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Autoreferát dizertačnej práce

In-beam gamma ray spectroscopy of ^{187}Au at the AFRODITE array (In-beam gamma spektroskopia izotopu 187Au na detektore AFRODITE)

na získanie akademického titulu philosophiae doctor

v odbore doktorandského štúdia:
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Abstrakt

Experiment PR235 bol uskutočnený v iThemba LABS za účelom študovania izotopu ^{187}Au pomocou in-beam gama spektroskopie. Na meranie gama žiarenia v terčovej pozícii bola použitá sféra detektorov AFRODITE. V experimente bola použitá kombinácia HPGe Clover a LEPS detektorov. Hlavným cieľom bolo študovať jadrovú štruktúru daného izotopu, ktorý vykazuje *tvarovú koexistenciu*. Analýza dát bola vykonaná na Fyzikálnom ústave, použitím vlastne vyvinutého softvéru a pomocou RadWare.

Rozpadová schéma ^{187}Au bola zostrojená z experimentálnych dát, obsahujúc prechody a rotačné pásy súvisiace s konfiguráciami *intruder stavov*. Intenzity prechodov boli získané pomocou RadWare výpočtov. Rozpadové schémy kontaminujúcich izotopov, prítomných v našich dátach, boli taktiež zostrojené.

Nové štruktúry pásov, súvisiace s *intruder stavmi*, ktoré boli predpovedané v PTRM výpočtoch a na základe parabolického trendu v systematike nepárnych izotopov zlata, neboli pozorované. Záverom je, že tieto konfigurácie musia mať odlišné štruktúry, ktoré budú musieť byť pozorované pomocou inej experimentálnej metódy. Naše analyzované dáta nepotvrdzujú nové prechody v ^{187}Au, ktoré boli publikované počas písania tejto práce.

Kľúčové slová: ^{187}Au, gama spektroskopia, jadrová štruktúra, tvarová koexistencia, jadrová deformácia

Abstract

The experiment PR235 was carried out at iThemba LABS to study the ^{187}Au isotope with in-beam gamma-ray spectroscopy. It employed the AFRODITE array for measurement of the outgoing gamma-rays in the target position. A combination of HPGe Clover and LEPS detectors was used in the experiment. The aim was to study nuclear structure of the isotope, known to exhibit *shape coexistence*. Data analysis was performed at the Department of Physics, using our own developed software and RadWare.

The level scheme of ^{187}Au was constructed from the experimental data, containing transitions and rotational bands associated with *intruder state* configurations. Intensities of transitions were obtained from RadWare calculations. Level schemes of contaminating isotopes, present in our data, were also constructed.

New band structures, associated with *intruder states*, that were predicted by PTRM calculations and the parabolic tendency in odd mass gold systematics, were not observed. Concluding that these configurations must have different structures, that have to be observed by a different experimental approach. Our analysed data does not confirm new transitions in ^{187}Au, that were published during the process of writing this work.

Keywords: ^{187}Au, gamma-ray spectroscopy, nuclear structure, shape coexistence, nuclei deformation

Introduction

Experimental studies of nuclear structure in exotic isotopes continue to play an important role in today's nuclear physics. One of the key questions in basic research of nuclear structure is the mechanism behind nuclear deformation. Contrary to the general perception that the atomic nucleus is a sphere, most nuclei are deformed and therefore display different types of shapes. Despite the fact that nuclear deformation was discovered by Bohr, Mottelson and Rainwater in 1953 [1], the underlying physics mechanism remains unclear to this day. For greater insight into the problematics of nuclear deformation, experimental data need to be obtained by systematic studies of suitable nuclei. Odd mass nuclei can give us information on both single particle and collective states in nuclei, such as deformation (axial, triaxial) and rotation, because of the presence of the odd. Neutron deficient odd mass Au isotopes are known to exhibit the *shape coexistence* phenomenon [2], where one nucleus has states with different deformations. Two types of excitations leading up to those states are known to be present in odd mass Au isotopes at low excitation energy [3]. Proton holes that couple to even-even Hg core and proton particles that couple to even-even Pt core, resulting in distinct groups of states. The proton-particle states are known as *intruder states*, since they intrude across the 82 closed shell. Their energies are dictated not only by single particle energies, but also by massive correlation energies resulting from changing of the shell occupancies. Both Hg and Pt even-even cores are known to have coexisting 0^+ states at low excitation energies, therefore at least four different types of configurations can be. Indeed, such configurations were observed in the ^{187}Hg → ^{187}Au beta-decay study [4], performed at the UNISOR facility in Oak Ridge National Laboratory (Tennessee, United States). Both gamma-rays and conversion electrons were simultaneously detected. Pairs of $11/2^-$ and $3/2^+$ states, connected with E0 transitions (model-independent fingerprints of the shape coexistence) were observed. However, rotational bands, expected to be built on these configurations were never observed in previous studies of ^{187}Au [4 - 7].

