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THE NUCLEAR STRUCTURE OF ^{223}Fr

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ABSTRACT

The γ -rays following the β^- -decay of ^{223}Rn have been investigated by means of γ -ray singles including multispectrum analysis, and $\gamma\gamma$ coincidence measurements using Ge detectors. Multipolarities of 38 transitions in ^{223}Fr have been established by measuring conversion electrons with a mini-orange electron spectrometer. Most of the observed transitions could be placed in a level scheme comprising 53 excited states of ^{223}Fr . The level structure is interpreted in terms of $K^\pi = 3/2^\pm$ and $1/2^\pm$ parity doublet bands, and a second $K^\pi = 3/2^\pm$ higher-lying parity doublet. The experimental data are compared with the theoretical predictions of the reflection-asymmetric rotor model.

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1. Introduction

Recently, both experimental and theoretical investigations have produced evidence for stable octupole deformation in a region of nuclei around $A=225$ (ref.¹) and references quoted therein; see also review article²). The nucleus ^{223}Fr lies close to the border of the region in which octupole deformation is expected. Evidence for octupole deformation has previously been presented for ^{221}Fr (refs.^{3,4}). However, for heavier francium isotopes there was not enough experimental information available to perform a similar analyses. Most of the available information on the ^{223}Fr level structure was obtained from α -decay studies⁵). The ground-state spin was measured with fast-beam high-resolution laser spectroscopy⁶). The anisotropies of several γ transitions in ^{223}Fr were published in ref.⁷).

In the present study we have measured γ -rays and conversion electrons following the β^- -decay of ^{223}Rn . On the basis of all experimental data a detailed level scheme for ^{223}Fr has been constructed. The levels have been grouped into rotational bands and the band properties have been used to test the picture of static octupole deformation in the ^{223}Fr nucleus.

2. Experiments and results

2.1. SOURCE PREPARATION

Radon isotopes were produced by a spallation reaction in a ^{232}Th target, induced by 600 MeV protons from the CERN Synchrocyclotron. After ionization in a plasma discharge ion source the nuclei were mass-separated in the ISOLDE on-line separator⁸). The beam was collimated in order to reduce contaminations from adjacent masses and deflected onto a movable tape system, working in a start-stop mode, to carry the activity in front of the detectors. The separated beam intensity was 7.4×10^5 atoms/ μA .

2.2. MEASUREMENTS OF γ -RAYS

The γ -radiation following the β^- -decay of ^{223}Rn was investigated by γ -ray singles measurements performed with two high-purity Ge detectors of 24 and 34 cm³ active volume (energy resolution: 1.8 keV FWHM at 1333 keV). In addition, the low-energy photons were measured with a high-purity "X-ray" detector (energy resolution: 0.70 keV FWHM at 122 keV), and fig.1 shows a spectrum taken with this detector. The half-life was obtained by means of multi-spectrum analysis (MSA), using cycles of 4 min collection time followed by seven measuring times of 5 minutes each. The spectra were gated by signals from an energy-loss plastic scintillation β -detector, to suppress γ -rays from background activities. A weighted average value of 25.3(4) min for the half-life was found which is somewhat larger than the value of 23.2(4) min given in ref.⁹). For the energy calibration the ^{223}Rn activity was measured simultaneously with a set of standard γ -ray sources ^7Be , ^{54}Mn , ^{57}Co , ^{60}Co , ^{65}Zn , ^{88}Y , ^{133}Ba , ^{137}Cs , ^{139}Ce and ^{241}Am . The same set of absolutely calibrated activities was used for the efficiency calibration of the γ -ray detectors. Energies as well as intensities of the γ -ray transitions assigned to the decay of ^{223}Rn are listed in table 1. The $\gamma\gamma$ coincidence measurements were performed simultaneously with the singles γ -ray measurements. The coincidence events were stored on magnetic tape in event-recorded mode. The taped information was sorted to extract spectra in coincidence with windows set on specific peaks and with similar windows on the neighbouring Compton distribution for background subtraction. Selected coincidence spectra are shown in fig.2.

2.3. MEASUREMENTS OF CONVERSION ELECTRONS

Singles spectra of conversion electrons were measured with the mini-orange electron spectrometer. The detector in the electron spectrometer was a 300 mm² Si(Li) crystal with a thickness of 2 mm, cooled to liquid-nitrogen temperature. Details of the experimental set-up and procedures are given in ref.¹⁰). A singles electron spectrum from the decay of ^{223}Rn is shown in fig.3. The overall energy resolution was ≈ 2.0 keV FWHM. The internal conversion coefficients were deduced from the singles electron and gamma-ray spectra. The measured conversion coefficients are listed in table 2, together with theoretical values¹¹) for E1, E2 and M1 transitions. The dominant multipolarities assigned to the transitions are

also listed. For the 69.21 keV transition, the M1/E2 mixing ratio of $(84.6 \pm 1.5)\%$ M1 + $(15.4 \pm 1.5)\%$ E2 can be obtained from measured conversion coefficients α_{L1+L2} and α_{L3} .

3. Level scheme

3.1. CONSTRUCTION

Most of the observed γ transitions following the β^- -decay of ^{223}Rn were placed in a decay scheme (see figs. 4a – 4d) based on the results of the coincidence experiments and on energy fits. Total transition intensities were determined using theoretical conversion coefficients¹¹⁾. The β -branchings to individual levels were deduced from intensity balances under the assumption of no β -feeding of the ^{223}Fr ground-state (spin $I=3/2$, ref.⁶⁾) from the ^{223}Rn ground-state ($I=7/2$, ref.¹²⁾). In addition, the multipolarity of the unobserved 12.90 keV transition is assumed to be M1 (for a possible E2 admixture see sec.3.2.1). The E1 multipolarity could be excluded from the intensity balance of the 12.90 keV level. Taking the experimental intensity limit of 20 (in units of table 1) and the conversion coefficient¹¹⁾ of 6.5 for the 12.90 keV E1 transition, its total intensity of 130 could be obtained, which is much lower than the summed total intensity of γ transitions feeding the 12.90 keV level (the intensity of the 592.55 keV γ line exceeds already intensity of the 12.90 keV transition – see table 1). Under these assumptions, a factor of 0.0118 should be used to convert relative γ -ray intensities given in table 1 to absolute intensities. This leads to β -branchings of $\approx 24\%$ to the 12.90 keV level and $\approx 22\%$ to the 82.10 keV state, with log ft values of 7.1 and 7.0, respectively. Besides the 12.90 and 82.10 keV levels, two other states at 605.40 and 736.87 keV have relatively high β -feedings of ≈ 14 and $\approx 11\%$, respectively, and log ft = 6.7 for both. The upper limits of β -branch intensities to the 82.10, 605.40 and 736.87 keV levels could be set at 26, 16, and 13%, respectively, under assumptions of no β -feedings to the ground-state and the first excited state at 12.90 keV. This leads to lower limits of the log ft values of 7.0, 6.7 and 6.6 for these levels, respectively. The log ft values obtained indicate that β -transitions from ^{223}Rn to levels considered in ^{223}Fr involve a spin change of 0 or 1. The log ft values were determined using the "f" –tables of ref.¹³⁾ and a Q_β -value of 1.96 MeV (for comments see subsec.4.1). The results are summarized in table

3. The summed intensity of all the γ -rays not placed in the level scheme corresponds to $\approx 4\%$ of the total intensity.

