Short-lived isomers in ^{192}Po and ^{194}Po

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Isomeric states in ^{194}Po and ^{192}Po were studied at the velocity filter SHIP. The isotopes were produced in the fusion-evaporation reactions ^{141}Pr(^{56}Fe, p2n)^{194}Po and ^{144}Sm(^{51}V, p2n)^{192}Po. Several new γ-ray transitions were attributed to the isomers and γ-γ coincidences for both isomers were studied for the first time. The 459 keV transition earlier tentatively proposed as de-exciting the isomeric level in ^{194}Po was replaced by a new 248 keV transition and the spin of this isomer was reassigned from (11^-) to (10^-). The de-excitation of the (11^-) isomeric level in ^{192}Po by the 154 keV transition was confirmed and a parallel de-excitation by a 733 keV ($E3$) transition to (8^+) level of the ground-state band was suggested. Moreover, side feeding to the (4^+) level of the ground-state band was proposed. The paper also discusses strengths of transitions de-exciting 11^- isomers in neighbouring Po and Pb isotopes.

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I. INTRODUCTION

Investigation of metastable, isomeric, states in atomic nuclei is a valuable probe for nuclear structure studies. A series of 11^- isomers present in all even-A polonium isotopes with $196 \leq A \leq 210$ is an excellent example. The isomers have a dominant configuration of $\pi[1h_{9/2}\otimes 1i_{13/2}]$ [1–3] and typical half-lives between 0.5 ns and 1 μs. Most of the isomers de-excite via $E3$ transitions to 8^+ levels [1–6]. $E3$ transition strengths were found to increase with decreasing neutron number [3, 7, 8], which was suggested to be due to the structure and deformation of the 8^+ states [8, 9].

Although short-lived isomers were also identified in the more neutron deficient ^{192,194}Po, their properties are currently not well known, mostly due to the limited statistics available from previous experiments. In early measurements, the level scheme of ^{194}Po ($T_{1/2} = 392(4)$ ms [10]) was deduced from in-beam studies performed at the Fragment Mass Analyzer (FMA) [11]. The ground-state band was established up to the (10^+) level. Based on γ-γ coincidences, side feeding from second (4_2^+) and (2_2^+) levels and an (11^-) level at 2619.8 keV de-exciting to the (10^+) level by 329.2 keV transition were suggested. Spin and parity assignments were based on systematics. A more recent study, containing both in-beam and delayed γ-ray spectroscopic measurements, was performed at the gas-filled recoil separator RITU at JYFL (Finland) [12]. Based on prompt γ-ray data, the ground-state band was extended up to the (16^+) level and the former (11^-) level was reassigned to 12^+ and moved to the ground-state band. Moreover, a side band up to a (10) level was established. In delayed γ-ray data, an (11^-) isomeric state at 2525 keV was tentatively proposed, de-exciting to the (8_2^+) level via a 459 keV ($E3$) transition. Spin and parity assignments were based on systematics. No coincidences between delayed γ rays were observed. The half-life of the isomeric state was determined to be 15(2) μs. Unexpectedly, the $B(E3)$ value of 8.4(12) W.u. for the 459 keV transition exhibits a significant decrease compared to $E3$ transitions in heavier neighbouring isotopes (27(5) W.u. for ^{196}Po [3], 25(3) W.u. for ^{198}Po [2]).

Studies of ^{192}Po ($T_{1/2} = 33.2(14)$ ms [13]) were also carried out at RITU at JYFL [12]. The ground-state band up to the (10^+) level was established based on prompt in-beam measurements. Moreover, three transitions from the band (262, 343 and 518 keV) were registered in delayed γ-ray measurements at the focal plane as well, which was the first observation of the isomer in ^{192}Po. The half-life was estimated to be of the order of 1 μs and an isomeric level was inferred to be above the

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(8^+) state.

A later study of delayed γ rays from ^{192}Po was performed at the velocity filter SHIP at GSI in Darmstadt (Germany) [14]. A de-excitation of the (11^-) isomeric level by the 154 keV transition to the (10^+) level of the ground-state band was tentatively proposed. The half-life of the isomer was evaluated to be 580(100) ns. No γ-γ coincidences were registered.

Our work presents analysis of data from the follow-up experiments performed at SHIP with the production of ^{194}Po and ^{192}Po. For the isomer in ^{194}Po, we obtained approximately 10 times higher statistics than the previous study [12]. For ^{192}Po, we combined our data with the previous experiment [14] in order to search for γ-γ coincidences. These measurements allowed us to study γ-γ coincidences in decays of isomers in both isotopes for the first time.

II. EXPERIMENT

The isotopes ^{194}Po and ^{192}Po were produced in the fusion-evaporation reactions ^{56}Fe+^{141}Pr and ^{51}V+^{144}Sm, respectively. Details of the experimental conditions are given in Table I. In these experiments we also obtained new data for ^{194}At [15] and ^{192}At [16]. During production of ^{194}Po, several beam energies were used. Most of the data were collected at the energy of 259 MeV in front of the target, which corresponds to the maximum of the excitation function.

Evaporation residues (ERs) produced in the fusion reactions were separated from the primary beam and products of other reactions by the velocity filter SHIP [17] and implanted into 300 μm thick, 16-strip position-sensitive silicon detector (PSSD). The time and position correlation method was employed to search for the nuclei investigated (for more details on the correlation method, see [18]). Upstream of the PSSD, six additional silicon detectors divided into 28 segments were placed, forming an open box (BOX detector) to detect escaping particles. The geometrical efficiency BOX detector was 80 % of the $2\,\pi$ solid angle. Low-energy calibration of both detectors was done using α decays of ERs implanted into the PSSD. The energy resolution of the PSSD for 7 MeV α particles was 35 keV (FWHM). Further upstream the beam, three time-of-flight detectors were installed [19]. They were used with coincidence or anti-coincidence conditions to distinguish implantations of incoming ions or decays in the detector, respectively. Moreover, in connection with information on energy, they enabled differentiation between ERs and scattered beam or target nuclei.

For detection of γ and x rays, a 4-crystal germanium clover detector was installed behind the PSSD. During the ^{194}Po measurement a clover with dimensions of $(124 \times 124 \times 140)\,\mathrm{mm}^3$ was used, while for the study of ^{192}Po a clover with dimensions of $(102 \times 102 \times 70)\,\mathrm{mm}^3$ was installed. The clovers were calibrated using ^{152}Eu and ^{133}Ba γ-ray sources. Energy resolutions for the 344 keV line were 1.8 keV (FWHM) and 2.5 keV (FWHM) during the studies of ^{194}Po and ^{192}Po, respectively. In order to obtain the absolute efficiency, we used the known absolute efficiency from other measurements with the same clover detectors. More details on the absolute-efficiency determination of the clover detector can be found elsewhere [20].

Two time intervals were used to measure particle-γ correlations. The time measurement in the first interval was covered by TAC unit for time differences $\lesssim 5\,\mu$s. In this paper, we refer to events registered within this time interval as coincidences. The second interval was for time differences $\geq 26\,\mu$s, where time was measured by a continuously running clock with a step of 1 μs. The time window $(5-26)\,\mu$s between these two intervals was unavailable due to the dead time of data acquisition system.

III. RESULTS AND DISCUSSIONS

A. Results for ^{194}Po

Using the PSSD + BOX detectors, we registered 1.6 million time-position correlations between implantations of the ERs into the PSSD and α particles from ^{194}Po within a time window of 1.2 s (which is $\approx 3\times$ half-life of ^{194}Po). Out of this number, 1.2 million correlations contained α particles fully stopped in the PSSD.

