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Study of Neutron-Deficient Polonium Isotopes

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Abstrakt

Témou práce je štúdium neutrónovo deficitných izotopov polónia a astátu s hlavným zameraním na γ spektroskopiu izomérnych stavov v ^{192,194}Po. Skúmané izotopy boli produkované vo fúzno-výparných reakciách $^{56}Fe + ^{141}Pr$ a $^{51}V + ^{144}Sm$ v GSI v Darmstadte (Nemecko). Produkty reakcií boli odseparované od primárneho zväzku rýchlostným filtrom SHIP a študované pomocou detektorov umiestnených za separátorom. Izoméru v ^{194}Po boli priradené štyri nové γ prechody a po prvý krát boli pre tento izomér analyzované γ-γ koincidencie. Prechod, ktorý bol predtým navrhnutý ako prechod de-excitujúci izomérnu hladinu, bol nahradený novým prechodom s energiou 248 keV. Priradenie spinu izoméru bolo zmenené z (11^-) na (10^-), čo spôsobilo nečakanú zmenu v sérii izomérov v izotopoch Po. Bola určená presnejšia doba polpremeny izoméru s hodnotou 12.9(5) μs. V prípade izoméru v ^{192}Po bol podporený predpokladaný spin a parita (11^-) a bolo mu priradených 14 nových γ prechodov. Aj pre tento izomér boli po prvý krát študované γ-γ koincidencie. Ku prechodu s energiou 154 keV, ktorý de-excituje izomérnu hladinu, bol navrhnutý paralelný $(E3)$ prechod s energiou 733 keV. Navyše bolo navrhnuté bočné napájanie pásu základného stavu kaskádou dvoch prechodov. Práca diskutuje systematiku 11^- izomérov a sily $E3$ prechodov v izotopoch Po a Pb z hľadiska nových spektroskopických výsledkov. Skúmaná bola aj jemná štruktúra α premeny ^{192}Po a ^{194}Po. Známe jemné α prechody vedúce na vzbudené 0^+ hladiny boli identifikované pre oba izotopy a boli vyhodnotené horné limity intenzít pre prípadné ďalšie, zatiaľ nepozorované α prechody. Bol pozorovaný náznak nového α prechodu v ^{192}Po. Pre izotopy $^{193-195}$Po a ^{194,195}At, produkované v reakcii $^{56}Fe + ^{141}Pr$, boli vyhodnotené excitačné funkcie. Výsledky boli porovnané s výpočtami uskutočnenými pomocou kódu HIVAP, ktorý je založený na štatistickom modeli.

Kľúčové slová: izomér, γ spektroskopia, excitačná funkcia

Abstract

The topic of this Thesis is the study of neutron-deficient polonium and astatine isotopes with main focus on γ-ray spectroscopy of isomeric states in ^{192,194}Po. Investigated isotopes were produced in fusion-evaporation reactions $^{56}Fe + ^{141}Pr$ and $^{51}V + ^{144}Sm$ at GSI in Darmstadt (Germany). Reaction products were separated from the primary beam by the velocity filter SHIP and studied using detectors placed at the focal plane of the separator. Four new γ transitions were attributed to the isomer in ^{194}Po and γ-γ coincidences were investigated for the first time for this isomer. The transition, which was in previous experiment suggested to de-excite the isomeric level, was replaced by the new 248 keV transition. Moreover, the spin of the isomer was reassigned from (11^-) to (10^-), which caused an unexpected change in the chain of isomers in Po isotopes. More precise half-life of 12.9(5) μs was determined. Spin and parity (11^-) of the isomer in ^{192}Po was supported and 14 new γ transitions were attributed to the isomer. Also for this isomer, γ-γ coincidences were studied for the first time. De-excitation of the isomeric level by the 733 keV ($E3$) transition parallel to the 154 keV transition was proposed. Moreover, side-feeding of the ground-state band by the cascade of two transitions was suggested. The Thesis discusses systematics of 11^- isomers and $E3$ transition strengths in neutron-deficient Po and Pb isotopes in respect to new decay-spectroscopy results. In addition, fine structure in the α decay of both ^{192}Po and ^{194}Po was investigated. Previously known fine α-decay lines decaying to excited 0^+ states were identified and upper limits of intensity for additional fine α transitions were evaluated. Hint of a new fine α transition in ^{192}Po was observed. Excitation functions of isotopes $^{193-195}$Po and ^{194,195}At produced in reaction $^{56}Fe + ^{141}Pr$ were evaluated. Results were compared with calculations performed using statistical model code HIVAP.

Keywords: isomer, γ spectroscopy, excitation function

Introduction

This report presents main results of the Dissertation Thesis "Study of neutron-deficient polonium isotopes". First, objectives of the Thesis are defined and experiment is briefly described. Afterwards, main results of the Thesis are following and Slovak summary is included at the end. The last part of this report is the list of author's publications.

In the region near $Z = 82$, one of the longest series of isomers is known. Isomeric states with spin and parity 11^- are present in all even-A polonium isotopes with $196 \leq A \leq 210$ and their typical half-lives are between 0.5 ns and 1 μs. Most of these isomers de-excite via $E3$ transitions to 8^+ states [1, 2, 3, 4, 5, 6] with unexpected increase of transition strengths towards lower neutron numbers. The increase was discussed in connection to deformation of nuclei in [7]. Short-lived isomeric states were identified also in isotopes ^{192,194}Po [8, 9]. However, their spins, parities and decay paths were uncertain.

The Thesis is based on analysis of data on ^{192,194}Po collected at the velocity filter SHIP at GSI, Darmstadt (Germany). At the beginning, objectives of the thesis are defined, followed by physical background mainly in radioactive decay and fusion reactions. Afterwards, the SHIP is described alongside with its detection system. Main part of the Thesis is aimed at γ spectroscopy of short-lived isomeric states in ^{192,194}Po and following discussion on systematics of (11^-) isomers in neutron-deficient Po and Pb isotopes. Main results and discussions are going to be published in *Physical Review C* [10].