3.2. LEVEL ENERGIES, SPIN AND PARITY ASSIGNMENTS

Previous assignments for levels in ^{223}Fr and their spin-parity values came from the alpha decay of ^{227}Ac , and have been summarized in ref.⁵). All excited states, except those at 370, 380 and 503 keV, were confirmed in the present work. Additionally, 39 new states were introduced in the level scheme of ^{223}Fr . The ground-state spin, $I=3/2$, has been measured with fast-beam laser spectroscopy⁶). Its negative parity is suggested by the log ft values determined in the beta decay of ^{223}Fr (ref.⁵); for the level scheme of ^{223}Ra see refs.^{14,15}). The parities given in table 3 for other levels have been established relative to this ground-state value from the multipolarities of the present work. The new spin assignments allow the interpretation of 19 low-lying levels in terms of 6 rotational bands. These are shown in fig.5, and are discussed separately in the following subsections.

3.2.1. The $I^\pi = 3/2^-$ ground state band

The negative parity levels shown at 12.90 and 82.10 keV in fig.5 can be assigned as 5/2 and 7/2 members, respectively, of a $K = 3/2$ ground-state band. The 69.21 keV and 82.10 keV transitions which depopulate the 82.10 keV level have M1 + E2 and E2 character, respectively, consistent with spin and parity of $7/2^-$ for this level. From the branching ratio $N_\gamma(69.21)/N_\gamma(82.10)$, the M1/E2 ratio can be obtained using the relation

$$\frac{N_\gamma(69.21)}{N_\gamma(82.10)} = \frac{T_\gamma(E2;69.21) + T_\gamma(M1;69.21)}{T_\gamma(E2;82.10)} \quad (1)$$

In the unified model¹⁶), relative values of the transition probabilities $T_\gamma(E2;69.21)$ and $T_\gamma(E2;82.10)$ can be predicted from the Alaga rules. With this assumption the experimental value of 4.26(32) for the branching ratio $N_\gamma(69.21)/N_\gamma(82.10)$ implies that the 69.21 keV gamma transition is $(85.1 \pm 1.1)\%$ M1 + $(14.9 \pm 1.1)\%$ E2, in excellent agreement with the M1/E2 mixing obtained from the conversion electron measurements (see sec.2.3).

The E2/M1 mixing ratio, δ^2 , in the rotational model is related to the intrinsic quadrupole moment Q_0 of the band and g-factors as follows:

$$\delta^2(I+1, K \rightarrow I, K) = 8.7 \times 10^{-7} \frac{E_\gamma^2 (\text{keV})}{I(I+2)} \left(\frac{Q_0(\text{b})}{g_K - g_R} \right)^2 \quad (2)$$

The value of $\delta^2 = 0.175(16)$ for the $E_\gamma = 69.21 \text{ keV } 7/2^- \rightarrow 5/2^-$ transition indicates a value of $Q_0/(g_K - g_R) = 21.7(10) \text{ b/n.m.}$ for the $K = 3/2$ ground-state band. This value of $Q_0/(g_K - g_R)$ can then be used to estimate that the $12.9 \text{ keV } (5/2^- \rightarrow 3/2^-)$ transition should be approximately 98.7% M1 and 1.3% E2. This provides some justification for the M1 multipolarity assumed in sec.3.1.

The I^π values and band assignments deduced from the γ -ray multipolarities are consistent with those deduced from the α -hindrance factors. Since the ground state of the α -decaying parent, ^{227}Ac , has $I^\pi = 3/2^-$ (see discussion in ref.¹⁷), the $I^\pi = 3/2^-$ ground state of ^{223}Fr has an α -hindrance factor of 7.0 (ref.⁵), and its associated band members also have low α -hindrance factors (fig.5).

3.2.2. The $K^\pi = 3/2^+$ band at 160.45 keV

A second rotational band beginning with spin $3/2^+$ at 160.45 keV has $5/2^+$ and $7/2^+$ members at 171.97 keV and 223.03 keV, respectively. The parities of these states are uniquely determined by E1 transitions to the ground-state rotational band. The spin of the state at 160.45 keV is $3/2$ or $5/2$. The reduced γ -branching ratio $B(E1; 147.52) / B(E1; 160.45) = 0.64(4)$ suggests $IK = 3/2 \ 3/2$ for this state. Since γ -rays from the 171.97 keV state go to levels having I^π values of $3/2^-$, $5/2^-$ and $7/2^-$, its spin is uniquely determined to $I^\pi = 5/2^+$. Finally, the state at 223.03 keV decays by three transitions to the $7/2^-$ (82.10 keV state, E1 transition), $3/2^+$ (134.50 keV) and $5/2^+$ (171.97 keV) states, tentatively suggesting a $7/2$ assignment and positive parity. This band, like the ground-state band, does not follow the rotational energy relationships, indicating that these $K^\pi = 3/2^\pm$ bands are significantly perturbed.

3.2.3. The $K^\pi = 1/2^-$ band at 55.00 keV

A rotational band containing levels at 55.00, 99.55, 100.95 and 188.95 (fig.5) with I^π values of $1/2^-$, $3/2^-$, $5/2^-$ and $7/2^-$, respectively, can be assigned. The negative parity of this band was established by observation of M1 transitions to the ground-state rotational band (see table 2). For the 55.00 keV transition the M1 multipolarity was deduced from the experimental total internal conversion coefficient of 24(7). This value was estimated from the coincidence events ratio of the 69.21 and 55.00 keV lines observed in the 140.93 and 79.50 keV gates, respectively. The spin of the state at 55.00 keV is $1/2$, $3/2$ or $5/2$. The non-observation of the 42.10 keV transition between the 55.00 and 12.90 $5/2^-$ states suggests spin $1/2$ for the 55.00 keV level. The state at 99.55 keV has $I^\pi = 3/2^-$, however, spin $5/2$ cannot be excluded. The spin value of $5/2$ is established for the 100.95 keV. For the 188.95 keV level the spin value of $7/2$ is suggested, however, the value of $5/2$ can not be excluded. Using the $3/2^-$, $5/2^-$ and $7/2^-$ band members and the rotational energy relationships

$$E_I = E_0 + (\hbar^2/2J) [I(I+1) + (-1)^{I+1/2} (I + 1/2) a] \quad (3)$$

the zeroth order position of the band head (E_0), the moment of inertia parameter ($\hbar^2/2J$) and the decoupling parameter (a) could be calculated as 63.54 keV, 6.36 keV and 0.956, respectively. The energy for the $1/2^-$ state is then calculated to be 62.2 keV, in good agreement with the observed value of 55.0 keV.