An energy spectrum of all γ rays collected in the focal-plane clover detector is shown in Fig. 1 (a). The request for coincidences (within 5 μs) between γ rays and ERs significantly reduces the background (Fig. 1 (b)). The most intense transitions come from isomers in ^{192}Pb and ^{194}Po, produced via αp and $p2n$ evaporation channels, respectively. In order to obtain γ rays originating specifically from ^{194}Po, we further required correlations of ERs with α decays of ^{194}Po for events from (b). The γ-ray spectrum for these events is shown in Fig. 1 (c). The application of the correlation procedure reduces the background and thus enhances γ-ray lines from the isomer in ^{194}Po. We identified all transitions from the isomer reported previously, mainly the 373 keV and 919 keV transitions that were suggested to feed 8^+ and 6^+ states of the ground-state band [12], respectively, and subsequent transitions down to the ground state (545, 462, 366 and 319 keV), see the decay scheme in Fig. 2. Moreover, we observed transitions from the side band up to the 9^- level (previously seen only in in-beam γ-ray spectroscopy [12]) and we attributed four new transitions with energies of 209, 248, 362, and 494 keV to the decay of the isomer. Registered transitions are summarised in Table II.

We deduced the half-life of the isomer using ER-γ-α(^{194}Po) correlations to be 12.9(5) μs (Fig. 4) by gating with an "OR" condition on the strongest lines from the isomer, i.e. 319, 366, 373 and 545 keV. Our value is consistent with the previously published half-life of 15(2) μs [12], but is more precise.

TABLE I. Experimental details. Beam energies are given in front of the target. The beam intensity is the average value during data collection. Target materials were compounds $^{141}PrF_3$, $^{144}SmF_3$, the thickness corresponding to the contribution of the chosen target element is stated. Two targets with different thickness were used during the production of ^{192}Po. Cross sections are from this work.

Reaction	Energy	Intensity	Enrichment	Thickness	Cross section
^{141}Pr(^{56}Fe, p2n)^{194}Po	259 MeV	450 pnA	100 %	372 μg/cm^2	20(5) μb
^{144}Sm(^{51}V, p2n)^{192}Po	235 MeV	150 pnA	96.47 %	392, 215 μg/cm^2	0.6(1) μb

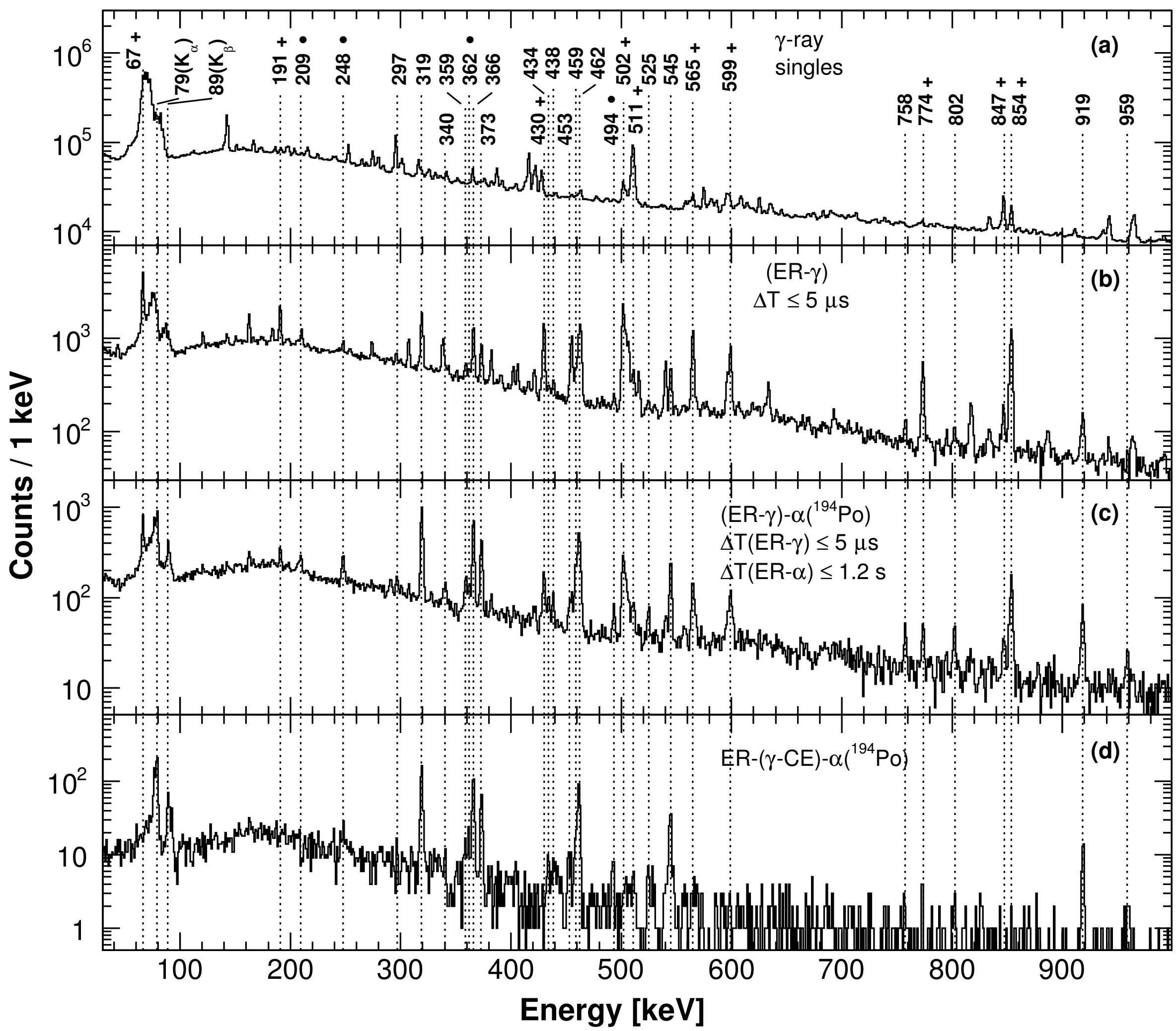

FIG. 1. (a) All γ rays registered during the production of ^{194}Po; (b) γ rays in coincidence with ERs; (c) γ rays in coincidence with ERs correlated with α decays of ^{194}Po with the correlation time up to 1.2 s; (d) γ rays in coincidence with conversion electrons from correlation chains ER-(γ-CE)-α(^{194}Po) within the time window $(26-100)\,\mu$s for ER-(γ-CE) correlations. Energies are in keV. Filled circles denote new transitions from ^{194}Po, while plus signs denote background lines (mostly from ^{192}Pb produced through the αp channel).

The last panel of Fig. 1 shows γ rays in coincidence with conversion electrons (CEs) from correlation chains ER-(γ-CE)-α(^{194}Po). The time difference for ER-(γ-CE) correlations was $(26-100)\,\mu$s. Strong background lines originating from isomers in ^{192}Pb disappeared due to their short half-lives ($T_{1/2}(11^-) = 0.756(14)\,\mu$s, $T_{1/2}(12^+) = 1.09(4)\,\mu$s [21]). The 248 and 209 keV transitions from the isomer in ^{194}Po are significantly suppressed, which could mean that they are highly converted and are sources of conversion electrons.