The subject of the present work is the study of the odd mass isotope ^{187}Au, aimed to expand the existing level scheme and observe the expected rotational bands connected to the previously established *intruder states*. For this purpose, the experiment PR235 was performed at iThemba LABS facility (Cape Town, South Africa), which employed the AFORDITE array for in-beam gamma-ray spectroscopy of ^{187}Au. The data analysis was carried out at the Slovak Academy of Sciences, using our own developed software and the RadWare software package [8, 9] for construction of the level scheme of the isotope. Complications surfaced in the data analysis as contaminations from other isotopes have been observed. From then on, these contaminations played a significant role in the analysis, having an effect on the final results. Level schemes of the identified contaminations have also been constructed. Band structures associated with the *intruder state* configurations were not observed, meaning that they have a different structure for the ^{187}Au isotope. The data from the experiment was compared with a new study of ^{187}Au that came out during the analysis.

Experiment PR235

The experiment PR235 was carried out at iThemba LABS employing the AFRODITE array to study the shape-coexistence in the odd-mass isotope ^{187}Au. The isotope was produced in the Heavy Ion fusion-evaporation reaction ^{181}Ta(^{12}C,6n)^{187}Au, with the beam delivered from a Separated-Sector-Cyclotron with the energy of 89 MeV. The used 6n reaction channel was determined to be the most dominant by calculation using the HIVAP statistical-evaporation model [10]. Most dominant contaminations (due to channels with charged-particle evaporation) were calculated to be lower by a factor 3 and the fission channel was under 10 %, therefore it was decided that recoil-decay tagging was not necessary.

Gold, with a proton number 79, is located in the vicinity of the 82 proton closed shell. By means of the Particle plus Triaxial Rotor Model (PTRM), where an odd quasiparticle is coupled to a triaxial rotating even-even core, odd mass Au isotopes can be expressed by coupling $_{80}$Hg cores with hole states from below the 82 closed proton shell ($s_{1/2}$, $d_{3/2}$, $h_{11/2}$) or by coupling $_{78}$Pt cores with particle states (protons in this case) from beyond the 82 closed proton shell ($h_{9/2}$, $f_{7/2}$, $i_{13/2}$). These particle states that cross the closed shell are called *intruder states*. It was shown that both types of excitations occur in the same isotope resulting in distinct group of states.

Unique parity proton-hole $h_{11/2}$ configurations in ^{187}Au have been experimentally observed in the studies of beta-decay ^{187}Hg → ^{187}Au [4, 5]. Particularly a pair of $h_{11/2}$ states connected by a transition with a strong E0 component are of interest (see Fig. 1). The interpretation is the coupling of the $h_{11/2}$ proton hole with two coexisting 0^+ states (ground state and one intruder state) in the ^{188}Hg core. The rotational band on the intruder $h_{11/2}$ was not identified. Finding this band is one of the main goals of the experiment PR235.

Positive parity band-heads $1/2^+$ and $3/2^+$ with quasi-rotational bands on them are found in Au isotopes. They correspond to coupling of $s_{1/2}$ and $d_{3/2}$ proton-hole states with even-even Hg cores. Additional positive parity states that decay via transitions with increased E0 components were observed above 500 keV in the beta-decay study of ^{187}Au (see Fig. 2). Rotational bands above those configurations were not identified. This should be possible with in-beam gamma-ray spectroscopy. Observing these rotational bands would determine if these states are strongly deformed intruders. The level scheme of ^{187}Au, containing several rotational bands, was constructed from in-beam data measured in the ^{172}Yb(^{19}F,4n)^{187}Au reaction [6]. The same reaction was used in another in-beam experiment [7] to study the ^{187}Au isotope and a similar level scheme was composed. With the experiment PR235 using recent experimental equipment and possibilities, we intended to identify new rotational bands, expand the existing and if possible, to assign rotational bands to proton-hole configuration observed in the beta-decay of ^{187}Hg.