3.2.4. The proposed $K^\pi = 1/2^+$ band

The 134.50 keV level has positive parity established by E1 transitions to the ground-state band, and probably has $I = 3/2$ since it decays to levels with spin $1/2$, $3/2$ and $5/2$. Levels at 219.50 keV and 243.60 keV can be assigned $7/2^+$ and $5/2^+$, respectively. However, the possibility of negative parity cannot be excluded for the latter state. It is proposed that these levels belong to a perturbed $K^\pi = 1/2^+$ band. The three known energies give $E_0 = 125.31$ keV, $\hbar^2/2J = 9.19$ keV, and $a = -1.375$. The calculated energy of the

$1/2^+$ state is then 144.8 keV but this level is not observed. The γ transition between this and the 55.00 keV $1/2^-$ level could be obscured by Fr X-rays.

3.2.5. The $K^\pi = 3/2^-$ band at 519.83 keV

A second rotational $K^\pi = 3/2^-$ band is observed with the band head at 519.83 keV (fig.5). The I^π assignment is based on the observation of a favoured α -decay ($HF=2.0$) from the $3/2^-$ ground-state of ^{227}Ac (ref.⁵). In the β decay of ^{223}Rn the 519.83 keV state is fed weakly ($\log ft > 10.0$). Its energy is determined by two γ transitions of 420.61 and 464.83 keV. Because of the low α -hindrance factor of 7.9, the 605.40 keV state has previously been tentatively assigned⁵) as the $5/2^-$ member of this band. The parity of this state is confirmed by the multiplicities of the deexciting γ transitions indicated in table 2. The relatively high β -feeding to this state (see subsect. 3.1) suggests spin $5/2$; however, $I = 7/2$ cannot be excluded. Finally, the 736.87 keV state is proposed as the $7/2$ band member. Its negative parity is established by four transitions with known multiplicities.

3.2.6. The proposed $K^\pi = 3/2^+$ band at 449 keV

The assignment of spin values $3/2^+$, $5/2^+$ and $7/2^+$ to the 449, 540.50 and 684.85 states, respectively, (creating a $K^\pi = 3/2^+$ band as shown in fig.5) must be considered very tentative. The state at 449 keV was observed only in the α -decay of ^{227}Ac , and has an α -hindrance factor of ≈ 105 (ref.⁵). The state at 540.50 keV has a low α -hindrance factor of 11. In the β -decay of ^{223}Rn this state is fed with $\log ft \approx 8.6$. The conversion electron data (table 2) do not determine the parity of this state. Positive parity for the 684.85 keV level is proposed because of the M1 multipolarity for the 461.81 keV γ transition which deexcites this state to the 223.03 ($7/2$)⁺ level.

3.2.7. The $K^\pi = 5/2^-$ band at 187.02 keV

The energy levels at 187.02 and 244.64 keV are tentatively assigned as the $5/2$ and $7/2$ members, respectively, of a $K^\pi = 5/2^-$ rotational band. The spin value of $5/2$ and negative parity are established for the 187.02 keV state. For the 244.64 keV level the spin value of

7/2 is suggested, however, the value of 5/2 can not be excluded. Its negative parity is consistent with multipolarities of the deexciting γ transitions. Both of these states have relatively low α -hindrance factors (fig.5).

3.2.8. Other established levels

In the energy region below 600 keV all levels observed in the present work are classified into rotational bands (fig.5), except those at 242.45 and 365.60 keV. The states at 370, 380 and 503 keV were observed only in the α -decay of ^{227}Ac (ref.⁵). In addition to the levels discussed in subs. 3.2.1. – 3.2.7., 35 states are observed above an excitation energy of 600 keV. The states at 647.55, 649.60 and 782.65 keV are assigned as $5/2^-$, $5/2^-$ and $5/2^+$, respectively. Definitive spin and parity assignments for all other levels cannot be made on the basis of the data presently available.

4. Comparison of the experimental data with theoretical predictions of the reflection – asymmetric rotor model

4.1. GROUND-STATE PROPERTIES

For ^{223}Fr the experimental and calculated ground-state spin, parity, spectroscopic magnetic dipole and electric quadrupole moments were discussed in detail by Leander and Chen¹⁸). The theoretical calculations were performed by coupling states of a deformed shell model including octupole deformation to a reflection-asymmetric rotor core. Leander and Chen¹⁸) reproduced the ground-state spin and parity $I^\pi = 3/2^-$ in ^{223}Fr . The magnetic moment of 1.22 n.m. calculated in the presence of octupole deformation was consistent with the experimental value of 1.17(2) n.m. (ref.⁶). Recently, Cwiok and Nazarewicz¹⁹) have calculated non-collective single-particle states in odd-A actinide nuclei using the reflection-asymmetric mean field approach with an average Woods-Saxon potential and a monopole pairing residual interaction. The equilibrium deformations were calculated independently for each low-lying one-quasiparticle state. According to the calculations¹⁹) the nucleus ^{223}Fr has a deformed $I^\pi = 3/2^-$ ground-state (in the calculations the $1/2^-$ and

$3/2^-$ levels are practically degenerated). Calculated octupole barriers¹⁹⁾ for the $\Omega = 1/2$ and $3/2$ orbitals in ^{223}Fr are approximately 400 keV.

According to Leander and Chen¹⁸⁾ the $I = 7/2$ [ref.¹²⁾] ground-state in the parent nucleus ^{223}Rn has a complex structure and has been interpreted in terms of mixing with another $7/2$ states, based mainly on the $\Omega = 7/2$ and $1/2$ orbitals. The potential energy surfaces calculated by Cwiok and Nazarewicz¹⁹⁾ for the low-lying band heads in ^{223}Rn are much more octupole-soft than in the heavier $N = 137$ isotones.