In the γ-γ coincidence analysis, we selected events from the correlation chains (ER-γ-γ)-α(^{194}Po). Coincidences

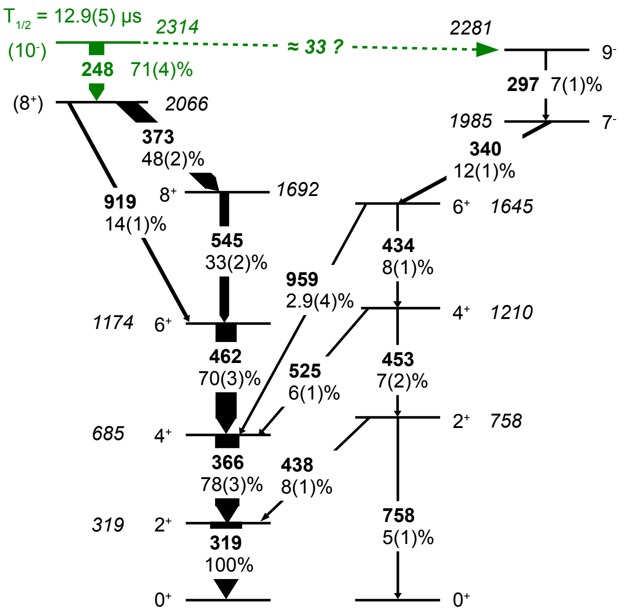

FIG. 2. (color online) Decay scheme of the isomeric state in ^{194}Po. It is a part of the scheme from [12] modified to include our observations. Proposed changes are highlighted in green and they are discussed further in the text (section III B). Energies are given in keV. A transition with energy ≈ 33 keV was not observed, but we discuss its possible existence in the text. Relative intensities were determined from (ER-γ)-α(^{194}Po) correlations (Fig. 1). The 453 keV transition was not clearly visible in the resulting spectrum, so we determined its relative intensity using ER-(γ-CE)-α(^{194}Po) correlations.

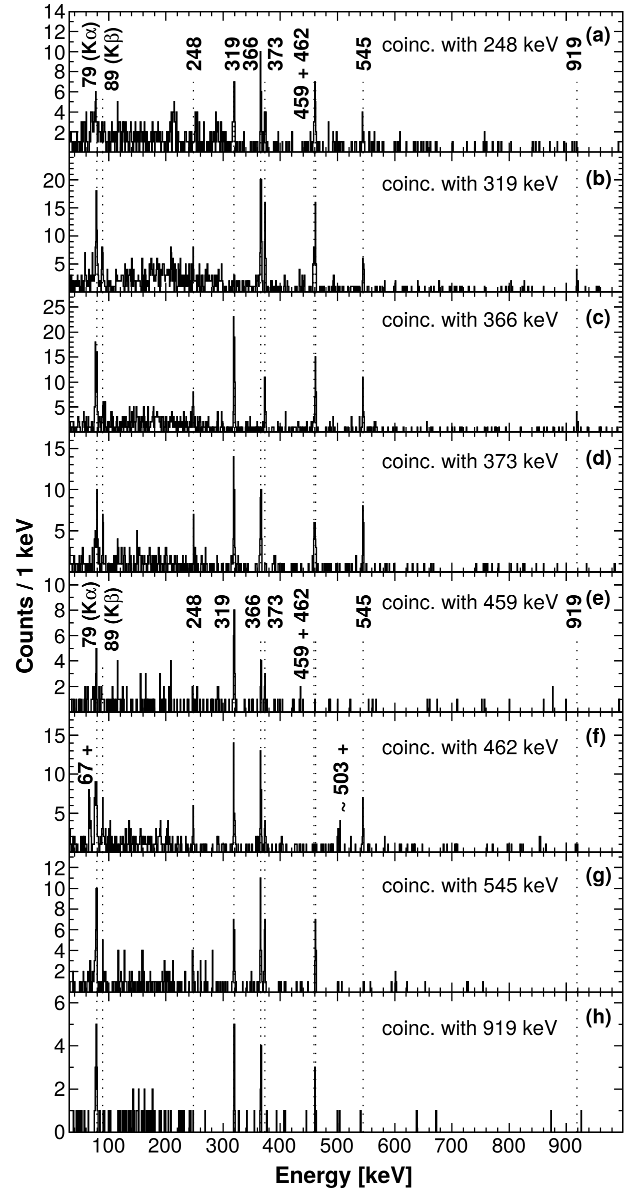

FIG. 3. Gamma-gamma coincidences for the isomer in ^{194}Po from correlation chains (ER-γ-γ)-α(^{194}Po): γ rays in coincidence with the (a) 248 keV, (b) 319 keV, (c) 366 keV, (d) 373 keV, (e) 459 keV, (f) 462 keV, (g) 545 keV and (h) 919 keV transitions. Gamma lines marked by a plus sign in panel (f) are from ^{192}Pb; the ≈ 503 keV line consists of the 502 and 504 keV transitions [21]. These transitions are in coincidence with the 463.4 keV transition from the same isotope, which partly overlaps the coincidence gate for the 462 keV transition.

are shown in Fig. 3 and coincident transitions are listed in Table III. The results agree with the previously published decay scheme [12], except for the placement of the 459 keV transition. This transition was suggested to deexcite the isomeric level. However, we did not observe any coincidences between the 459 keV and subsequent 545, 462, or 919 keV transitions. In order to minimize mixing of coincidences with 459 and 462 keV transitions, which partly overlap, we used narrow gates for these transitions in Fig. 3: $(457.0-459.5)$ keV for the 459 keV transition and $(460.5-463.5)$ keV for the 462 keV transition. Thus, we avoided most of the overlapping region at the cost of lower statistics. To make sure that we did not miss mutual coincidences between the 459 and 462 keV transitions, we also examined events from a gate on the energy of both of these transitions, including the overlapping region: $(457.0-463.5)$ keV. The result in upper panel of Fig. 5 shows no counts significantly above the level of the background. To further illustrate the absence of coincidences between the 459 keV and subsequent transitions according to the former decay scheme [12], we created spectrum with an "OR" gate on 545, 462 and 919 keV transitions (i.e. summed spectrum of separate coincidence gates on each of the transitions). Then we compared it to γ rays from an "OR" gate on all transitions which are in coincidence with both the 459 and the 462 keV lines (i.e. 248, 319, 366, 373 keV) in the bottom panel of Fig. 5. Since the 459 keV transition is in coincidence with the 319 and 366 keV transitions, it may feed the 4^+ state of the ground-state band. Nevertheless, it is also in coincidence with the 373 keV (Fig. 3 (d)) and possibly the 248 keV transition and its position in the decay

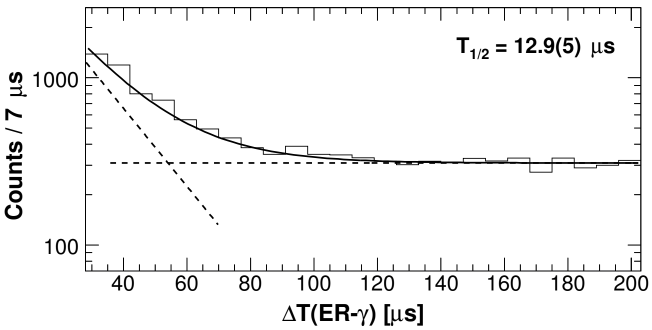

FIG. 4. Time difference between ER implantations and subsequent emissions of γ rays from ER-γ-α(^{194}Po) correlations with an "OR" gate on the 319, 366, 373 and 545 keV transitions. The solid line represents the fit with an exponential function plus a constant. The two components are indicated separately by dashed lines.

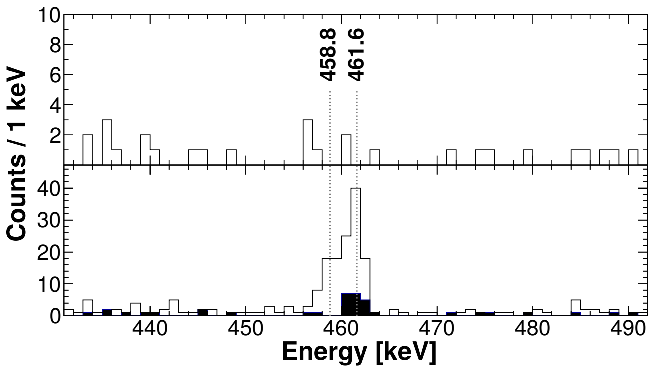

FIG. 5. Top panel: coincidences with a gate of (457.0 − 463.5) keV. Bottom panel: coincidences with 248, 319, 366 or 373 keV transitions (open histogram) compared to coincidences with 462, 545 or 919 keV transitions (solid histogram).

scheme still remains unclear.