Remaining results include study of the fine structure in the α decay of ^{192,194}Po and evaluation of production cross-sections of $^{193-195}$Po and ^{194,195}At, which were synthesized in the reaction $^{56}Fe + ^{141}Pr \longrightarrow ^{197}At^*$. Cross-sections are compared with results of calculations in statistical model code HIVAP. Partial preliminary results on cross-sections and γ spectroscopy were published in *AIP Conference Proceedings* [11]. The Thesis is complemented by an appendix dedicated to new detection system at SHIP, mainly the analysis code for this new system.

1. Objectives

Decay Spectroscopy of ^{192}Po and ^{194}Po

The first objective of the Thesis is γ-ray spectroscopy of isomeric states in ^{194}Po and ^{192}Po, on which only limited information was available so far. Isomeric states with $I^\pi = 11^-$ are present in all heavier, even-A isotopes of Po up to ^{210}Po. The dominant configuration of the 11^- levels is $\pi h_{9/2} i_{13/2}$ [8] and they are decaying mostly via $E3$ transitions to 8^+ states. These decays exhibit unexpected enhancement of $B(E3)$ values with decreasing neutron number [2, 1]. Isomers in ^{194}Po and ^{192}Po are expected to have a similar character as the isomers in heavier Po isotopes based on the systematics [8, 9]. However, their spin and parity assignments and decay schemes were uncertain. In respect to unexpected increase of $B(E3)$ values, it is of interest to determine whether the chain of the 11^- isomeric states continues down to ^{194}Po and ^{192}Po and what would be the behaviour of $E3$ transition strengths. Additional goal is to investigate and confirm fine-structure α decays in discussed nuclei.

Cross Sections for the Production of At and Po Isotopes

The second objective of the Thesis is to evaluate experimental reaction cross sections for isotopes produced in reactions $^{56}Fe + ^{141}Pr \longrightarrow ^{197}At^{*}$ via pn and pxn channels. The goal is to obtain excitation functions of the reactions, i.e. dependence of the reaction cross section on the excitation energy of the compound nucleus. The next step is to compare the experimental data with results of calculation using statistical model code HIVAP. This will help to improve accuracy of cross-sections calculations in this area of isotopes, which is important for planning of future experimental measurements. Cross sections are extremely sensitive to excitation energy. A change in excitation energy of few MeV can result in change of the cross section greater than one order of magnitude, as for example for production reactions of neutron deficient bismuth and polonium isotopes [12].

2. Experiment

The isotopes ^{194}Po and ^{192}Po were studied at the velocity filter SHIP in GSI Darmstadt (Germany). They were produced in fusion-evaporation reactions $^{56}Fe + ^{141}Pr \longrightarrow ^{194}Po + p2n$ and $^{51}V + ^{144}Sm \longrightarrow ^{192}Po + p2n$. Targets were mounted on a rotating wheel, which rotated with frequency synchronized to pulsed structure of the projectile beam provided by the accelerator UNILAC. Evaporation residues (ERs) were separated from the primary beam by the SHIP and implanted into the position-sensitive 16-strip silicon detector PSSD. The PSSD was complemented by 6 more silicon strip detectors mounted around it parallel to the beam and forming so called BOX detector. Its purpose is to detect particles escaped from the PSSD, i.e. α particles, conversion electrons or fission fragments. For detection of γ and x rays, four-crystal germanium clover detector was mounted behind the PSSD in close geometry. Time and position correlation method was employed to identify events of interest.

The isotope ^{194}Po was produced in run R250. Resolution of the PSSD in the energy range from 6 to 7 MeV was approximately 31 keV (FWHM), energy resolution of the clover detector was 1.8 keV (FWHM) for the 344 keV line from ^{152}Eu. The isotope ^{192}Po was produced in runs R224 and R225. They will be together denoted in following text as R224. Energy resolution of the PSSD was 35 keV (FWHM) for the ^{192}Po peak (7167 keV). To achieve higher precision of clover detector calibration, we made separate calibration for lower energies and separate calibration for higher energies. Energy resolution of lower-energy part was 2.5 keV (FWHM) for the 344 keV line of ^{152}Eu. In higher-energy part, resolution was 2.7 keV (FWHM) for the 964 keV line.