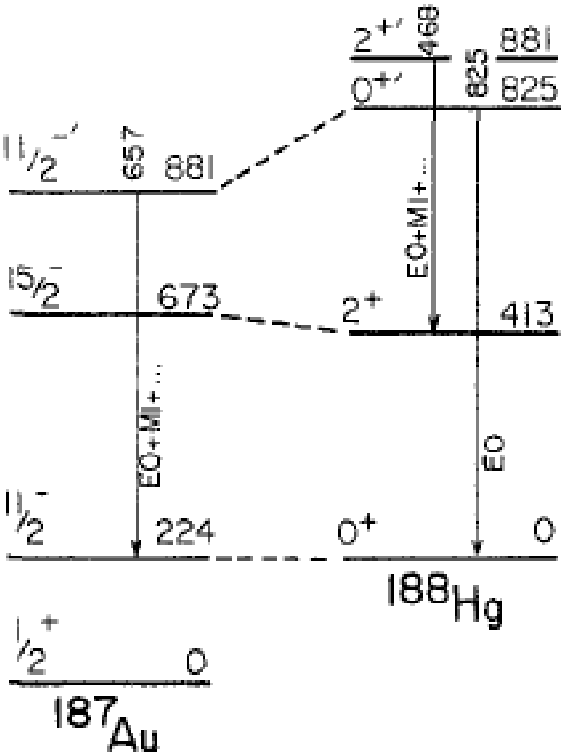


Figure 1: Unique parity proton-hole $h_{11/2}$ configurations in ^{187}Au, taken from [5].

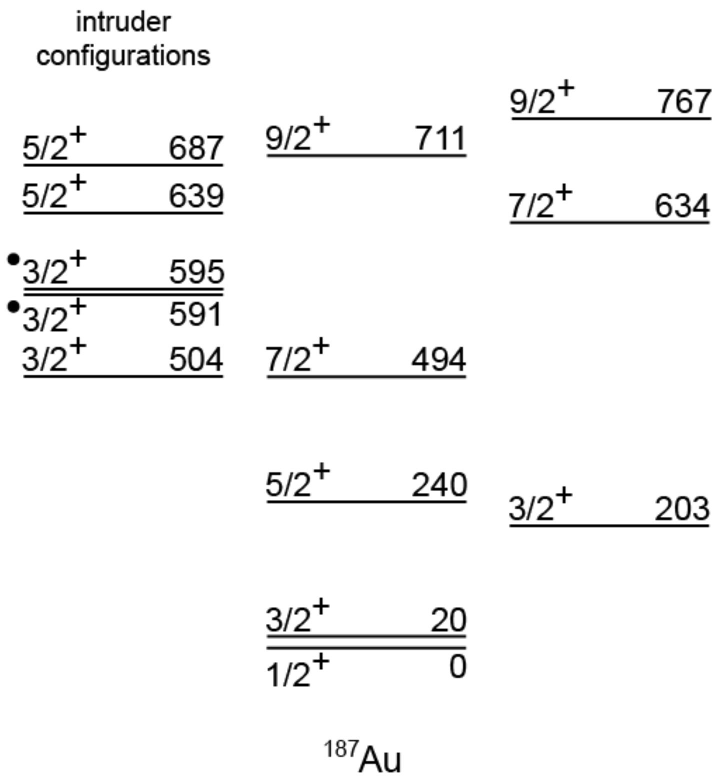


Figure 2: Positive parity states connected to the $s_{1/2}$ and $d_{3/2}$ proton-hole states. Circles indicate states that decay via E0 transitions.

The AFRODITE Array

AFRODITE (AFRican Omnipurpose Detector for Innovative Techniques and Experiments) is a 4π gamma-ray detector array at iThemba LABS (see Fig. 3). It employs a combination of two types of germanium detectors. HPGe Clover detectors with BGO suppression shields for higher energy photons and segmented HPGe LEPS detectors for low energy photons. The aluminium array frame of AFRODITE has a rhombicuboctahedron shape with a total of 18 openings. There are 3 angle positions for detectors in respect to the beam direction, at 45°, 90° and 135° degrees. A hydraulically movable target ladder inside the target chamber controls the position of the target.