The new 248 keV transition is in coincidence with all investigated transitions from the ground-state band and with the 373 keV transition. Tentatively, it is also in coincidence with the 459 keV transition. Coincidences between the 248 and the 919 keV transition seem to be missing, but this is likely caused by the low intensity of the 919 keV line. We would expect only a few counts, and there is one count at the right energy in Fig 3 in both panel (a) and (h), which is inconclusive given the level of the background. Based on these observations, we suggest replacing the 459 keV transition with the 248 keV transition in the decay scheme.

B. Discussion for ^{194}Po

In order to determine the multipolarity of the 248 keV transition, we deduced a K-conversion coefficient of this transition from the number of Po K x rays and com-

TABLE II. Gamma rays from (ER-γ)-α(^{194}Po) correlations, attributed to decay of the isomer in ^{194}Po. Reference energies and multipolarities were taken from the previous study [12]. Transitions without the reference energies were observed for the first time. Tentative multipolarity assignments are in brackets. For transitions with unknown multipolarity, we evaluated lower limits of their relative intensities using conversion coefficients for $E1$ multipolarities. In the case of transitions between levels with $\Delta J = 0$ (i.e. 373, 438 and 525 keV transitions), we used conversion coefficients for $M1$ multipolarities, since this is the most probable multipolarity based on Weisskopf estimates [22]. However, conversion coefficients could be increased by possible admixtures of $E0$ components or decreased by possible admixtures of $E2$ components. I_γ and I_t stand for γ-ray intensity and total transition intensity, respectively. All intensities are relative to the intensity of the 319 keV γ rays/transition.

E_γ [keV]	$E_{\gamma\ ref}$ [keV]	I_γ [%]	I_t [%]	Multipolarity
209.4(2)		14(1)	≥ 14(1)	
248.0(1)		18(1)	71(4)	($M2$)
296.8(2)	297.7(3)	7(1)	7(1)	$E2$
319.3(1)	319.7(3)	100	100	$E2$
340.1(3)	340.8(3)	12(1)	11(1)	$E1$
358.8(1)	359.2(5)	14(1)	≥ 13(1)	
362.2(2)		12(1)	≥ 11(1)	
366.1(1)	366.5(3)	80(3)	78(3)	$E2$
373.3(1)	373.1(5)	41(2)	48(2)	($M1$)
434.1(2)	433.9(5)	8(1)	8(1)	$E2$
438.4(1)	438.1(5)	7(1)	8(1)	($M1$)
458.8(2)	458.6(5)	26(2)	≥ 24(1)	
461.6(2)	461.8(3)	74(3)	70(3)	$E2$
493.6(2)		6(1)	≥ 6(1)	
524.9(1)	524.4(5)	6(1)	6(1)	($M1$)
545.0(1)	545.2(3)	35(2)	33(2)	$E2$
757.6(2)	758.1(5)	5(1)	5(1)	$E2$
802.0(2)	802.7(5)	7(1)	≥ 6(1)	
918.5(2)	918.3(5)	16(1)	14(1)	($E2$)
958.7(4)	958.7(5)	3.1(5)	2.9(4)	$E2$

pared the result with theoretical values for possible multipolarities. The efficiency calibration of the Ge-clover detector was performed with ^{152}Eu and ^{133}Ba γ-ray sources, therefore it covered the region of Po K x rays ($75-90$ keV) with points for the 122 keV (^{152}Eu), 80 and 53 keV (^{133}Ba) lines. The number of Po K x rays was determined from the summed coincidence spectrum ("OR" condition) for gates on the 319, 366, 462, 545 and 373 keV transitions (Fig. 6). It was was corrected for expected number of Po K x rays from other transitions present in the spectrum than the 248 keV transition. The resulting K-conversion coefficient was 2.3(4), while theoretical values are 2.56(4) for an $M2$ multipolarity, 0.694(10) for an $M1$ multipolarity and values for $E3$, $E2$ and $E1$ multipolarities are below 0.3 [23]. It has to be noted, that our value is only an upper limit, since we cannot rule out

TABLE III. List of γ-γ coincidences for de-excitation of the isomer in ^{194}Po (from Fig. 3). Energies are given in keV, tentative coincidences are written in italic.

Gate	Coincident transitions
248	*Po K x rays*, 319, 366, 373, 459, 462, 545
319	Po K x rays, 248, 366, 373, 459, 462, 545, 919
366	Po K x rays, 248, 319, 373, 459, 462, 545, 919
373	Po K x rays, 248, 319, 366, 459, 462, 545
459	Po K x rays, *248*, 319, 366, 373
462	Po K x rays, 248, 319, 366, 373, 545
545	Po K x rays, 248, 319, 366, 373, 462
919	Po K x rays, 319, 366, 462

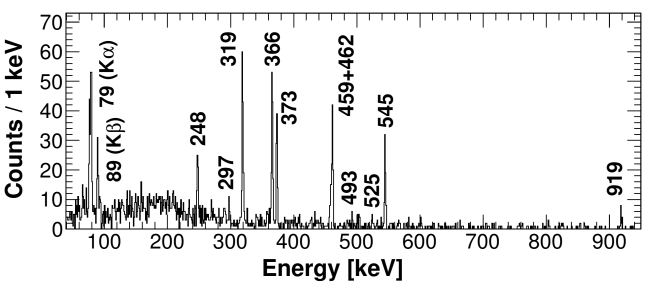

FIG. 6. Summed coincidence spectrum ("OR" condition) for gates on 319, 366, 462, 545 and 373 keV transitions.

additional sources of Po K x rays, such as significant $E0$ components in $\Delta J = 0$ transitions (373, 525 and 438 keV) or other unobserved highly-converted transitions. However, all theoretical values of K conversion coefficients for possible multipolarities of the 248 keV transition except for $M2$ are well below 1, thus contributions of other sources of Po K x rays would have to be high. In addition, Po K x rays in coincidence with the 248 keV transition seem to be relatively less abundant than for most of the other transitions (Fig. 3). Moreover, when we compare the γ spectrum from (ER-γ)-α(^{194}Po) correlations with the spectrum from ER-(γ-CE)-α(^{194}Po) correlations (Fig. 1 (c) and (d)), we can see that the 248 keV line is suppressed compared to most of the other lines from the isomer in the latter spectrum, which indicates that this transition is highly converted. These observations strongly suggest that the 248 keV transition has $M2$ multipolarity.

Another approach to assign the multipolarity is to investigate the intensity balance in γ-γ coincidences. Assuming population of the 8^+ level in the ground-state band only by the 373 keV transition, and applying the gate on the 373 "OR" 545 keV transition, the intensities of 248 and subsequent 366 and 319 keV transitions should be the same (see the decay scheme in Fig. 2). We compare the results in Table IV, where the intensity of the 248 keV transition was calculated for several possible multipolarities. The intensity of the 462 keV transition is not included in the table due to possible admixtures

TABLE IV. Intensity balance of the 248, 366 and 319 keV transitions obtained from γ-γ coincidences. The intensity of the 248 keV transition was calculated for several possible multipolarities. Intensities are relative to the intensity of the 319 keV transition. ICC$_{\rm tot}$ stands for total internal conversion coefficient, values were taken from [23].

Gate: 373 "OR" 545 keV			
Transition energy [keV]	Multipolarity	ICC$_{\rm tot}$	Intensity [%]
319	$E2$	0.1051(15)	100(20)
366	$E2$	0.0713(10)	105(21)
248	$E1$	0.0489(7)	27(8)
248	$M1$	0.854(12)	48(14)
248	$E2$	0.228(4)	32(9)
248	$M2$	3.50(5)	117(33)
248	$E3$	1.661(24)	69(20)

of the 459 keV transition. The comparison favours $M2$ character of the 248 keV transition.