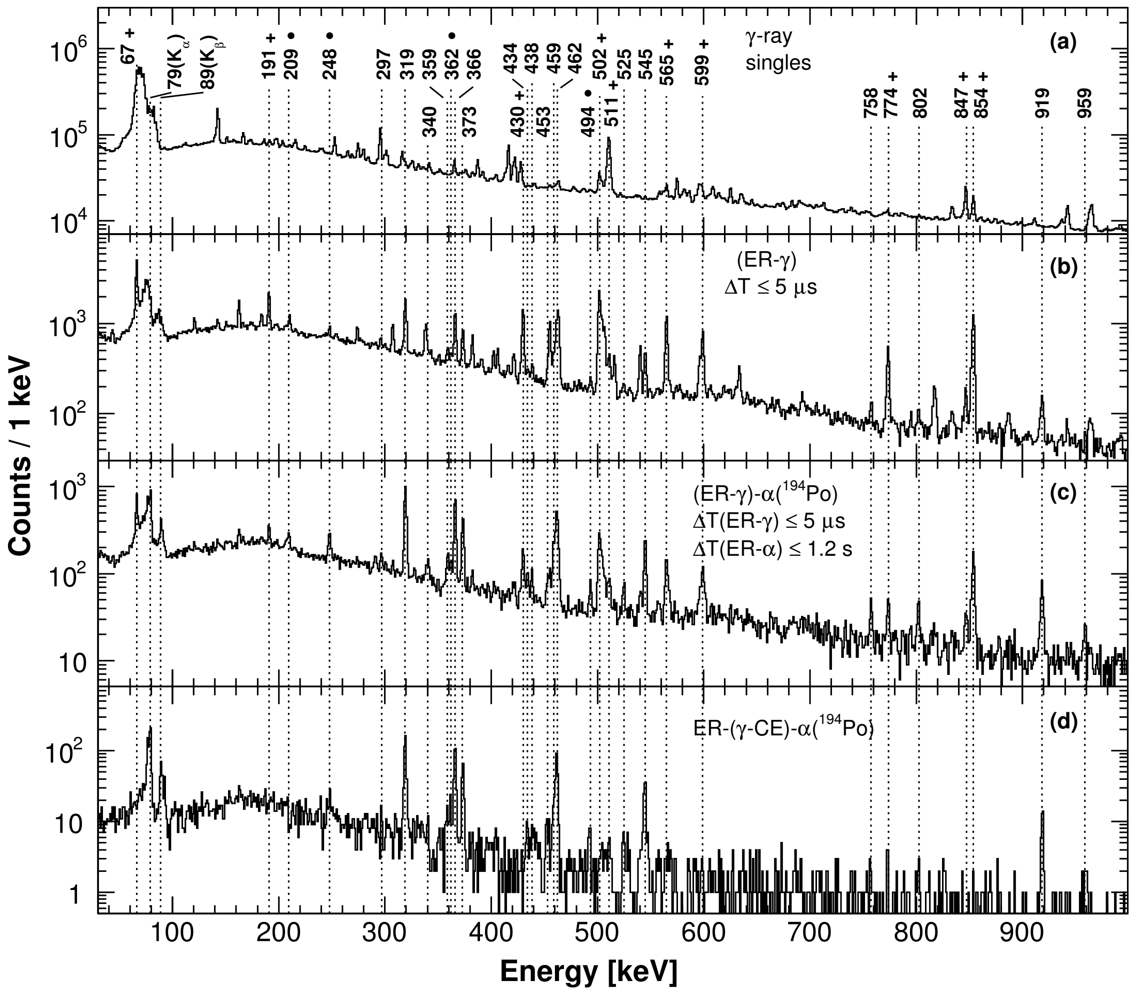

Figure 1: (a) all γ rays registered during production of ^{194}Po; (b) γ rays in coincidence with ERs; (c) γ rays in coincidence with ERs correlated to α decays of ^{194}Po with the correlation time up to 1.2 s; (d) γ rays in coincidence with conversion electrons from correlation chains ER-(γ-CE)-α(^{194}Po)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

3. Results

Gamma Spectroscopy of Isomeric State in ^{194}Po

In total, we registered approximately 1.6 million of ^{194}Po α particles in correlations with ERs using PSSD + BOX detectors. Correlation time window was equal to three half-lives of ^{194}Po ($T_{1/2}$(^{194}Po) = 392 ms [13]) and position difference of two correlated signals along the strips of PSSD was required to be ≤ 0.6 mm.

An energy spectrum of all γ rays collected in the focal-plane clover detector is shown in Fig. 1 (a). The amount of background γ rays is significantly reduced, when coincidences within 5 μs window between γ rays and ERs were required (see Fig. 1 (b)). In order to obtain γ rays originating specifically from ^{194}Po, we furthermore requested correlations of ERs to 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. We identified all previously reported transitions from the isomer, mainly the 373 keV and 919 keV transitions that were suggested to feed 8^+ and 6^+ states from the ground-state band [8], respectively, and subsequent transitions from this band (545, 462, 366 and 319 keV). Moreover, we observed transitions from the side band up to 9^- level (formerly seen only in prompt γ-ray spectroscopy [8]) 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 1.

Table 1: 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 previous study [8]. 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 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 [14]. However, conversion coefficients could be increased by possible admixtures of $E0$ components or decreased by possible admixtures of $E2$ components. Intensities are relative to the intensity of the 319 keV transition. Mult. stands for multipolarity.

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

We deduced a half-life of the isomer using ER-γ-α(^{194}Po) correlations to be 12.9(5) μs which is consistent with the previously published value of 15(2) μs [8], but more precise. As a result of significantly higher statistics ($\approx 10\times$) than in previous measurement [8], we observed γ-γ coincidences of γ rays emitted by the isomer in ^{194}Po for the first time. Specifically, we analysed γ-γ coincidences for seven most intensive γ transitions and with more limited statistics, also for the 919 keV transition. Coinciding lines are listed in Table 2. For (ER-γ-γ)-α(^{194}Po) correlations the time window was equal to three half-lives of ^{194}Po.

Behaviour of the 319, 366 and 373 keV transitions in respect to γ-γ coincidences is consistent with the level scheme from previous experiment [8]. According to the level scheme, the 459

Table 2: List of γ-γ coincidences for de-excitation of the isomeric state in ^{194}Po. Energies are given in keV, tentative coincidences are written in italic.

Gate	Coinciding lines
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

keV transition should be in coincidence with all the other transitions from the isomer. However, we did not see coincidences of the 459 keV transition with the 545 keV, 462 keV and 919 keV transitions. It was in coincidence only with the 319, 366, 373 and probably also the 248 keV transitions and its proper position in the decay scheme remains unclear. Keeping in mind the exception of the 459 keV transition, coincidence spectra of 545, 462 and 918 keV transitions agree with the level scheme.

The new 248 keV transition is in coincidence with all investigated transitions, except of the 919 keV transition. However, missing γ-γ coincidences between the 248 and the 919 keV transition (possibly also between 459 and 919 keV) are likely to be caused by low intensity of the 919 keV line. Based on these observations, we suggested to replace the 459 keV transition by the 248 keV transition in the decay scheme.

Discussion for ^{194}Po

Our observation is summarised in Fig. 2, which shows a modified decay scheme from previous study [8]. We included only transitions observed in our measurement. In order to determine multipolarity of the 248 keV transition, we deduced K-conversion coefficient using number of Po K x rays from coincidence analysis to be 2.3(4). The value agrees with theoretical K-conversion coefficient for the $M2$ multipolarity of the transition, which is equal to 2.56(4) [15]. Our value is only an upper limit, since we cannot rule out additional sources of Po K x rays, as e.g. significant $E0$ component of $\Delta J = 0$ 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 contribution of other sources of Po K x rays would have to be high. These observations strongly suggests that the 248 keV transition is of $M2$ multipolarity. The suggestion is also supported by intensity balance.