A Q_β value of 1.35 MeV is obtained from the atomic masses of ^{223}Rn and ^{223}Fr predicted by Moller and Nix²⁰⁾. This value is lower than 1695.45 keV, the highest excited state energy experimentally observed in ^{223}Fr (see table 3). The inclusion of octupole deformation ($\epsilon_3 \approx 0.08$) in the theoretical mass calculations raises Q_β for the $^{223}\text{Rn} \rightarrow ^{223}\text{Fr}$ decay by 0.61 MeV (refs.^{21,22)}), and leads to predicted Q_β value of 1.96 MeV.

4.2.INTERPRETATION IN TERMS OF PARITY - DOUBLETS

For odd-A nuclei with a stable octupole deformation the rotational bands with degenerate states of the same spin but opposite parity are expected. Fig.5 shows the levels of ^{223}Fr grouped in rotational bands. These bands, assigned above, may be collected into $K^\pi = 3/2^\pm$ and $1/2^\pm$ parity doublet bands, and a second $K^\pi = 3/2^\pm$ higher-lying parity doublet band. The parity splitting (the energy splitting between states of the same spin but opposite parity) is 160.45 keV for the first $K^\pi = 3/2^\pm$ bands. The low hindrance factor (≈ 34) for the alpha transition⁵⁾ to the 160.45 keV level is consistent with an $I^\pi = 3/2^+$ assignment for the band head of the parity doublet $K = 3/2$ band.

The relatively low α -hindrance factors to the states of the $K^\pi = 1/2^\pm$ bands (fig.5) suggest appreciable Coriolis mixing with the states of the $K^\pi = 3/2^\pm$ bands. The α -hindrance factor to the $I^\pi = 1/2^-$ state at 55.00 keV is rather high (1150), since the Coriolis mixing cannot bring in any admixtures of the $K^\pi = 3/2^-$ levels that are populated by allowed unhindered transitions. The decoupling parameter values of the $K^\pi = 1/2^\pm$ bands have similar magnitudes but opposite signs ($a = 0.956$ and -1.375), as expected for an octupole

deformed nucleus. A second $K = 3/2$ parity doublet may be formed by the $K^\pi = 3/2^-$ and $K^\pi = 3/2^+$ bands at 519.83 and 449 keV, respectively, as described in subsec.3.2.5 and 3.2.6.

4.3. ENERGY LEVEL SYSTEMATICS

Following the method of Leander and Chen¹⁸⁾ the low-energy spectrum of ^{223}Fr has been calculated as part of the present study. Fig.6 shows a comparison of the experimental and predicted levels. The calculations were performed using the standard set of parameters¹⁸⁾ with an octupole deformation $\beta_3 = 0.1$. The theoretical model reproduces the ordering of the low-lying band heads of $K^\pi = 3/2^\pm$ and $K^\pi = 1/2^\pm$ that are seen experimentally. The calculated energy spacings between the parity doublet bands are smaller than the experimental values, which could result from soft octupole deformation. The experimentally observed second $K^\pi = 3/2^+$ and $K^\pi = 3/2^-$ doublet is reproduced by the present calculations, with predicted band heads at 589 and 541 keV, respectively. However, the relatively small moments of inertia suggest that the calculated bands are strongly perturbed in the comparison with the observed bands. In the experimental level structure the states at 187.02 and 244.64 keV are tentatively assigned to a $K^\pi = 5/2^-$ band (fig.5), that is much lower than the predicted band heads of 890 and 936 keV for the $K^\pi = 5/2^-$ and $5/2^+$ parity doublet, respectively. Besides the second $K^\pi = 3/2^\pm$ parity doublet, the theoretical calculations also predict another $K^\pi = 1/2^\pm$ parity doublet. However, the experimental assignment of this $K^\pi = 1/2^\pm$ doublet is not possible based on the present data. Previously such a "sister" doublet was identified in the nucleus ^{227}Ac [ref.18)]. Two doublets with opposite signs of the parity splittings were already predicted in the schematic four-level model²³⁾. The existence of a second parity doublet with the same K value was also predicted by Piepenbring²⁴⁾ using the extension of the multiphonon method. However, calculated data are not available for Fr isotopes.

According to the recent calculations of Cwiok and Nazarewicz¹⁹⁾ in the octupole deformed nucleus ^{223}Fr the lowest one-quasiparticle band head energies are $\Omega = 1/2$ (0 keV), $3/2$ (5 keV), $1/2$ (422 keV) and $3/2$ (434 keV) orbitals with parity contents of -0.48 , -0.24 , $+1$

and -0.46 , respectively. For these states (except for the 422 keV state) the calculated octupole barriers are around 400 keV, which is smaller than for $^{219,221}\text{Fr}$.

4.4. ELECTRIC DIPOLE MOMENT

In octupole deformed nuclei a large E1 moment may arise. Such a moment should manifest itself by very enhanced E1 transitions between rotational states of the parity doublet bands.

Between the 223.03 and 171.97 keV levels in ^{223}Fr , interpreted as $7/2^+$ and $5/2^+$ rotational states of a $K = 3/2$ band (figs.4a and 5), the 51.06 keV γ transition is identified.

Its total intensity of $35(10)$, in table 1 units, is established from $\gamma\gamma$ coincidences (table 2). Taking a value of $Q_0 / g_K - g_R = 21.7(10)$, as for the ground-state band (see 3.2.1), the character of the 51.06 keV transition can be estimated as $91.3\% \text{ M1} + 8.7\% \text{ E2}$. The γ branching ratio of the 140.93 keV ($7/2^+ \rightarrow 7/2^-$) and 51.06 keV ($7/2^+ \rightarrow 5/2^+$) transitions permits the $B(E1) / B(E2)$ ratio to be obtained. In the unified model these ratios are related to intrinsic electric multipole moments, Q_λ :

$$\frac{B(E1; I+1, K \rightarrow I+1, K)}{B(E2; I+1, K \rightarrow I, K)} = \frac{4}{5} \left(\frac{Q_1}{Q_0} \right)^2 \frac{(2I+3) \cdot I}{(I+K+1) \cdot (I-K+1)} \quad (4)$$

The obtained ratio of $B(E1) / B(E2) = (2.7 \pm 0.8) \cdot 10^{-7} \text{ fm}^{-2}$ leads to the electric dipole moment value of $Q_1 = 0.24 \pm 0.04 \text{ e} \cdot \text{fm}$ for ^{223}Fr , under the assumption of the same quadrupole moments of $Q_0 = 585(5) \text{ e} \cdot \text{fm}^2$ [refs. ^{6,25}] for the parity doublet bands and independent of spin. This result could be compared with the experimental electric dipole moments which are of the order of $0.1 - 0.3 \text{ e} \cdot \text{fm}$ in the neighbouring octupole deformed Ra [ref. ²⁶] and Th [ref. ²⁷] nuclei. The recent theoretical calculations^{28,29}) explained the observed trends of E1 moments in Ra and Th nuclei. However, theoretical data are not available for Fr isotopes.