To sum up, our data show $M2$ as being the most probable multipolarity of the 248 keV transition, which leads to an initial isomeric level with $I^\pi = (10^-)$. This assignment is unexpected, as no such isomer has been identified in neighbouring isotopes. The configuration of this state is uncertain, since our measurement cannot provide direct information on the structure and there are no systematics to compare with. Various configurations can form a 10^- level in even-A Po isotopes. For example, 10^- states with configurations of $\pi\{13/2^+[606] \otimes 7/2^-[514]\}$ and $\pi\{11/2^+[615] \otimes 9/2^-[505]\}$ were theoretically predicted in ^{194}Po within the framework of Nilsson model [25]. However, the only observed 10^- excited state in Po isotopes with determined configuration is the level with an excitation energy of 3.2 MeV in ^{210}Po. A configuration of $\pi[h_{9/2} \otimes i_{13/2}]$ was attributed to this level [24], which is the same as the configuration of 11^- isomers in Po isotopes [7]. Therefore, it is a plausible configuration also for the (10^-) isomeric state proposed in this study. Parallel $(M2)$ and $(M1)$ transitions in ^{194}Po would then connect states with the same configurations as the parallel $E3$ and $E2$ decays of 11^- isomers to the 8^+ and 9^- states in $^{198-202}$Po, where it is observed that $E3$ decays dominate over $E2$ decays [2, 4]. For transitions with the relevant energies, ratios of Weisskopf half-life estimates corrected for internal conversion are $t_{1/2}(E3)/t_{1/2}(E2) \approx 700 - 1000$ for $^{198-202}$Po and $t_{1/2}(M2)/t_{1/2}(M1) \approx 100$ for the (10^-) state in ^{194}Po. Based on Weisskopf estimates, these lower-multipolarity transitions should then be even more preferred in case of $^{198-202}$Po than in ^{194}Po. The hindrance of these $(M1)$ and $E2$ transitions may be caused by significant change in configuration between the initial and final states.

The overall intensity balance in the decay scheme (Fig. 2) is adequate, especially considering possibility of small unobserved side feedings. The exceptions are the subsequent 373 and 545 keV transitions with intensities of 48(2) % and 33(2) %, respectively. The intensity of the 373 keV transition was calculated using conversion coefficient for $M1$ multipolarity. However, admixtures of electric multipoles are possible, which would affect the intensity. Admixtures of $E0$ would increase while admixtures of $E2$ would decrease the transition intensity. Similarly, the intensity of the 248 keV transition preceding the 373 keV transition may be affected (decreased) by $E3$ admixtures. Nevertheless, since the ground-state band was firmly established by in-beam studies [12], our γ-γ coincidences strongly place the 373 keV transition above the 8_1^+ level. Therefore, the intensity balance cannot be improved by moving the 373 keV transition to another place.

Transitions in the right part of the scheme (side band), originating from the 9^- level with an energy of 2281 keV, were previously observed only in an in-beam measurement at RITU [12]. In our study, we weakly observed these transitions in delayed γ-ray spectroscopic data, which indicates population of these levels also by the decay of an isomeric state in addition to direct production. Possible explanations may be a 33 keV transition (unobserved in our measurement) from the (10^-) isomeric level to the 9^- level or another isomeric state above the 9^- level.

Possible $E0$ components of $\Delta J = 0$ transitions between the side-band and ground-state band (438 and 525 keV) were discussed in previous studies based on missing intensities [3, 12, 26]. However, our statistics were not sufficient to create coincidence gates on side-band transitions to investigate the intensity balance in detail.

One could expect the presence of a 421 keV ($E2$) transition between the (8^+) 2066 keV level and the 6^+ 1645 keV level as well as a 622 keV ($M2$) transition between the (10^-) 2314 keV and the 8^+ 1692 keV level. However, we did not observe evidence of either transition. Based on the amount of the background, we estimated upper limits on their relative intensities to be $\lesssim$ 2.4 % for the 421 keV and $\lesssim$ 2.2 % for the 622 keV transition.

TABLE V. Gamma rays attributed to the isomer in ^{192}Po from (ER-γ)-α(^{192}Po) correlations. Reference energies were taken from [14]. Gamma transitions without reference energies were observed for the first time. Tentative lines are written in italic. I_γ and I_t stand for γ-ray intensity and total transition intensity, respectively. All intensities are relative to the intensity of the 262 keV γ rays/transition. Multipolarities of transitions from the ground-state band are based on the decay scheme from [12]. Multipolarities of the 154, 363, 445 and 733 keV transitions are discussed in the text. For the rest of listed transitions, we evaluated lower limits of their relative intensities using conversion coefficients for $E1$ multipolarities.

E_γ [keV]	$E_{\gamma\ \mathrm{ref}}$ [keV]	I_γ [%]	I_t [%]	Multipolarity
153.9(3)	154	27(5)	27(5)	($E1$)
262.1(1)	262	100	100	($E2$)
343.1(2)	343	98(11)	90(10)	($E2$)
362.8(3)	363	36(6)	32(5)	($E2$)
376.8(10)		21(5)	$\geq$ 18(4)	
422.4(5)		7(3)	$\geq$ 6(3)	
430.7(5)	431	17(5)	$\geq$ 14(4)	
437.9(3)	438	30(6)	26(5)	($E2$)
445.0(2)	445	53(8)	52(8)	($M1$)
517.8(4)	518	25(5)	22(5)	($E2$)
578.4(4)	578	15(4)	13(4)	($E2$)
606.3(4)	605	14(4)	$\geq$ 12(4)	
624.6(4)		14(4)	$\geq$ 12(4)	
651.8(7)		8(3)	$\geq$ 6(3)	
659.6(10)		9(4)	$\geq$ 7(3)	
685.7(6)		9(4)	$\geq$ 7(3)	
720.4(10)		17(5)	$\geq$ 14(4)	
733.1(4)		8(3)	7(3)	($E3$)
834.6(10)		7(3)	$\geq$ 6(3)	
965.7(10)		10(4)	$\geq$ 8(3)	
1096(1)				
1172(1)				
1231(1)				
1258(1)				

C. Results for ^{192}Po

During the measurement investigating ^{192}Po, we registered approximately 110 000 ER-α(^{192}Po) correlations using the PSSD + BOX detectors, of which 83 000 correlations involved α particles fully stopped in the PSSD. The maximum time difference in the correlation search was 133 ms ($\approx 4 \times$ half-life of ^{192}Po). Registered γ rays are shown in Fig. 7 and 8. In each figure, panel (a) shows all γ rays registered. In (b), γ rays in coincidence with ERs and in (c) γ rays from (b) that are also correlated with α decays of ^{192}Po are displayed. We attributed γ lines which emerged in panel c) and were relatively weak or not visible in panel b) to the isomer. We confirmed all previously-known transitions, including ground-state band transitions down from the (10^+) level with energies of 578, 518, 438, 343 and 262 keV. Moreover, we attributed 14 new γ transitions to the isomer, although 6 of them are only tentative. All transitions attributed to the isomer are summarised in Table V and the decay scheme is shown in Fig. 9.

In order to enhance the statistics for the γ-γ coincidence analysis, we re-analysed data from an earlier study [14] and combined them with our more recent data. (For the spectra in Fig. 7 and 8, only data from the recent measurement were used due to worse background conditions at higher energies in [14]). We were searching for γ-γ coincidences from (ER-γ-γ)-α(^{192}Po) correlation chains. Resulting spectra are shown in Fig. 10 and coincident lines are listed in Table VI.