This multipolarity assignment yields $I^{\pi} = (10^{-})$ for the initial isomeric level. The value of the spin is unexpected, as no such isomer has been identified in neighbouring isotopes. The

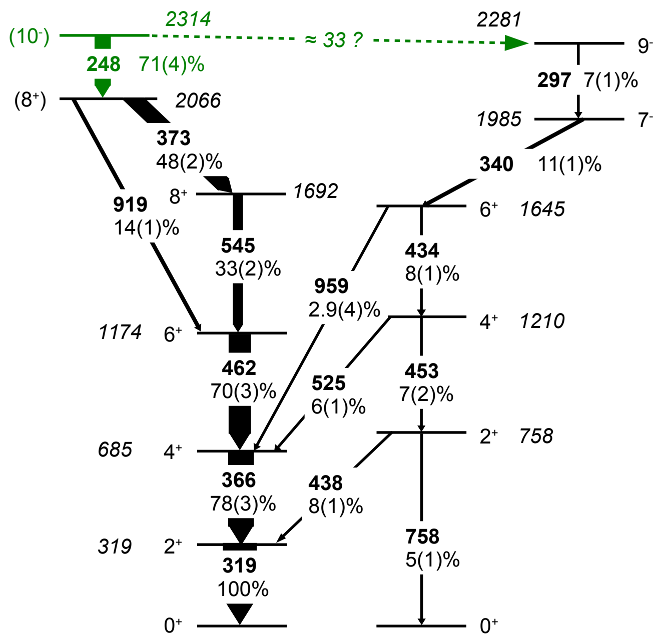

Figure 2: Decay scheme of the isomer in ^{194}Po. It is a part of the scheme from [8] modified accordingly to our observation. Proposed changes are highlighted by a green color. A transition with energy ≈ 33 keV was not observed, but we discuss its possible existence in the text.

configuration of this state is uncertain, since our measurement cannot provide direct information on the structure and there are no systematics to compare with. 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 [16], which is the same as the configuration of 11^- isomers in Po isotopes [17]. 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, 3]. The hindrance of these $(M1)$ and $E2$ transitions may be caused by significant change in configuration between the initial and final states.

Transitions at the right part of the scheme (side band), originating at 9^- level with an energy of 2281 keV, were previously observed only in in-beam measurement at RITU [8]. In our study, we observed these transitions in delayed γ-ray spectroscopic data, which means these levels are populated by the decay of an isomeric state. Possible explanation may be 33 keV transition (unobserved in our measurement) from (10^-) isomeric level to 9^- level or another isomeric state above 9^- level.

Gamma Spectroscopy of Isomeric State in ^{192}Po

In total, we registered approximately 110 000 ER-α(^{192}Po) correlations using PSSD + BOX detectors. Upper limit for position difference of two correlated events was set to be ≤ 0.7 mm. Correlation time was 132.8 ms, which is equal to 4 half-lives of ^{192}Po ($T_{1/2}$ = 33.2 ms [18]).

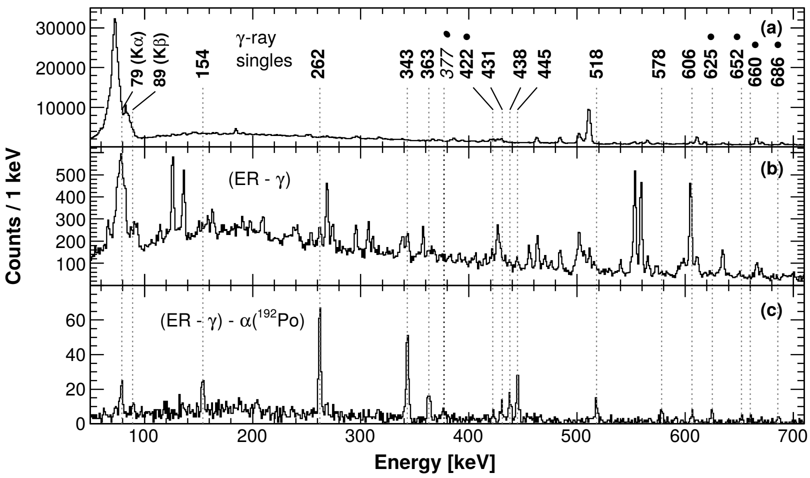

Figure 3: Lower-energy parts of γ-ray spectra: (a) all γ rays collected during measurement with production of ^{192}Po; (b) γ rays registered in coincidence with ERs; (c) γ rays in coincidence with ERs correlated to α decays of ^{192}Po. New transitions are denoted by full circles, the γ line with label written in italic is tentative.

To search for ^{192}Po γ rays, we used (ER-γ)-α(^{192}Po) correlations, similarly as in the case of ^{194}Po. Large suppression of unwanted events is shown in Fig. 3 (the lower energy part of the spectrum). The figure compares a spectrum of all registered γ rays (top panel), a spectrum of γ rays in coincidence with any ER (middle panel) and the spectrum of γ rays from (ER-γ)-α(^{192}Po) correlations. Statistics for γ rays from the isomer was $\approx 2\times$ higher than in previous experiment [9].

On the basis of comparison of spectra in Fig. 3 and the same comparison also for higher energy part, we are confident to assign γ-ray peaks, that emerged in (ER-γ)-α(^{192}Po) correlations and were invisible or very weak in ER-γ coincidences only, to the isomer in ^{192}Po. We confirmed all previously-known transitions, including ground-state band transitions down from (10^+) level with energies 578, 518, 438, 343 and 262 keV. Moreover, we attributed 14 new γ transitions to the isomer, however, 6 of them are only tentative. All γ-ray peaks assigned to the ^{192}Po are summarised in Table 3.

In order to perform γ-γ coincidence analysis, we combined our new data with data from previous study [9], which was also performed at the SHIP. As a result, we observed γ-γ coincidences also for this isomer for the first time by employing (ER-γ-γ)-α(^{192}Po) correlations. Coinciding transitions are listed in Table 4.