5. Conclusion

In the present experiment, the γ -rays following the β -decay of ^{223}Rn have been investigated. Multipolarities of 38 transitions in ^{223}Fr were determined. Most of the observed transitions could be placed in a level scheme comprising 53 excited states of ^{223}Fr .

On the basis of the present β -decay and previous α -decay studies⁵⁾, most of the observed ^{223}Fr levels below 600 keV could be assigned to $K^\pi = 3/2^\pm$ and $1/2^\pm$ parity doublet bands, and a second $K^\pi = 3/2^\pm$ parity doublet. There is overall agreement between the experimental data and theoretical predictions of the reflection - asymmetric rotor model.

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Figure captions

Fig.1. Singles γ -ray spectrum of ^{223}Rn measured with the "X-ray" detector. Measuring cycle: 2 min collection, 35 min counting.

Fig.2. Gamma-ray spectra in coincidence with the 622.3 keV and 634.7 + 635.8 + 636.8 keV transitions in ^{223}Fr . The appropriate spectra coincident with the Compton distribution close to the gated peaks have been subtracted.

Fig.3. Electron spectrum from the decay of ^{223}Rn to ^{223}Fr . Measuring cycle: 120s collection, 120s counting. Peaks are labelled with internal conversion lines which contribute to their intensity. The inset shows the lower-energy part of the spectrum.

Fig.4a. Level scheme of ^{223}Fr constructed with γ -rays from ^{223}Rn decay. The dots indicate coincidences.

Fig.4b. Level scheme of ^{223}Fr (continued).

Fig.4c. Level scheme of ^{223}Fr (continued).

Fig.4d. Level scheme of ^{223}Fr (continued).

Fig.5. Rotational bands in ^{223}Fr . Alpha decay hindrance factors, HF, taken from ref.⁵), are given above or below the levels. The lower limits of HF factors are indicated in parenthesis.

Fig.6. Experimental levels (solid lines) and calculated levels
with spin $I \leq 11/2$ (dashed lines) below 1000 keV in ^{223}Fr .

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TABLE 1

Energies, intensities and placements in the level scheme
of γ -rays following the decay of ^{223}Rn

γ -ray energy (keV)	Relative γ -ray intensity	Initial level (keV)
12.90 ^{a,b}	≤ 20	12.90
25.95 ^{a,b}	26(8) ^c	160.45
37.47 ^{a,b}	140(40) ^c	171.97
45.95 ^{a,b}	$\approx 150^c$	100.95
51.06 ^{a,b}	35(10)	223.03
52.52 ^{a,b}	24(5) ^c	187.02
53.3(3) ^a	≈ 3.0	242.45
55.00(5)	10.2(4)	55.00
55.80(5)	3.4(4)	244.64
57.56(5)	2.8(4)	244.64
69.21(5)	185(10)	82.10
70.60(10)	3.7(5)	242.45
72.4(2) ^a	6.7(13)	171.97
76.30(10) ^d	1.7(5)	
79.50(10)	62(10) ^a	134.50
82.10(5)	43.4(22)	82.10
83.0(1) ^a	≈ 1.5	243.60
83.24(5)	330(13)	Fr-XK α_2
85.0(5) ^a	≈ 1.0	219.50
86.10(5)	580(30)	Fr-XK α_1
86.1(1) ^a	48(5)	187.02
86.7(3) ^a	≈ 12	99.55
88.0(1) ^a	≈ 50	100.95
88.0(1) ^a	11.0(14)	188.95
88.5(5) ^a	≈ 1.0	223.03
89.90(5)	17.4(15)	171.97
96.82(5)	68(5)	Fr-XK β
97.47(5)	128(7)	Fr-XK β
99.55(5)	25(2)	99.55
100.20(5)	56(3)	Fr-XK β
100.95(5)	76(4)	100.95
104.87(5)	35(2)	187.02
106.80(5)	50(3)	188.95
118.58(10)	2.7(6)	219.50
121.58(5)	51.5(20)	134.50
134.50(5)	24.0(20)	134.50
137.35(5)	35.4(14)	219.50
140.93(5)	214(7)	223.03
142.74(5)	9.4(4)	365.60
143.65(5)	23.3(9)	244.64
146.0(2) ^a	1.8(6)	365.60
147.52(5)	38.0(15)	160.45
159.08(5)	57.0(21)	171.97
160.45(5)	76.5(30)	160.45
161.38(5)	15.1(6)	243.60

TABLE 1— continued

γ -ray energy (keV)	Relative γ -ray intensity	Initial level (keV)
162.50(5)	49.5(20)	244.64
171.95(5)	$\equiv 100$	171.97
174.15(5)	25.0(10)	187.02
176.10(5)	16.0(6)	188.95
206.65(5)	81.1(32)	219.50
216.40(5)	19.0(8)	999.15
229.60(5)	8.6(4)	242.45
231.79(5)	6.5(4)	244.64
242.41(5)	6.6(4)	242.45
243.69(5)	24.9(12)	243.60
283.45(5)	11.0(5)	365.60
319.5(5) ^a	≈ 4	684.85
351.8(5) ^a	4.0(15)	540.50
360.73(5)	32.6(13)	605.40
382.0(5) ^a	2.0(6)	605.40
385.32(10)	4.3(2)	1070.10
397.8(5) ^a	≈ 3	763.25
402.80(5)	15.4(7)	647.55
404.7(5) ^a	4.2(14)	649.60
416.52(5)	355(14)	605.40
420.61(20)	1.0(2)	519.83
424.76(10)	2.3(3)	647.55
428.10(20) ^d	1.1(2)	
439.60(5)	8.8(5)	540.50
441.08(5)	14.0(6)	540.50
458.65(5)	32.6(12)	647.55
460.85(10)	14.9(6)	649.60
461.81(5)	30.3(12)	684.85
464.83(10)	7.2(4)	519.83
477.8(3) ^a	4.5(9)	649.60
485.85(20) ^d	1.4(2)	
492.21(5)	112(3)	736.87
493.3(3) ^a	≈ 10	736.87
498.30(20) ^d	1.4(2)	
499.75(10) ^d	4.5(3)	
502.59(10) ^d	7.3(4)	
504.35(10)	2.6(2)	605.40
505.85(5)	25.3(13)	605.40
509.75(10)	12.1(6)	698.60
514.3(5) ^a	3(1)	736.87
517.8(5) ^a	4(1)	736.87
520.75(5)	6.6(4)	763.25
523.26(5)	72.8(30)	605.40
526.52(10)	7.3(4)	698.60
527.60(10)	7.2(4)	540.50
532.80(20) ^d	1.6(2)	
540.40(5)	18(6) ^a	540.50
540.4(5) ^a	6(2) ^a	763.25
540.4(5) ^a	6(2) ^a	782.65
543.70(10)	2.8(2)	763.25