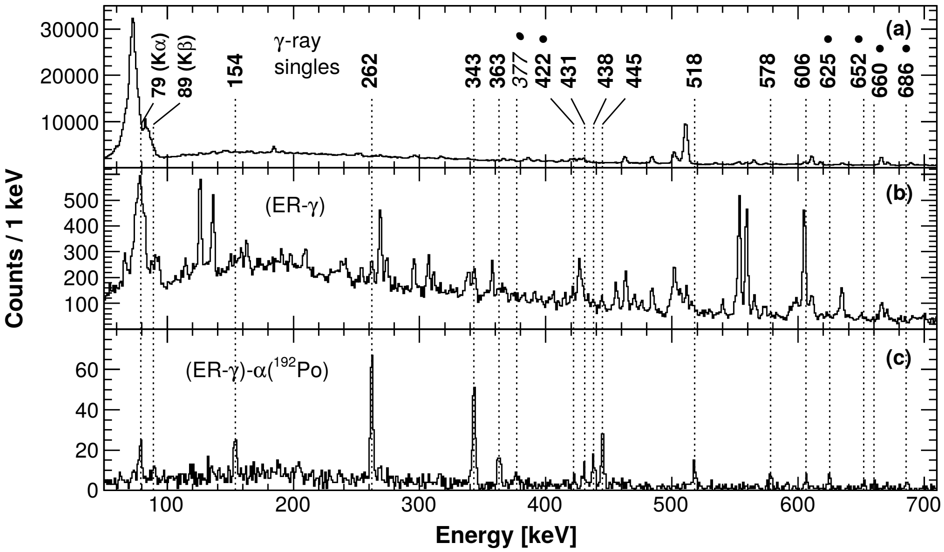

FIG. 7. Lower-energy parts of γ-ray spectra: (a) all γ rays collected during the measurement investigating ^{192}Po; (b) γ rays registered in coincidence with ERs; (c) γ rays in coincidence with ERs correlated to α decays of ^{192}Po. New transitions are denoted by filled circles. The γ line with label written in italic is tentative.

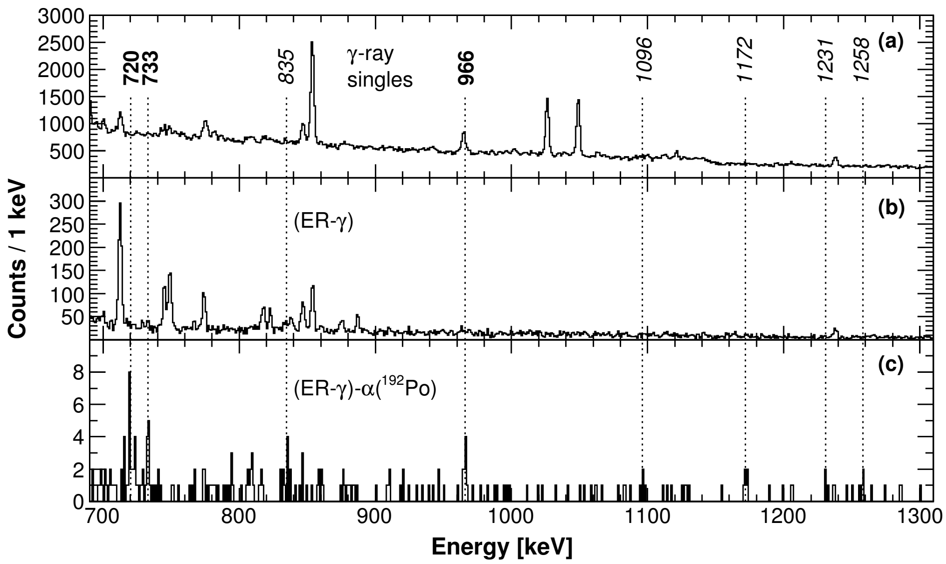

FIG. 8. Higher-energy parts of γ-ray spectra: (a) all γ rays collected during the measurement investigating ^{192}Po; (b) γ rays registered in coincidence with ERs; (c) γ rays in coincidence with ERs correlated to α decays of ^{192}Po. All transitions are new. Gamma lines with labels written in italic are tentative.

D. Discussion for ^{192}Po

It was suggested in [14] that the 154 keV transition may de-excite the (11^-) isomer above the (10^+) level of the ground-state band. The suggestion was based on the supposed $E1$ multipolarity of the transition, which was deduced from the low number of observed K x rays. A firm placement in the decay scheme was not possible due to a lack of γ-γ coincidences, but our γ-γ coincidence data support the suggestion (Fig. 10). An $E1$ character of this transition is indicated by the relative intensities of subsequent transitions. Other characters for the 154 keV transition would result in higher internal conversion coefficients and consequently in higher relative intensities (Table VII). In addition, any magnetic multipole order can be excluded based on the low number of K x rays also in our measurement.

Based on the γ-γ coincidence analysis, we suggest a side-feeding of the ground-state band on top of the (4_1^+) level by the 445 keV transition. This transition is clearly in coincidence with the 262 keV transition and most likely with the 343 keV transition as well (Fig. 10). The side-

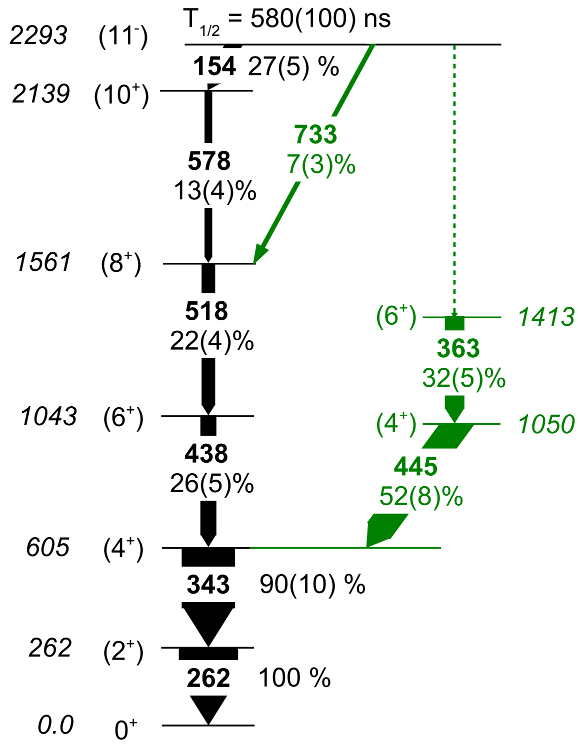

FIG. 9. (color online) Decay scheme of the (11^-) isomeric state in ^{192}Po. The ground-state band up to the (10^+) level is taken from [12]. The placement of the 154 keV transition was proposed in the previous study [14]. Our changes to the decay scheme are highlighted in green and discussed in section III D. Energies are given in keV.

TABLE VI. List of γ-γ coincidences for de-excitation of the isomer in ^{192}Po (from Fig. 10). Tentative lines are written in italic. Energies are given in keV.

Gate	Coinciding transitions
154	*Po K x rays*, 262, 343, 438, 518, 578
262	*Po K x rays*, *154*, 343, 363, 430, *438*, 445
343	Po *K* x rays, *154*, 262, 438, 445, *518*, *578*
363	262, 445
430	262, *343*
438	154, 343
445	262, *343*, *363*
518	*154*, *343*