Discussion for ^{192}Po

It was suggested already in [9] that the 154 keV transition may de-excite (11^-) isomer above the (10^+) level of the ground-state band. The suggestion was based on supposed $E1$ multipolarity of the transition, which was deduced from the low number of observed K x rays. Firm placement into the decay scheme was not possible due to lack of γ-γ coincidences, but our γ-γ coincidence data support the suggestion. An $E1$ character of this transition is indicated by relative intensities

Table 3: Gamma rays attributed to the isomer in ^{192}Po from (ER-γ)-α(^{192}Po) correlations. Reference energies were taken from [9]. Gamma transitions without reference energies were observed for the first time, tentative lines are written in italic. Intensities are relative to the intensity of the 262 keV line. Multipolarities of transitions from ground-state band are based on decay scheme from [8], multipolarities of 154, 363, 445 and 733 keV transitions are discussed in 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 [%]	Multipolarity	E_γ [keV]	I_γ [%]	Multipol.
153.9(3)	154	27(5)	($E1$)	624.6(4)	≥ 12(4)	
262.1(1)	262	100	($E2$)	651.8(7)	≥ 6(3)	
343.1(2)	343	90(10)	($E2$)	659.6(10)	≥ 7(3)	
362.8(3)	363	32(5)	($E2$)	685.7(6)	≥ 7(3)	
376.8(10)		≥ 18(4)		720.4(10)	≥ 14(4)	
422.4(5)		≥ 6(3)		733.1(4)	7(3)	($E3$)
430.7(5)	431	≥ 14(4)		*834.6(10)*	≥ 6(3)	
437.9(3)	438	26(5)	($E2$)	965.7(10)	≥ 8(3)	
445.0(2)	445	52(8)	($M1$)	*1096(1)*		
517.8(4)	518	22(5)	($E2$)	*1172(1)*		
578.4(4)	578	13(4)	($E2$)	*1231(1)*		
606.3(4)	605	≥ 12(4)		*1258(1)*		

Table 4: List of γ-γ coincidences for de-excitation of the isomeric state in ^{192}Po. 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*

of subsequent transitions. If we assumed another possible character for the 154 keV transition, it would result in higher internal conversion coefficient and the relative intensity would be significantly higher. In addition, any magnetic multipole 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. The side-feeding is

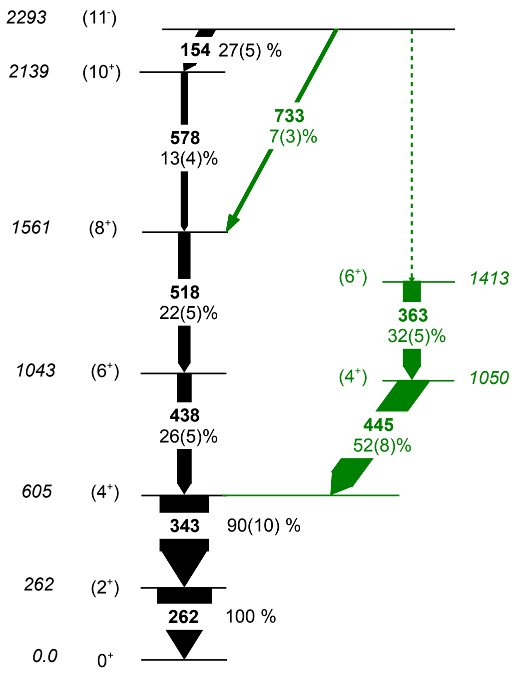

Figure 4: Decay scheme of the (11^-) isomeric state in ^{192}Po. Ground-state band up to (10^+) level is taken from [8], placement of the 154 keV transition was proposed in a previous study [9]. Our changes to the decay scheme are highlighted by green color.

also supported by the balance of relative intensities. The (4^+_1) level is populated by the 438 keV transition with the relative intensity of only 26(5) % while the subsequent 343 keV transition has the relative intensity of 90(10) % (Fig. 4). Connecting the 445 keV transition to the (4^+_1) level adds the relative intensity of 52(8) % to the feeding of the level. We also tentatively placed the less intense 363 keV transition into the cascade with the 445 keV transition, because of mutual coincidences. In this way, we suggested two additional levels, (4^+_2) and (6^+_2). Their spins and parities were tentatively assigned based on similar levels present in ^{194}Po [8] and ^{196}Po [1].

Moreover, we tentatively suggested to place the 733 keV transition between (11^-) and (8^+) levels, which gives an $(E3)$ character to this transition. The placement is based mainly on energy balance and systematic presence of $E3$ transitions in decay paths of 11^- isomers in Po isotopes. Nevertheless, we also observed a hint (3 counts) of this transition in γ-γ coincidence analysis.

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 dominant configuration of $\pi\{(h_{9/2})\otimes(i_{13/2})\}$ are present [1, 2, 3, 4, 5, 6, 19, 7]. Isomers were identified also in ^{194}Po and ^{192}Po with the same supposed spin and parity [8, 9]. In the most cases, these 11^- isomers de-excite via $E3$ transitions to 8^+ levels ($^{210,208,202-196}$Po [6, 5, 3, 17, 1] and $^{196-190}$Pb [7, 19]).

The isomer in ^{210}Po de-excites via two $E3$ transitions [6]. One of them leads to $\pi\{(h_{9/2})\otimes(f_{7/2})\}_{8^+}$ state with strength of 19(3) W.u. It is characterised by a single-particle transition $\pi i_{13/2} \rightarrow \pi f_{7/2}$ and belongs to group of transitions with average strength of 22 W.u. [20]. The second one and 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 $\pi(1h^2_{9/2})_{8^+}$ states. They are characterised by a spin-flip transition $\pi i_{13/2} \rightarrow \pi h_{9/2}$, which typically causes low average $B(E3)$ value of 3 W.u. [20]. However, for $^{202\text{-}196}$Po and $^{196\text{-}190}$Pb, $B(E3)$ values are gradually increasing with decreasing neutron number up to 25(3) and 24(4) W.u. in ^{198}Po and ^{196}Po, respectively [2, 1].

It was discussed in earlier works [1, 17], that higher $B(E3)$ values for $^{196-200}$Po might be caused by admixture of 3^- octupole collective state into the initial state, and/or admixtures to the final state from either $\pi\{(h_{9/2}) \otimes (f_{7/2})\}_{8^+}$ or $\{(11^-) \otimes (3^-)\}_{8^+}$ state [1, 17]. Later, another explanation was proposed, that high $B(E3)$ values are caused by an oblate deformation, which results in an admixture of the 8^+ state with $f_{7/2}$ orbital into the lower 8^+ state. Resulting strength of such $E3$ transition is ≈ 20 W.u. [7, 19].