TABLE 1— continued

γ -ray energy (keV)	Relative γ -ray intensity	Initial level (keV)
546.53(5)	65.6(26)	647.55
548.0(3) ^a	12(3)	736.87
548.55(5)	36(3) ^a	649.60
550.10(5)	19.9(10)	649.60
559.10(20) ^d	1.3(3)	
563.10(10)	5.4(3)	782.65
565.52(5)	44.3(20)	647.55
566.8(5) ^{a,d}	8.6(21)	
567.60(5)	26.1(14)	649.60
571.75(5) ^d	20.6(11)	
576.10(5)	19.1(10)	763.25
578.40(20) ^d	1.3(2)	
590.1(3) ^a	8(2)	834.50
590.9(3) ^a	≈ 10	834.50
591.3(5) ^a	5(2)	763.25
592.55(5)	555(23)	605.40
595.80(10)	5.9(6)	839.30
605.40(10)	9.2(5)	605.40
610.65(5)	19.4(8)	782.65
619.65(10)	7.2(4)	839.30
622.25(5)	86.7(35)	782.65
634.65(10)	36.1(40)	647.55
635.80(10)	320(13)	736.87
636.75(10)	76.5(40)	649.60
641.00(20) ^d	1.7(2)	
645.50(10) ^d	3.4(2)	
647.75(10)	5.2(3)	647.55
648.1(5) ^a	3.7(10)	782.65
649.73(5)	187(7)	649.60
654.78(5)	253(10)	736.87
659.10(20) ^d	1.2(2)	
665.20(10) ^d	2.2(2)	
667.35(5)	9.2(5)	839.30
669.70(5)	13.1(5)	892.60
673.20(5)	22.3(11)	892.60
674.25(20)	2.9(4)	834.50
676.88(20) ^d	2.0(3)	
680.80(20) ^d	2.5(2)	
687.55(10) ^d	3.5(3)	
690.11(20) ^d	1.7(2)	
691.90(20) ^d	1.0(2)	
698.90(20)	1.8(2)	698.60
705.44(10)	3.6(3)	892.60
707.60(20) ^d	1.1(2)	
709.80(20) ^d	1.3(2)	
719.80(20) ^d	1.3(3)	
724.00(5)	141(6)	736.87
734.55(10)	15.5(6)	921.60
736.75(10)	19.6(8)	736.87
744.15(10)	6.3(3)	987.75

TABLE 1— continued

γ -ray energy (keV)	Relative γ -ray intensity	Initial level (keV)
750.80(20)	1.4(2)	763.25
752.40(5)	25.0(25)	834.50
753.75(10)	12.3(6)	1359.15
762.90(20)d)	1.5(3)	
781.70(10)	6.0(4)	1322.10
782.60(10)	3.9(4)	782.65
788.10(10)d)	4.6(4)	
791.30(20)	1.7(2)	892.60
793.80(20)	2.1(2)	1399.15
795.20(20)d)	2.2(2)	
800.00(20)	2.6(3)	1042.30
801.60(20)d)	1.5(2)	
803.10(20)d)	1.6(2)	
810.60(20)	1.2(2)	892.60
812.50(20)	1.2(2)	1035.25
815.55(10)	4.8(3)	1035.25
818.60(10)	27.5(11)	1359.15
821.65(20)	2.7(2)	834.50
825.90(20)d)	1.7(2)	
827.40(20)	2.3(3)	999.15
830.00(10)	4.1(3)	1001.95
835.20(20)	3.4(3)	995.60
841.50(10)	8.9(4)	1001.95
847.05(10)	12.2(5)	1070.10
850.65(10)	4.5(3)	1070.10
854.00(20)d)	2.4(2)	
855.95(10)d)	4.1(21)	
858.50(10)	3.4(3)	(1102.80)
863.45(10)	3.3(3)	1035.25
866.35(20)d)	2.9(4)	
867.45(10)	5.4(5)	1001.95
873.15(10)d)	4.1(3)	
881.80(10)	5.7(4)	1042.30
883.0(5) ^a	3(1) ^a	1102.80
883.05(10)	12(2) ^a	1070.10
891.20(20)d)	1.5(2)	
892.80(20)	2.0(2)	892.60
894.60(10)	10.2(4)	995.60
898.10(10)	10.5(4)	1070.10
900.80(10)	3.5(3)	1035.25
902.40(20)d)	2.3(3)	
908.40(20)d)	1.7(2)	
913.75(10)	5.9(3)	1102.80
915.75(10)	5.7(3)	1102.80
918.45(10)d)	4.5(4)	
919.80(20)d)	2.8(3)	
931.30(10)	4.7(4)	1120.25
935.45(10)d)	9.4(4)	
942.40(10)	11.9(5)	1102.80
944.30(10)	7.4(4)	999.15