Clover detectors contain four separate n-type coaxial HPGe (High Purity Germanium) crystals arranged in a four-leaf Clover, which are placed in one cryostat 0.2 mm apart from one another. Each crystal (called element of Clover detector) has its own preamplifier and acquires signals separately. To supress the Compton background in the gamma-ray spectra, each Clover detector is surrounded by a Compton suppression shield made of bismuth germanium oxide $Bi_4Ge_3O_{12}$ (BGO). LEPS (Low Energy Photon Spectrometer) are detectors made of a single p-type HPGe crystal. The detector is electrically segmented into four quadrants. Signals from each quadrant are processed individually, making the LEPS operating similarly as Clover detectors. For the experiment PR235, AFRODITE was equipped with 14 detectors, 8 Clover and 6 LEPS detectors.

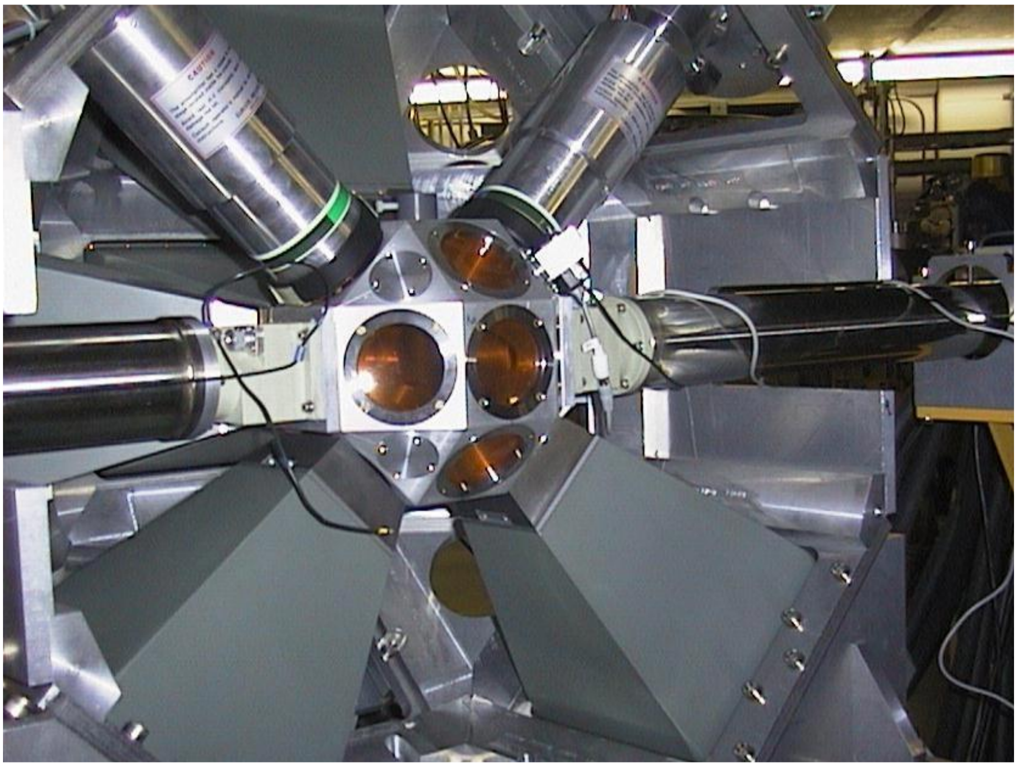


Figure 3: Target chamber of the AFRODITE array, taken from [11].

Data acquisition and analysis

The data acquisition system for the experiment PR235 was based on Digital Gamma Finder (DGF) Pixie-16 modules developed by XIA LLC. Each module accepts signals directly from preamplifiers of the germanium crystals and the BGO shields. All events are time-stamped with an internal 100 MHz clock. The digitalized data were transported into the controller PC, where the events are reconstructed by the Event builder of the Multi Instance Data Acquisition System (MIDAS) developed at STFC Daresbury Laboratory. For the experiment PR235, only events when two or more germanium crystals generated coincidence signals were written down.

The analysis of the data from the experiment was carried out solely at the Institute of Physics. The obtained data was written in a tree structure consisting of the channel (number of the detector crystal where the event was registered), raw energy (uncalibrated energy of the registered event) and a time-stamp from the internal clock, which determines the time when the event was registered during the experiment. We developed our own software, that can read and sort the raw data, where we included the calibrations of all the separate crystals, correction for the Doppler effect, and the Add-back technique. The main output of our software, needed for further analysis, are two-dimensional spectra, so called γ-γ matrixes that contain all the coincidences of the selected detectors. The main data analysis was performed using the RadWare software package [8, 9], where a proposed level scheme is constructed based on the observed transitions. Intensities, internal conversion coefficients, transition and level energies of ^{187}Au transitions were obtained in RadWare. Similar to the γ-γ matrixes, triple coincidence structures, called γ-γ-γ cubes can be constructed in RadWare. The requirements for this are at least three detectors and a high data statistic, since only events registered at the same time in three and more detectors are suitable. In a γ-γ-γ cube, spectra that are in coincidence with two transitions at once can be generated and analysed. We used the Clover γ-γ-γ cube to confirm or reject the transitions assigned in γ-γ matrixes.