The 733 keV transition in ^{192}Po with tentative ($E3$) yields B($E3$) value of 2(1) W.u. (or 0.6(3) W.u. when branching ratio equal to relative intensity from Table 3 is considered), which corresponds to values of standard spin-flip $E3$ transitions in [20]. Therefore it does not follow the interpretation from [19, 7] and changes the trend compared to $^{200-196}$Po. This may be a hint that e.g. the configuration of the (8^+) state populated in ^{192}Po is different compared to heavier Po isotopes or that the shape of nucleus has changed.

The 154 keV ($E1$) transition in ^{192}Po has very low strength compared to heavier isotopes $^{208-204}$Po. However, $B(E1)$ values for more neutron deficient Po nuclei are not known and there is 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.

Fine structure in the α decay of ^{192}Po and ^{194}Po

Fine structure in the α decay of ^{192}Po and ^{194}Po was already investigated in the past as a method for identification of low lying excited 0^+ states in ^{188}Pb and ^{190}Pb and thus study shape coexistence in these isotopes, e.g. in [9] and [21]. Since fine structure α decays lead to daughter nucleus in an excited state, de-excitation via internal conversion may take place, which is accompanied by emission of conversion electrons (CE) and x rays. In the case the state in daughter nucleus is the lowest excited state and it has $I^\pi = 0^+$, it may de-excite only by emission of CE. Depending on CE direction, its energy can be absorbed in the PSSD and summed with energy signal of α particle or it may escape from the PSSD and be registered in BOX detectors. Therefore, BOX detectors can be used for gating of ER-α correlations in search for fine structure in α decay. Moreover, a coincidence with x ray from daughter atom may be also required as a more strict condition.

To search for transitions in the fine structure of ^{192}Po α decay, we used combined data from R199 and R224. The results of our investigation are presented in Fig. 5. In the top panel, all ER-α correlations from R199 + R224 are shown, time and position windows were the same as for γ-ray analysis. In the middle panel, there are ER-α correlations gated by BOX detectors, which means, that the signal from BOX detectors (presumed CE) was required in coincidence with α particle. The last panel presents ER-[α-x ray(Pb)] correlations gated by BOX detectors.

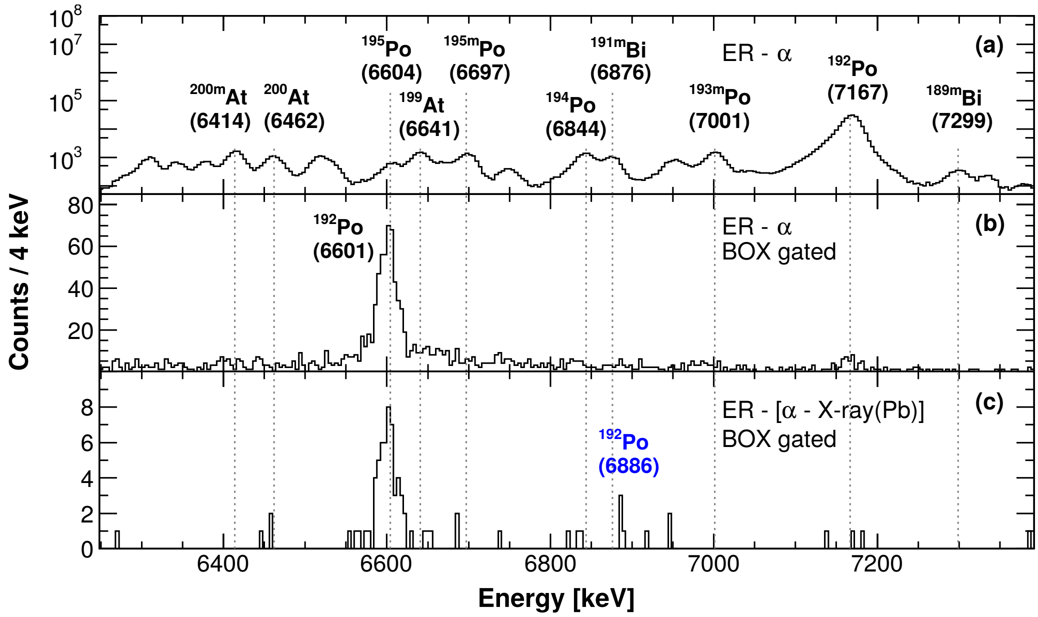

Figure 5: Fine structure in α decay of ^{192}Po. Panel a): α spectrum from ER-α correlations; panel b): α spectrum from ER-α correlations, with required coincidence between α and CE registered in BOX detectors; panel c): α spectrum from ER-[α-x ray(Pb)] correlations, with required coincidence between α and CE registered in BOX detectors.

The known fine α transition with energy of 6601 keV is present in both BOX gated spectra. Taking corrections for α and CE summing from [9] into account account, the energy of the line was deduced to be 6591(5) keV and the intensity relative to main α transition from ^{192}Po is 1.2(2) %. This is consistent with values from [9], where the energy of 6591(8) keV and intensity of 1.5(3) % were determined. With the given level of the background, upper limit of the intensity of unobserved another α transition is 0.06 % of the main α transition. A hint of a new line at energy 6886 keV appeared in the last panel, where the most strict conditions were applied. After correction for summing with CE energy, the energy of the new line would be 6876(7) keV. However, intensity of this tentative line is 0.11(6) %, which is slightly above the detection limit for ER-(α-CE) correlations, but there is no clear indication of this line in corresponding spectrum (Fig. 5, panel (b)).

In the same way as in the case of ^{192}Po, we investigated also fine structure in the α decay of ^{194}Po. The known fine α decay with the energy of 6194 keV [22] is clearly visible both in panel (b) and (c) with measured energy of 6198 keV, which after correction for summing with CEs would be 6188(5) keV. The intensity of 6188(5) keV line deduced from ER-(α-CE) correlations is 0.24(4) % of the main α transition in ^{194}Po, which is consistent with value 0.22 % from [22]. Upper limit for the intensity of another unobserved α transition is 0.03 % of the main α transition.