TABLE 1— continued

γ -ray energy (keV)	Relative γ -ray intensity	Initial level (keV)
948.45(10)	28.8(12)	1120.25
953.30(10) ^d	5.5(3)	
956.65(10) ^d	9.5(4)	
959.85(10)	7.3(3)	1120.25
962.80(10) ^d	11.5(5)	
975.68(10) ^d	3.0(2)	
977.40(20)	1.3(2)	1221.10
982.70(10)	2.4(3)	
984.30(10) ^d	2.8(3)	
988.34(5) ^d	21.4(11)	1512.45
992.40(20)	1.9(3)	
995.70(20)	1.4(3)	
998.15(10)	5.3(3)	1221.10
1000.30(10) ^d	3.1(3)	
1001.85(10)	7.5(4)	
1004.45(10) ^d	3.7(4)	1102.80
1011.76(10) ^d	2.7(3)	
1017.80(10) ^d	6.2(3)	
1019.90(3) ^d	1.3(2)	
1022.80(10) ^d	3.4(3)	
1029.70(10) ^d	5.6(3)	
1030.90(20) ^d	3.2(5)	1552.10
1032.22(10)	10.3(7)	
1037.90(10)	4.7(3)	
1044.80(20) ^d	1.9(2)	1120.25
1052.60(20) ^d	1.5(2)	
1054.90(20) ^d	1.2(3)	
1070.50(10) ^d	5.9(7)	
1075.70(3) ^d	1.2(3)	
1077.40(10)	3.7(3)	
1082.40(10) ^d	2.5(3)	1322.10
1087.60(10) ^d	4.0(3)	
1090.00(10)	4.9(3)	
1094.15(10) ^d	3.5(3)	1102.80
1099.30(10)	4.1(3)	
1102.80(20)	1.6(2)	
1107.30(20)	1.8(2)	1120.25
1118.50(10) ^d	4.7(6)	
1133.6(5) ^d	1.6(3)	
1135.25(10) ^d	3.7(4)	
1139.50(10)	2.7(3)	
1150.10(20) ^d	1.7(3)	
1154.50(10)	5.3(3)	1359.15
1156.70(10)	4.4(3)	
1161.00(10) ^d	2.9(3)	
1170.15(10)	3.0(3)	1399.15
1175.30(10)	3.6(3)	
1187.10(10)	5.2(3)	
1208.20(10)	3.7(3)	1221.10
1210.20(10)	4.3(3)	
		1399.15

TABLE 1— continued

γ -ray energy (keV)	Relative γ -ray intensity	Initial level (keV)
1221.10(10)	2.4(3)	1322.10
1229.60(10) ^d	3.5(3)	
1239.95(10)	14.6(8)	1322.10
1246.60(20) ^d	3.5(4)	
1248.80(20) ^d	2.7(4)	
1249.80(20) ^d	1.8(3)	
1258.20(10)	3.2(3)	1359.15
1268.85(10)	5.9(3)	1512.50
1277.30(20)	2.6(3)	1359.15
1286.10(20) ^d	1.7(3)	
1296.25(10)	11.6(6)	1540.70
1298.20(10)	9.3(5)	1399.15
1304.60(10) ^d	3.0(3)	
1307.50(10)	8.2(5)	1552.10
1309.50(20)	1.8(3)	1322.10
1313.20(10) ^d	3.9(3)	
1315.90(20)	2.5(3)	1398.30
1317.60(10)	14.3(8)	1540.70
1329.10(10)	7.5(4)	1552.10
1332.60(10)	8.4(4)	1552.10
1350.80(10)	3.5(3)	1573.80
1353.80(20) ^d	1.9(3)	
1358.90(20)	1.5(2)	1359.15
1365.50(20) ^d	2.0(3)	
1367.4(5) ^a	3.0(10)	1590.80
1368.7(5) ^a	2.4(8)	1540.70
1369.3(5) ^d	2.2(5)	
1371.40(20)	2.6(3)	1595.00
1375.40(20)	3.8(4)	1595.00
1379.70(20)	2.4(3)	1552.10
1385.70(20)	2.6(3)	1398.30
1390.60(20) ^d	2.2(3)	
1394.8(5) ^a	1.6(5)	1566.70
1402.0(5)	3.1(5)	1590.80
1403.40(10)	11.2(6)	1590.80
1406.20(20)	7.4(5)	1566.70
1407.70(20) ^d	5.4(5)	
1409.70(10)	11.2(6)	1629.30
1423.25(10)	6.7(5)	1595.00
1435.80(20) ^d	1.9(3)	
1439.80(10)	4.8(4)	1540.70
1451.30(20)	2.8(3)	1552.10
1470.90(20) ^d	1.7(3)	
1472.8(5)	1.4(3)	1573.80
1475.80(20) ^d	1.8(3)	
1491.60(20)	2.9(3)	1573.80
1506.5(5) ^d	1.2(2)	
1513.00(20)	1.6(2)	1595.00
1535.00(20)	2.4(2)	1695.45
1540.50(20)	3.9(3)	1540.70

TABLE 1— continued

γ -ray energy (keV)	Relative γ -ray intensity	Initial level (keV)
1547.40(20)	2.1(2)	1629.30
1563.6(5) ^{d)}	1.3(2)	
1565.9(5)	1.1(2)	1566.70
1620.6(5) ^{d)}	1.1(2)	

a) Data from coincidence measurements.

b) Energy corresponds to the spacings of known levels in ^{223}Fr .

c) Total transition intensity.

d) γ -rays not placed in the level scheme.

TABLE 2

Internal conversion coefficients for ^{223}Fr transitions

Transition energy (keV)	Initial level (keV)	Conversion shell	Internal conversion coefficients			Dominant multi- polarity		
			Theoretical ¹¹⁾					
			Experiment	E1	E2		M1	
55.00	55.00	L + M + ...	24(7) ^{a)}	0.54	155	17.2	M1 + (E2)	
57.56	244.64	L	9.8(39)	0.36	93.2	11.5	M1	
69.21	82.10	L _I + II	8.2(13)	0.16	20.8	6.6	}	M1 + (E2)
		L _{III}	2.88(35)	0.063	17.0	0.043		
82.10	82.10	L _I + II	11(4)	0.10	9.5	4.0	}	E2
		M	3.4(10)	0.034	4.6	0.97		
99.55	99.55	L	2.8(5)	0.083	6.7	2.3	}	M1
100.95	100.95	L	2.4(5)	0.080	6.3	2.2		
		M	0.52(9)	0.019	1.7	0.54	}	M1
104.87	187.02	M	0.34(15)	0.017	1.4	0.47		
106.80	188.95	L	2.1(4)	0.069	4.9	1.9	M1	
121.58	134.50	L	<0.18	0.050	2.8	1.3	E1	

TABLE 2— continued

Transition energy (keV)	Initial level (keV)	Conversion shell	Internal conversion coefficients				Dominant multi- polarity	
			Experiment	Theoretical ¹¹⁾				
				E1	E2	M1		
134.50	134.50	L	<0.05	0.038	1.7	0.98	E1	
140.93	223.03	L	≤0.03	0.034	1.4	0.86	E1	
143.65	244.64	L	0.71(14)	0.032	1.3	0.81	M1	
160.45	160.45	L	<0.044	0.024	0.80	0.59	E1	
162.50	244.64	L	0.69(14)	0.023	0.76	0.57	M1,E2	
171.95	171.97	L	<0.07	0.020	0.59	0.49	E1	
176.10	188.95	L	0.50(10)	0.019	0.53	0.45	M1,E2	
206.65	219.50	K	<0.08	0.066	0.15	1.6	}	
		L	0.014(5)	0.013	0.26	0.29		E1
360.73	605.40	K	0.32(6)	0.019	0.048	0.34	M1	
402.80	647.55	K	0.27(6)	0.015	0.038	0.25	M1	
416.52	605.40	K	0.23(3)	0.014	0.036	0.23	}	
		L	0.044(7)	0.0024	0.017	0.041		M1
		M	0.014(3)	0.00057	0.0046	0.010		