Experimental results and discussion

Results for ^{187}Au

The ^{187}Au isotope has a half-life of 8.3 minutes. The ground state of the isotope is $1/2^+$ [12], corresponding to the $3s_{1/2}$ orbital. It decays by electron capture (~100%) to ^{187}Pt and a very small percentage (0.003%) by alpha decay to ^{183}Ir. The level scheme of ^{187}Au, deduced from the experimental data is shown in Fig. 4 and 5. It was constructed in RadWare and contains transition energies, level energies, spins and parities of the states and intensities of transitions. The transition intensities in the level scheme are displayed as the thickness of the arrows, the thicker the arrow, the higher the intensity of the transition. The blank part of the arrows (e.g. $13/2^- \rightarrow 9/2^-$ transition in *Band 1*) represents the percentage of the transition that decays via conversion electrons. The placement of the individual transitions into the level scheme was based on γ-γ and γ-γ-γ coincidences that were constructed from the data. Most of the transitions were assigned based on coincidence gates, the final order of the transitions in the scheme was mainly determined by their intensity and energy (higher spin transitions have usually higher transition energy).

Band 1 in our level scheme contains the highest intensity transitions and can be described as the main band in ^{187}Au. The band-head has a spin of 9/2$^-$ and is located at 120 keV. It has a half-life of 2.3 seconds and decays by isomeric transition (100%) to the 3/2$^+$ state by a 101 keV E3 transition [13]. The 3/2$^+$ state has a half-life of 6.5 nanoseconds [6] and decays to the 1/2$^+$ ground state at 0 keV, which has an oblate shape [7]. The 9/2$^-$ state corresponds to a proton, located at the 1h$_{9/2}$ orbital, coupled with an even-even $_{78}$Pt core. The proton crosses the closed shell at 82 and therefore the 9/2$^-$ state is categorized as an *intruder state*. Fig. 6 shows the spectrum gated at the 638.6 keV, where transitions from *Band 1* are observed. No transitions from *Band 4* are present, confirming that the side-feeding occurs at the 29/2$^-$ state. The band-head of *Band 3* has a spin of 13/2$^+$ and is located at 1122 keV. The 13/2$^+$ state corresponds to a 1i$_{13/2}$ orbital proton coupled with an even-even $_{78}$Pt core. Like the 9/2$^-$ state in *Band 1*, the 13/2$^+$ is also an intruder state. *Band 3* contains a doublet consisting of 469.9 keV and 471.8 keV transitions. Fig. 7 shows the spectrum gated at both transitions, confirming this doublet. The band-head of *Band 6* has a spin of 11/2$^-$ and lies at 224 keV. The state is isomeric, with a half-live of 48 nanoseconds [14], and decays via a 103.6 keV M1 + E2 transition to the 9/2$^-$ state of *Band 1*. The 11//2$^-$ state corresponds to a 1h$_{11/2}$ orbital hole coupled with an even-even $_{80}$Hg core. It is the lower one of the h$_{11/2}$ states seen in Fig. 1.

