times10^{-3}$
		$(20)^-$	573.5	47.1(12)	$M2$	0.3033	$1.12(4)\times10^{-2}$
	$(22)^+$ 4417 keV						
	686(17) ns	$(20)^-$	663.3	52.9(14)	$M2$	0.1980	$6.6(3)\times10^{-3}$
		$(19)^-$	573.5	47.1(12)	$E3$	0.0861	19.6(8)
^{211}Fr	$45/2^-$ 4657 keV						
	178(20) ns	$39/2^+$	728.3	100(1)	$E3$	0.045	33(4)
^{209}Fr	$45/2^-$ 4660 keV						
	606(26) ns	$39/2^+$	620.2	100.0(2)	$E3$	0.0686	28.8(12)
		$41/2^+$	335.5	1.1(2)	$M2$	1.602	$4.9(9)\times10^{-3}$

$^{(a)}$ For transitions in ^{210}Fr the values are taken from Ref. [13].
$^{(b)}$ For convenience J_i^π and J_f^π only represent one of the possible spin assignment for the states.

residual interactions (see Ref. [2] and references therein) for ^{210}Fr and the two neighbouring isotopes. In ^{210}Fr a number of high spin positive parity states are predicted, although it is not obvious, at first sight, which should be associated with the isomer. The 23^+ state is the favoured candidate however, according to the calculations, there could be a competitive $E2$ γ-decay to a lower 21^+ state. This is not observed, but neither are the equivalent transitions in the neighbouring isotopes, which probably indicates the level of uncertainty in the calculation. This is consistent with the current (tentative) spin assignment for the state and the likely $E3$ decays to the 3844 and 3754 keV states; the latter proposition depends, of course, on the configuration of those states. (Core excitation that could produce high spin positive parity states are unlikely to occur at such low energy.)

For nuclei near A$\sim$208, enhanced $E3$ transition strengths are usually observed when a proton (or proton-hole) de-excites from $|\tilde{i}_{13/2}\rangle$ to $|\tilde{f}_{7/2}\rangle$ and/or when a neutron (or neutron-hole) de-excites from $|\tilde{j}_{15/2}\rangle$ to $|\tilde{g}_{9/2}\rangle$ [1]. The tilde signifies that the states are actually superpositions of the single particle excitation with a coupling of the 3^- phonon (for example $|\tilde{i}_{13/2}\rangle = |i_{13/2}\rangle + |f_{7/2} \otimes 3^-\rangle$), for which the strength has been measured at $\sim$32(2) W.u. [14]. Such $E3$ γ-ray strengths were compiled by Bergström *et al.* [15], and discussed in detail by Byrne *et al.* [6]. The en-

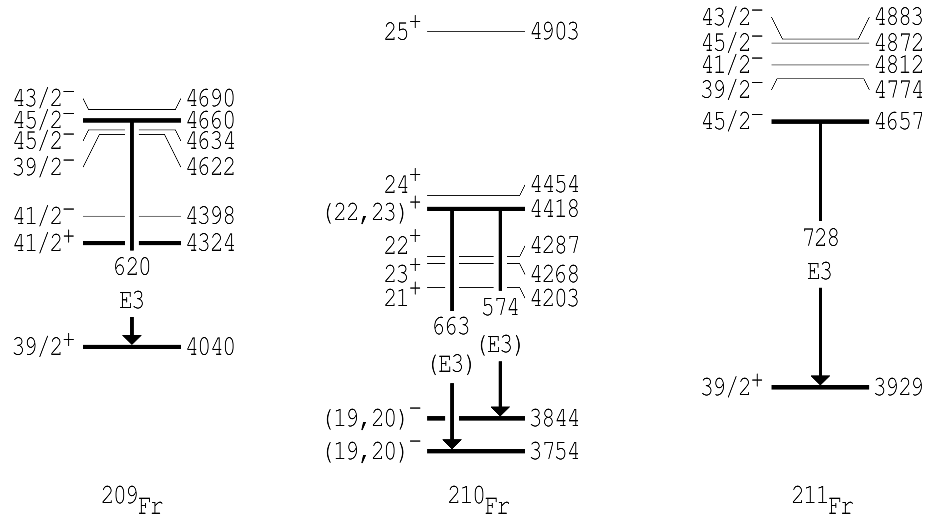

Figure 4. Comparison between experimental energies of the isomer states and calculated energies for the different members of the $h^3_{9/2}i^2_{13/2}$ multiplet (coupled to the appropriate neutron configuration, see text) in ^{209}Fr, ^{210}Fr and ^{211}Fr. Experimental states and transitions are in bold.

hanced strengths for ^{209}Fr and ^{211}Fr [5, 6] (see Table 3) are consistent with the transition strengths expected for the $\tilde{i}_{13/2} \rightarrow \tilde{f}_{7/2}$ proton de-excitation. If the 573.5 and 663.3 keV transitions were to be $E3$, it can be seen in Table 2 that the strengths would be somewhat less enhanced than the typical values observed.

There remains the possibility that the 573.5 and 663.3 keV transitions are of $M2$ multipolarity, which would also lead to a significant lifetime. This would obviously have implications for the configuration of the two lower states. Considering the possible configuration changes, the implied $M2$ strength for the 663.3 keV γ-ray, of $\sim$0.006 W.u., is consistent with a j-forbidden $M2$ transition [5]. One possibility then, is that the state at 3754 keV is a member of the $\pi(h^3_{9/2}i_{13/2}f_{7/2}) \otimes \nu(p^{-2}_{1/2}f^{-1}_{5/2})$ multiplet ($\Delta\ell = 4$ for the transition) but it would not be from the $\pi(h^4_{9/2}i_{13/2}) \otimes \nu(p^{-2}_{1/2}f^{-1}_{5/2})$ multiplet since a transition strength of $\sim$0.1 W.u. would be expected [6]. Similarly, the implied strength for a 573.5 keV $M2$ is lower than allowed $M2$ values but it is also higher than a typical j-forbidden $M2$ transition strength. The issues of the multipolarity of these transitions and the constraints on the configurations of the two states at 3754 and 3844 keV are under investigation.

5 Conclusion

A new level scheme for ^{210}Fr has been established, including a high spin isomer at an excitation energy of 4417 keV with a lifetime of 686(17) ns. The presence of such an isomer was anticipated from the observation of related isomers in the neighbouring nuclei ^{209}Fr and ^{211}Fr. Preliminary analysis suggests that the state arises from the 22$^+$ or 23$^+$ coupling of the $\pi(h^3_{9/2}i^2_{13/2}) \otimes \nu(p^{-2}_{1/2}f^{-1}_{5/2})$ configuration. A more complete analysis of the possibilities for the states discussed here, will be covered in a future report [12].

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