TABLE 2— continued

Transition energy (keV)	Initial level (keV)	Conversion shell	Internal conversion coefficients				Dominant multi- polarity
			Experiment	Theoretical ¹¹⁾			
				E1	E2	M1	
458.65	647.55	K	0.22(3)	0.011	0.029	0.18	M1
460.85	649.60	K	0.17(4)	0.011	0.029	0.18	M1
461.81	684.85	K	0.17(4)	0.011	0.029	0.17	M1
492.21	736.87	K	0.14(2)	0.0098	0.026	0.15	}
		L	0.029(6)	0.0017	0.010	0.026	
523.26	605.40	K	0.14(2)	0.0087	0.023	0.13	M1
546.53	647.55	K	0.12(2)	0.0080	0.021	0.11	M1
565.52	647.55	K	0.057(17)	0.0075	0.020	0.10	M1 + E2
567.60	649.60	K	0.065(17)	0.0074	0.019	0.10	M1 + E2
571.75	—	K	0.17(5)	0.0073	0.019	0.10	M1
576.10	763.25	K	<0.06	0.0072	0.019	0.098	E1 or E2
592.55	605.40	K	0.070(7)	0.0068	0.018	0.091	}
		L	0.0130(13)	0.0011	0.0058	0.016	
		M	0.0052(10)	0.00027	0.0015	0.0038	M1 + E2

TABLE 2— continued

Transition energy (keV)	Initial level (keV)	Conversion shell	Internal conversion coefficients				Dominant multi- polarity
			Experiment			Theoretical ¹¹⁾	
			E1	E2	M1		
605.40	605.40	K	<0.05	0.0065	0.017	0.086	E1 or E2
622.25	782.65	K	0.066(10)	0.0062	0.016	0.080	M1 + (E2) ^{b)}
634.65	647.55	K	0.061(6) ^{b)}	0.0059	0.016	0.075	M1 + (E2) ^{b)}
635.80	736.87						
649.73	649.60	K	0.058(6)	0.0057	0.015	0.071	M1
		L	0.019(4)	0.00094	0.0044	0.013	
654.78	736.87	K	0.051(6)	0.0056	0.015	0.070	M1
		L	0.015(3)	0.00092	0.0043	0.012	
724.00	736.87	K	0.038(6)	0.0046	0.012	0.054	M1 + E2

a) Value from coincidence measurements.

b) The conversion coefficient shown is the average value for the two lines which are not resolved in the electron spectrum. It is consistent with both transitions being M1 + (E2).

TABLE 3
Properties of energy levels in ^{223}Fr

Level energy (keV)	I^π	β -branching %	log ft	Previously assigned level energies ^{b)}
0(g.s.)	$3/2^-$	0 ^{a)}	—	0
12.90(5)	$5/2^-$	24	7.1	12.6
55.00(5)	$1/2^-$	<1.2	>8.3	54
82.10(5)	$7/2^-$	22	7.0	82.8
99.55(5)	$3/2, 5/2^-$	1.2	8.3	
100.95(5)	$5/2^-$	<2.4	>8.0	100.0
134.50(5)	$3/2^+$	2.0	8.0	134
160.45(5)	$3/2^+$	<0.2	>9.0	160
171.97(5)	$5/2^+$	2.6	7.9	171
187.02(5)	$5/2^-$	4.4	7.6	187
188.95(7)	$5/2, 7/2^-$	<1.1	>8.2	
219.50(7)	$7/2^+$	0.5	8.6	218
223.03(7)	$(7/2)^+$	1.6	8.1	
242.45(5)	$(5/2^\pm)$	<0.7	>8.4	
243.60(10)	$(5/2^+)$	<0.2	>8.9	243
244.64(10)	$(7/2)^-$	<0.2	>8.9	
365.60(10)	$(9/2^+)$	0.2	8.8	364
				370
				380
				449
				503
519.83(12)	$3/2^-$	<0.01	>10.0	518
540.50(10)	$(5/2^+)$	0.2	8.6	539
605.40(7)	$5/2, 7/2^-$	14	6.7	601
647.55(10)	$5/2, 7/2^-$	2.5	7.4	
649.60(10)	$5/2^-$	4.5	7.2	
684.85(10)	$(7/2)^+$	0.3	8.3	
698.60(10)		0.2	8.5	
736.87(7)	$(7/2)^-$	11	6.7	
763.25(10)		0.5	8.0	
782.65(7)	$5/2^+$	1.2	7.6	
834.50(10)		0.5	7.9	
839.30(10)		0.2	8.3	
892.60(10)		0.5	7.8	
921.60(11)		0.2	8.1	
987.75(14)		0.1	8.4	
995.60(10)		0.2	8.0	
999.15(10)		0.3	7.9	
1001.95(10)		0.2	8.0	
1035.25(10)		0.1	8.3	
1042.30(10)		0.1	8.3	
1070.10(10)		0.5	7.5	
1102.80(10)		0.5	7.5	
1120.25(10)		0.6	7.4	
1221.10(10)		0.1	7.9	
1322.10(10)		0.3	7.2	
1359.15(10)		0.7	6.8	
1398.30(10)		0.1	7.5	
1399.15(10)		0.3	7.1	
1512.45(14)		0.1	7.2	

TABLE 3— continued

Level energy (keV)	I^π	β -branching %	log ft	Previously assigned level energies ^{b)}
1540.70(10)		0.4	6.5	
1552.10(10)		0.3	6.6	
1566.70(20)		0.1	7.0	
1573.80(15)		0.1	7.0	
1590.80(30)		0.2	6.6	
1595.00(30)		0.2	6.6	
1629.30(20)		0.1	6.8	
1695.45(20)		0.1	6.5	

a) Assumed no beta feeding of the ground-state of ^{223}Fr (for comments see sec.3.1).

b) Taken from ref.⁵).

W.Kurcewicz et al., Fig.1.

W.Kurcewicz et al., Fig.2.

W.Kurciewicz et al., Fig.3.

W.Kurcewicz et al., Fig.4a.

W.Kurcewicz et al., Fig.4b.

W.Kurcewicz et al., Fig.4c.

W.Kurcewicz et al., Fig.4d.

W. Kurciewicz et al., Fig. 6.