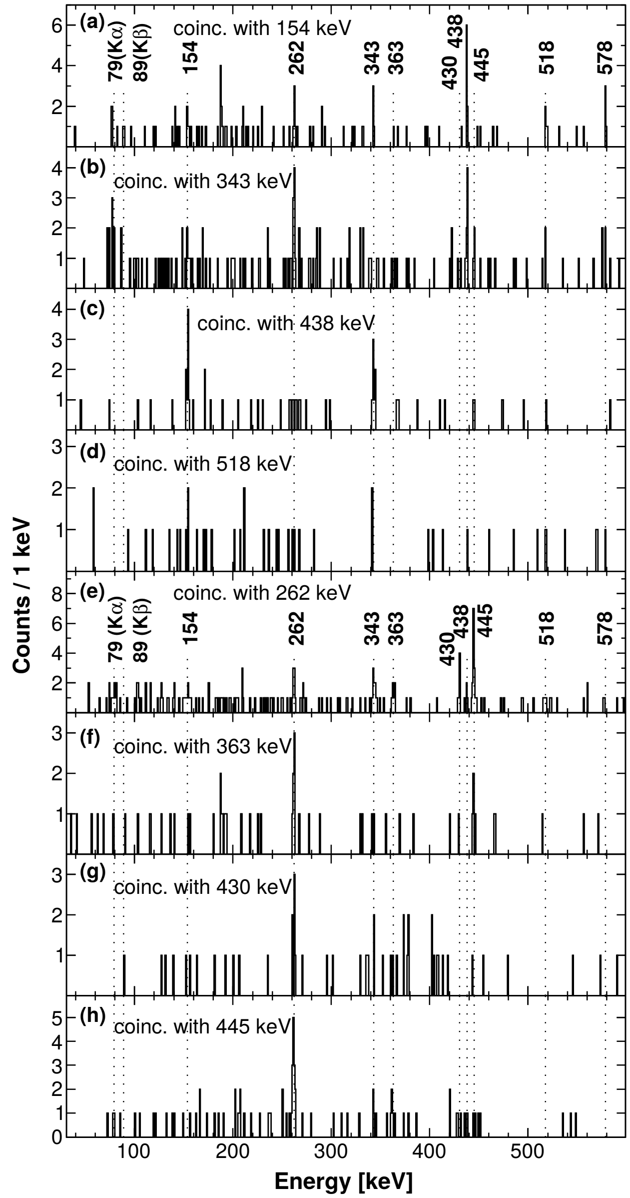

FIG. 10. Gamma-gamma coincidences for de-excitation of the isomer in ^{192}Po from the correlation chains (ER-γ-γ)-α(^{192}Po): γ rays in coincidence with the (a) 154 keV, (b) 343 keV, (c) 438 keV, (d) 518 keV, (e) 262 keV, (f) 363 keV, (g) 430 keV and (h) 445 keV transitions.

feeding is also supported by the balance of relative intensities. The (4_1^+) level is populated by the 438 keV transition with a relative intensity of only 26(5) % while the subsequent 343 keV transition has a relative intensity of 90(10) % (Fig. 9). Connecting the 445 keV transition to the (4_1^+) level adds a relative intensity of 52(8) % to the feeding of the level (if we assume $M1$ multipolarity of the transition, see discussion below).

We also tentatively placed the less intense 363 keV transition into the cascade with the 445 keV transition, because of mutual coincidences (see Fig. 10). However, concerning the ground-state band, the 363 keV transition has clear coincidences only with the 262 keV transition. Coincidences with the 343 keV transition are uncertain. It has to be noted, that also the 445 keV line has significantly stronger coincidences with the 262 keV than with the 343 keV transition. This may be a hint that the 262 keV line is in fact a doublet, which is supported also by the activity with the same energy in coincidence spectrum of the 262 keV line (Fig. 10 (e)). To resolve this

TABLE VII. Comparison of intensities of 154, 363 and 445 keV transitions for various possible multipolarities. Intensities are relative to the intensity of the 262 keV transition.

Multipolarity	Relative intensity [%]		
	154 keV	363 keV	445 keV
$E1$	27(5)	31(5)	45(7)
$M1$	98(17)	40(7)	52(8)
$E2$	51(9)	32(5)	47(7)
$M2$	449(80)	60(10)	68(10)
$E3$	430(76)	40(7)	52(8)

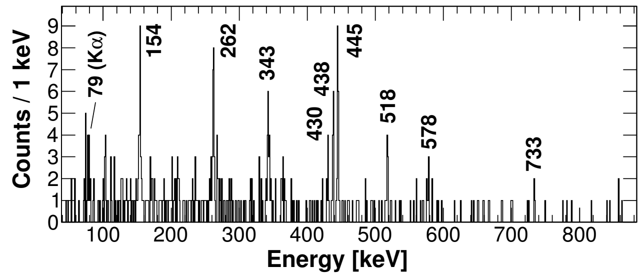

FIG. 11. Coincident γ rays with an "OR" gate on the 262, 343, 438 and 518 keV transitions of the ground-state band.

situation and the connection of the side band up to the (11^-) level, data of enhanced quality are needed.

In this way, we propose two additional levels, (4_2^+) and (6_2^+). Their spins and parities were tentatively assigned based on analogous levels present in ^{194}Po [12], where pairs of levels 6_1^+ and 4_2^+, 8_1^+ and 6_2^+, lie at similar excitation energies. The same situation is also observed in ^{196}Po for (6_1^+) and (4_2^+) levels [3]. However, the intensities of side-band transitions in ^{192}Po are remarkable, since they are higher than the intensities of parallel ground-state band transitions. In ^{194,196}Po, side-band transitions are significantly weaker than the ground-state band transitions. The assignments yield an $(M1)$ multipolarity as the most probable one based on Weisskopf estimates [22] for the 445 keV and $(E2)$ for the 363 keV transition. These multipolarities were used to evaluate relative intensities of the transitions. Considering other possible multipolarities (Table VII), relative intensities would change only moderately (with the exception of $M2$ multipolarity). Based on intensity balance of feeding and depopulation of the (4_1^+) level, there should be no strong $E0$ component in the 445 keV transition. However, coincidences with the 363 keV transition are too weak to be employed to determine precisely any possible missing intensity of the 445 keV transition.

We tentatively placed the 733 keV transition connecting the (11^-) and (8^+) levels, which gives an $(E3)$ character to this transition. The placement is based mainly on energy balance and the systematic presence of $E3$ transitions in the decay paths of 11^- isomers in Po isotopes. Nevertheless, we also observed a hint (3 counts) of this transition in γ-γ coincidences (Fig. 11), while gating with "OR" condition on all subsequent transitions (262, 343, 438 and 518 keV). Adding the 154 or 578 keV transitions to the gate did not increase the number of counts for the 733 keV transition.

E. 11^- isomeric states in even-A Po and Pb isotopes

In all even-A neutron deficient polonium isotopes from ^{210}Po to ^{196}Po and lead isotopes from ^{196}Pb to ^{190}Pb, 11^- isomeric states with a dominant configuration of $\pi[h_{9/2} \otimes i_{13/2}]$ are present [1–6, 8, 9]. Isomers were also identified in ^{194}Po and ^{192}Po and the same spin and parity was assumed [12, 14]. The 11^- isomers de-excite via $E2$ transitions to 9^- levels ($^{202-198}$Po [2, 4] and ^{196,194}Pb [9]), via $E1$ transitions to 10^+ levels ($^{208-204}$Po [4–6] and $^{196-190}$Pb [8, 9]) or, as in most cases, via $E3$ transitions to 8^+ levels ($^{210,208,202-196}$Po [1, 3, 4, 6, 7] and $^{196-190}$Pb [8, 9]).

The isomer in ^{210}Po de-excites via two $E3$ transitions [1]. One of them leads to a $\pi[h_{9/2} \otimes f_{7/2}]_{8^+}$ state, which is characterised by a fast single-particle transition $\pi i_{13/2} \to \pi f_{7/2}$ and its strength is 19(3) W.u. The second leads to a $\pi[1h_{9/2}^2]_{8^+}$ state, which is characterised by slow spin-flip single-particle transition $\pi i_{13/2} \to \pi h_{9/2}$ and its strength is 3.7(1) W.u. [1, 27]. All other $E3$ transitions (for which the configuration of the final state is known) de-exciting 11^- isomers in Po and Pb isotopes lead to 8^+ states with the latter configuration. However, for $^{202-196}$Po and $^{196-190}$Pb, $B(E3)$ values are gradually increasing with decreasing neutron number (see Fig. 12) up to 25(3) and 27(5) W.u. in ^{198}Po and ^{196}Po, respectively [2, 3]. The increase was discussed in previous studies as presumably due to the admixtures of a collective octupole 3^- state in the initial and/or the final state [3, 7]. In another approach, admixtures of the $7/2^-[514]$ orbital into the final state due to an oblate deformation were suggested [8, 9].