Production Cross-Sections

Several beam energies (236, 242, 250, 259 and 273 MeV) were used for the measurement with the production reaction $^{56}Fe + ^{141}Pr \longrightarrow ^{197}At^*$, which allowed us to evaluate dependences of cross-sections on the excitation energy of compound nucleus (CN) - excitation functions. For planning of new experiments, it is crucial to know the excitation function, so that optimal reaction and beam energy can be chosen to achieve sufficient production of studied nuclei. If no experimental data for the specific reaction are available, the excitation function can be estimated using for example statistical model code calculations. To improve the accuracy of such calculations, experimental data for similar reactions are important.

We determined cross-sections for the respective products in *xn* and *pxn* channels for reaction mentioned above, using ER-α or ER-α-α correlations corrected for detection efficiency, branching ratios, half-lives and transmission through the separator. Excitation energies of compound nuclei were calculated for the beam energy in the middle of the target. We compared experimental values with calculations performed with the statistical model code HIVAP [23, 24] using two different modes. The first mode involves fusion barrier approximated by a truncated Gaussian and employs fluctuations of the barrier, which enables to estimate sub-barrier fusion. The second mode involves simple fusion barrier approximated by an inverted parabola without barrier fluctuations and strongly suppresses sub-barrier fusion. We used scaling parameter for theoretical fission barrier of CN with value $C_f = 0.69$ based on comparison with experimental points. The value agrees with systematics from [12], where $C_f \approx 0.70$ is needed for Bi or Po compound nuclei with $A = 197$, which is close to our value of C_f for the CN ^{197}At.

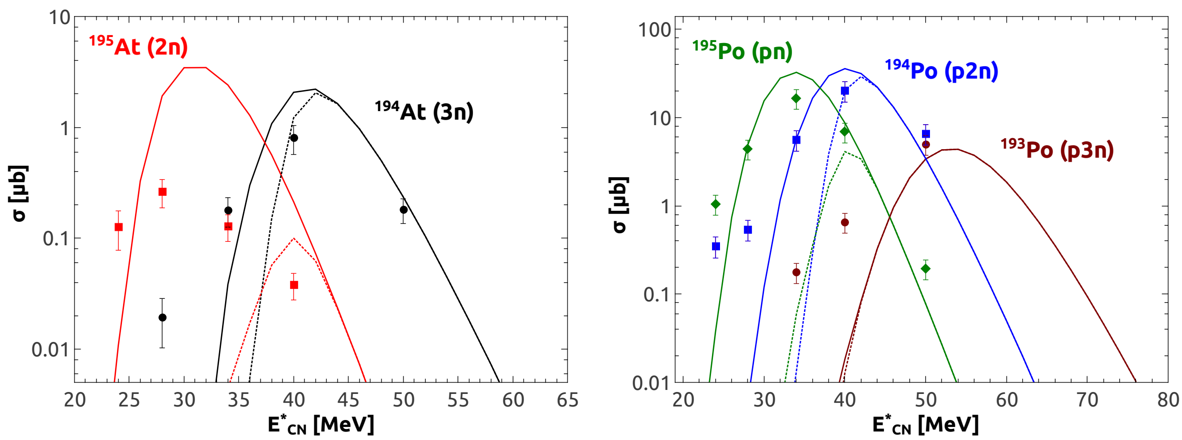

Figure 6: Cross sections of *xn* and *pxn* channels of the reaction $^{56}Fe + ^{141}Pr \longrightarrow ^{197}At^*$ as functions of excitation energy of CN. Experimental values are denoted by points. Lines represent HIVAP calculations using $C_f = 0.69$. Solid lines are for the mode with barrier fluctuations, dashed lines are for the mode with fusion barrier approximated by an inverted parabola.

Comparison of both modes of calculations with experimental values for *xn* and *pxn* channels separately is shown in Fig. 6. We can see that $2n$ channel is only partially suppressed by the fusion barrier, since experimental points are closer to calculation with barrier fluctuations. The suppression of $3n$ channel is even weaker. In the case of *pxn* channels, suppression by the fusion barrier is weak for both pn and $p2n$ channels. For the reaction $^{51}V + ^{144}Sm \longrightarrow ^{195}At^{*}$, in which ^{192}Po was produced, only one beam energy of 235 MeV was used, thus we could not establish excitation functions. However, we evaluated cross-section for ^{192}Po and compared it with HIVAP calculations with scaling factor deduced from systematics in [12].

Zhrnutie

V dizertačnej práci Study of neutron-deficient polonium isotopes prezentujeme štúdium neutrónovo deficitných izotopov polónia ^{192}Po a ^{194}Po metódami rozpadovej spektroskopie. Hlavným cieľom bola γ spektroskopia krátkožijúcich izomérov v ^{192,194}Po, o ktorých boli doposiaľ známe iba obmedzené informácie. Predpokladalo sa však, že patria do dlhého radu 11^- izomérov nachádzajúcich sa v izotopoch Po s párnym A od ^{210}Po po ^{196}Po, ktoré de-excitujú prevažne $E3$ prechodmi na 8^+ stavy. Sily týchto prechodov vykazujú nečakaný nárast s klesajúcim neutrónovým číslom [2, 1]. Doplnkovým cieľom bolo štúdium jemnej štruktúry α premeny skúmaných izotopov. Druhým cieľom bolo vyhodnotenie účinných prierezov produkcie izotopov Po a At, ktoré boli produkované v našich meraniach a porovnanie týchto hodnôt s výpočtami uskutočnenými v kóde HIVAP založenom na štatistickom modeli.

Experimenty boli uskutočnené na rýchlostnom filtri SHIP v GSI, Darmstadt (Nemecko). Študované izotopy boli produkované vo fúzno výparných reakciách $^{56}Fe + ^{141}Pr \longrightarrow ^{194}Po + p2n$ a $^{51}V + ^{144}Sm \longrightarrow ^{192}Po + p2n$. Produkty fúznych reakcií (PR) boli oddelené od primárneho zväzku separátorom SHIP a privedené do detekčného systému. Na identifikáciu želaných eventov sme využili časovú a polohovú korelačnú metódu. Identifikovali sme približne 1.6 milióna α premien ^{194}Po, ktoré boli korelované s implantáciou PR do detektora. Na vyselektovanie γ kvánt pochádzajúcich z izoméru v ^{194}Po sme vyžadovali koincidencie medzi korelovanými PR a γ kvantami vrámci intervalu $\approx 5\,\mu$s. Počet zaregistrovaných γ kvánt z tohto izoméru bol približne 10 krát vyšší než v predošlom meraní [8]. Pozorovali sme všetky γ prechody známe pre jeho de-excitáciu a priradili mu štyri nové γ prechody s energiami 209, 248, 362 a 494 keV. Určili sme polčas rozpadu izoméru $T_{1/2} = 12.9(5)\mu$s, čo je konzistentné s hodnotou z predošlej štúdie $T_{1/2} = 15(2)\mu$s [8], ale zároveň presnejšie.