The 733 keV transition in ^{192}Po with a tentative $(E3)$ character populates the (8^+) level, for which different configuration alternatives exist. The first alternative is a $\pi[h_{9/2}^2]$ configuration, which follows assignments of 8^+ levels from ground-state bands in heavier Po isotopes. The second possible character of this level is a $4p-2h$ oblate intruder state suggested by level-energy systematics [29]. This possibility is supported by laser-spectroscopy studies [30]. In the former case, a spin-flip transition $\pi i_{13/2} \to \pi h_{9/2}$ is required for de-excitation of the (11^-) isomer. One could expect $B(E3)$ value of around 3 W.u. [27] or the increased value based on systematics in heavier neighbouring isotopes. The second possible configuration (oblate $4p-2h$ intruder) would mean a change compared to heavier isotopes, where $\pi[h_{9/2}^2]$ 8^+ states are populated by $E3$ transitions. How-

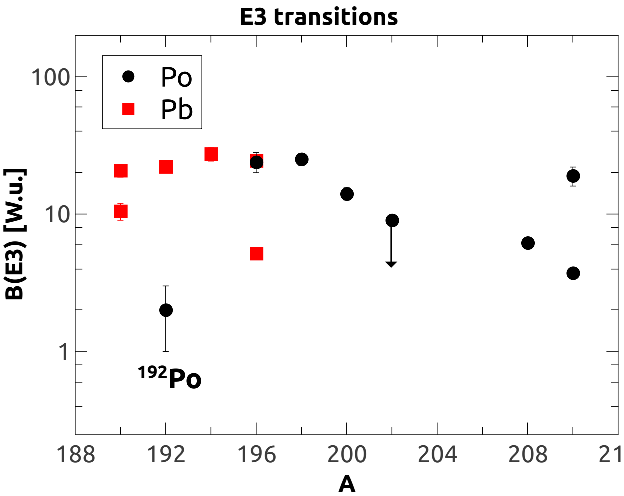

FIG. 12. (color online) Strengths of $E3$ transitions de-exciting 11^- isomers in even-A Po and Pb isotopes. The value for ^{192}Po is from this work. Remaining values were calculated using data from [1–4, 6, 8, 9]. In the case of ^{202}Po, the value calculated using the half-life from [28] is taken as an upper limit.

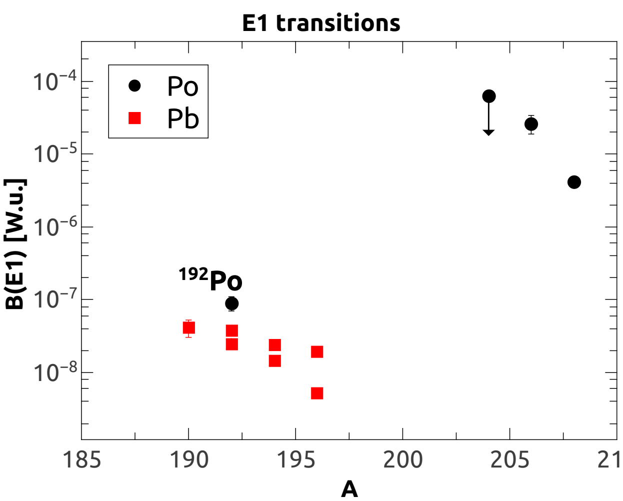

FIG. 13. (color online) Strengths of $E1$ transitions de-exciting 11^- isomers in even-A Po and Pb isotopes. The value for ^{192}Po is from this work. Remaining values were calculated using data from [4–6, 8, 9].

ever, we may still anticipate an increased B($E3$) value due to suggestion that the $E3$ strength enhancement in Pb and Po isotopes is caused by an oblate deformation [8, 9]. In contrast, our value of 2(1) W.u. (or 0.6(3) W.u. when branching ratio equal to relative intensity from Table V is considered) corresponds to values of standard spin-flip $E3$ transitions in [27]. Therefore it does not follow the interpretation from [8, 9] and changes the trend compared to $^{200-196}$Po.

The 154 keV ($E1$) transition in ^{192}Po has a strength of $9(2)\times10^{-8}$ W.u., which is very low compared to heavier isotopes $^{208-204}$Po. However, $B(E1)$ values for more neutron deficient Po nuclei are not known and there are no established systematics. $E1$ transition strengths for neighbouring nuclides are known only in Pb isotopes, and our value for ^{192}Po is within the same order of magnitude (Fig. 13).

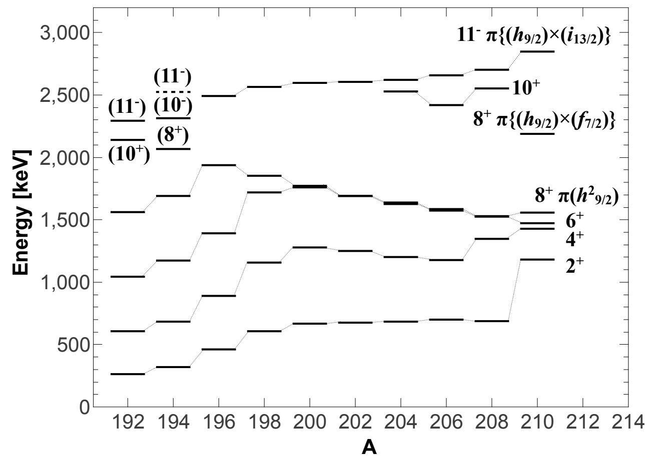

FIG. 14. Systematics of 11^- isomeric levels and lower-lying 8^+, 6^+, 4^+ and 2^+ levels in even-A Po isotopes. The 10^+ states are also plotted if they are in decay path of the isomer. The (10^-) isomeric level in ^{194}Po is shown as well. For simplicity, only yrast levels are plotted for $I^\pi \leq 6^+$. Values for ^{192}Po and ^{194}Po are from this work. The dashed level denotes the energy of the (11^-) level in ^{194}Po from the previous study [12]. Remaining data are from [1–4, 6].

The systematics of excitation energies of 11^- isomers alongside the 8^+ and lower-lying yrast levels in even-A neutron deficient Po isotopes are shown in Fig. 14. The energies of the 11^- levels have a decreasing trend with decreasing neutron number. The only exception was the value for ^{194}Po from a previous study [12], where de-excitation of the isomer via the 459 keV transition was proposed, yielding an excitation energy of 2525 keV. This was higher than the excitation energy of 2491 keV in ^{196}Po [3] but we did not observe evidence for this or another 11^- isomeric level in ^{194}Po. We confirmed excitation energy of the isomer in ^{192}Po, so the energies of remaining 11^- levels decrease monotonically.

IV. CONCLUSIONS

We investigated delayed γ rays from ^{194}Po and ^{192}Po produced in fusion evaporation reactions and attributed several new γ transitions to decays of isomers in these isotopes. We observed for the first time γ-γ coincidences for both isomers and suggested changes in their proposed decay schemes.

In the case of the isomer in ^{194}Po, we replaced the previously proposed 459 keV $E3$ transition de-exciting the isomeric level by a new 248 keV transition. Our analysis shows this transition to be most probably of $M2$ character, which results in an unexpected $I^\pi = (10^-)$ assignment for the isomer. We observed also transitions up to the 9^- level from the side band, which were previously registered only in in-beam studies. Therefore, levels in the side band have to be also populated, in addition to direct production, either by the decay of the isomeric (10^-) state or another unobserved isomer.

For the decay path of the isomer in ^{192}Po, we confirmed the de-excitation of the isomeric level by the 154 keV ($E1$) transition and tentatively suggested a parallel 733 keV ($E3$) transition to the (8^+) level of the ground-state band. Furthermore, we established side feeding of the ground-state band on top of the (4^+) level by a cascade comprising the 363 and 445 keV transitions.

The tentative 733 keV ($E3$) transition in ^{192}Po has a strength of only 2(1) W.u. Thus it lacks an enhancement of the $B(E3)$ value systematically present in neighbouring isotopes. The transition strength of the 154 keV ($E1$) transition is of the same order of magnitude as $B(E1)$ values in Pb isotopes with similar A.

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