Vďaka štatistike nahromadenej počas merania sme mohli po prvý krát pre tento izomér študovať γ-γ koincidencie. ($E3$) prechod s energiou 459 keV, ktorý bol navrhnutý v [8] ako prechod de-excitujúci izomér s predbežne priradeným spinom a paritou (11^-) sme nahradili novým prechodom s energiou 248 keV. Tomuto prechodu sme na základe konverzného koeficientu priradili multipolaritu $M2$, čo znamená nečakanú zmenu spinu izoméru na $I^\pi = (10^-)$ namiesto $I^\pi = (11^-)$. Toto priradenie spinu je v kontraste so známou systematikou izomérov v izotopoch Po a vyžaduje detailné štúdium v budúcich experimentoch. Výsledky prezentované v tejto práci sú však získané z experimentálnych dát, ktoré sú na hranici toho čo je možné v súčasnosti dosiahnuť.

Zároveň sme pozorovali γ prechody z bočného pásu až po 9^- hladinu, ktoré boli predtým registrované iba v in-beam meraní [8]. Znamená to, že bočný pás musí byť napájaný rozpadom izoméru. Možným vysvetlením je (nepozorovaný) prechod s energiou ≈ 33 keV z (10^-) izoméru na 9^- stav alebo napájanie z neznámeho izoméru nachádzajúceho sa nad 9^- stavom.

Rovnakým spôsobom ako v prípade ^{194}Po sme analyzovali aj dáta pre ^{192}Po. Zaznamenali sme približne 110 000 PR-α(^{192}Po) časových a polohových korelácií. Pre γ kvantá z izoméru sme opäť vyžadovali koincidencie s korelovanými PR vrámci $\approx 5\,\mu$s. Nahromadená štatistika bola približne dvakrát väčšia ako v predošlom meraní [9]. Pozorovali sme všetky známe γ prechody pre daný izomér a priradili sme mu 14 nových γ prechodov, z toho 6 však iba predbežne.

Pre účely γ-γ koincidenčnej analýzy sme spojili naše nové dáta s dátami z predošlého merania, ktoré bolo tiež uskutočnené na seprátore SHIP [9]. Aj pre tento izomér sme tak po prvý krát pozorovali γ-γ koincidencie. Podporili sme návrh z [9], že prechod s energiou 154 keV de-excituje izomérny stav (11^-) na (10^+) hladinu. Navyše sme navrhli paralelnú de-excitáciu izoméru pomocou 733 keV ($E3$) prechodu na (8^+) stav. Na základe γ-γ koincidencií a súladu relatívnych intenzít sme navrhli bočné napájanie pásu základného stavu na (4^+) hladinu kaskádou prechodov s energiami 363 a 445 keV.

V spojitosti so systematikou 11^- izomérov v izotopoch Po s párnym A, pre ^{194}Po sme pozorovali iba vyššie diskutovaný (10^-) izomérny stav, čo znamená nečakané prerušenie v systematike. Pre izomér v ^{192}Po naše meranie podporuje očakávané priradenie (11^-) v súlade so systematikou. Nový prechod s energiou 733 keV, ktorý de-excituje izomér v ^{192}Po má $B(E3) = 2(1)$ W.u. To predstavuje nečakaný pokles oproti silám $E3$ prechodov v $^{196-200}$Po, kde boli pozorované stúpajúce $B(E3)$ hodnoty s klesajúcim netrónovým číslom [2, 1]. Tento pokles môže naznačovať zmenu konfigurácie (8^+) stavu, ktorý je napájaný daným ($E3$) prechodom, prípadne zmenu tvaru jadra.

Pre oba izotopy, ^{192}Po a ^{194}Po, sme študovali aj jemnú štruktúru α premeny. Využili sme PR-α korelácie, kde pre α časticu bola vyžadovaná koincidencia (vrámci $\approx 5\,\mu$s) s konverzným elektrónom. Známy α prechod s energiou 6194 keV z jemnej štruktúry α premeny v ^{194}Po [22] sme potvrdili a pozorovali s energiou 6188(5) keV. Pre potenciálny ďalší α prechod sme určili horný limit 0.03 % z intenzity hlavného α prechodu v ^{194}Po. Pre ^{192}Po sme tiež potvrdili známy α prechod s energiou 6591(8) z jemnej štruktúry [9] a namerali sme preň energiu 6591(5) keV. Zároveň sme pozorovali náznak ďalšej jemnej α čiary s energiou 6876(7) keV.

Vyhodnotili sme excitačné funkcie pre izotopy $^{193-195}$Po a ^{194,195}At produkované v reakcii $^{56}Fe + ^{141}Pr \longrightarrow ^{197}At^*$. Výsledky sme porovnali s výpočtami s použitím kódu HIVAP vychádzajúceho zo štatistického modelu. Na správnu reprodukciu excitačných funkcií bola potrebná redukcia teoretickej štiepnej bariéry v HIVAPe, pričom toto zníženie bolo konzistentné so systematikou zostavenou pre reakcie vedúce na zložené jadrá Po a Bi s podobným hmotnostným číslom [12]. Pre reakciu $^{51}V + ^{144}Sm$ bola použitá iba jedna energia zväzku, preto nebolo možné zostaviť excitačné funkcie. Vyhodnotili sme však účinný prierez produkcie ^{192}Po a opäť porovnali s výpočtami v HIVAPe.

Výsledky týkajúce sa krátkožijúcich izomérov boli akceptované na publikáciu vo *Physical Review C* [10] a čiastkové predbežné výsledky z účinných prierezov a γ spektroskopie boli publikované v *AIP Conference Proceedings* [11]. Ciele práce boli splnené.

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