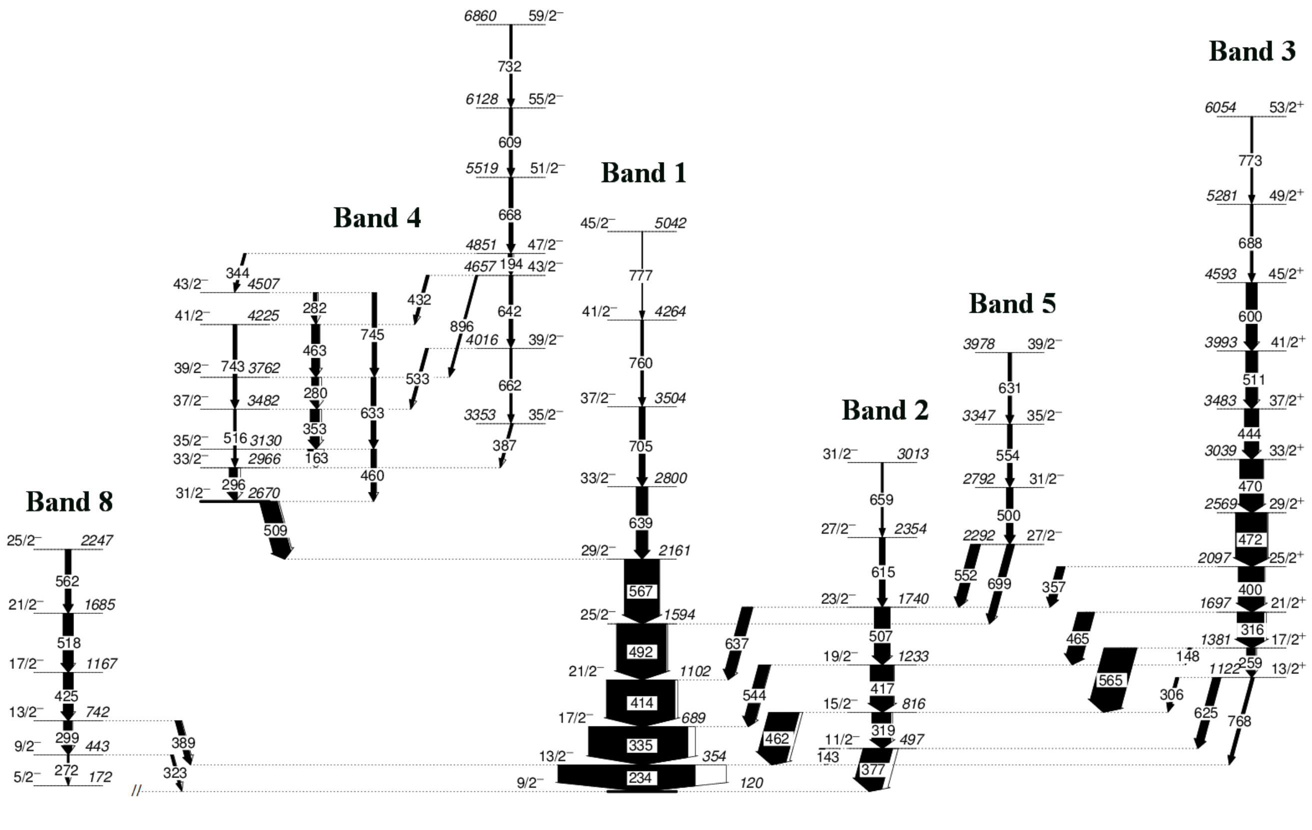


Figure 4: Level scheme of ^{187}Au, deduced from our experimental data.

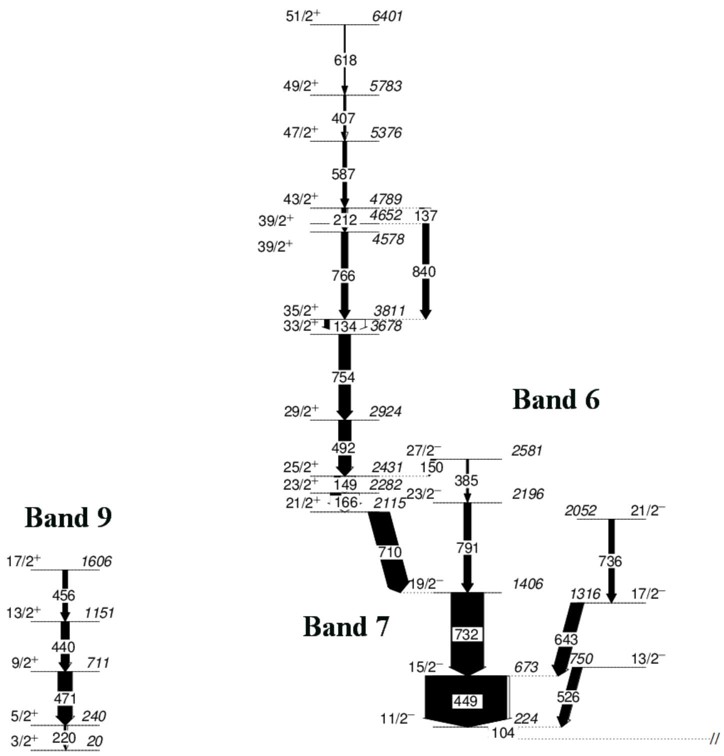


Figure 5: Level scheme of ^{187}Au, deduced from our experimental data - continued.

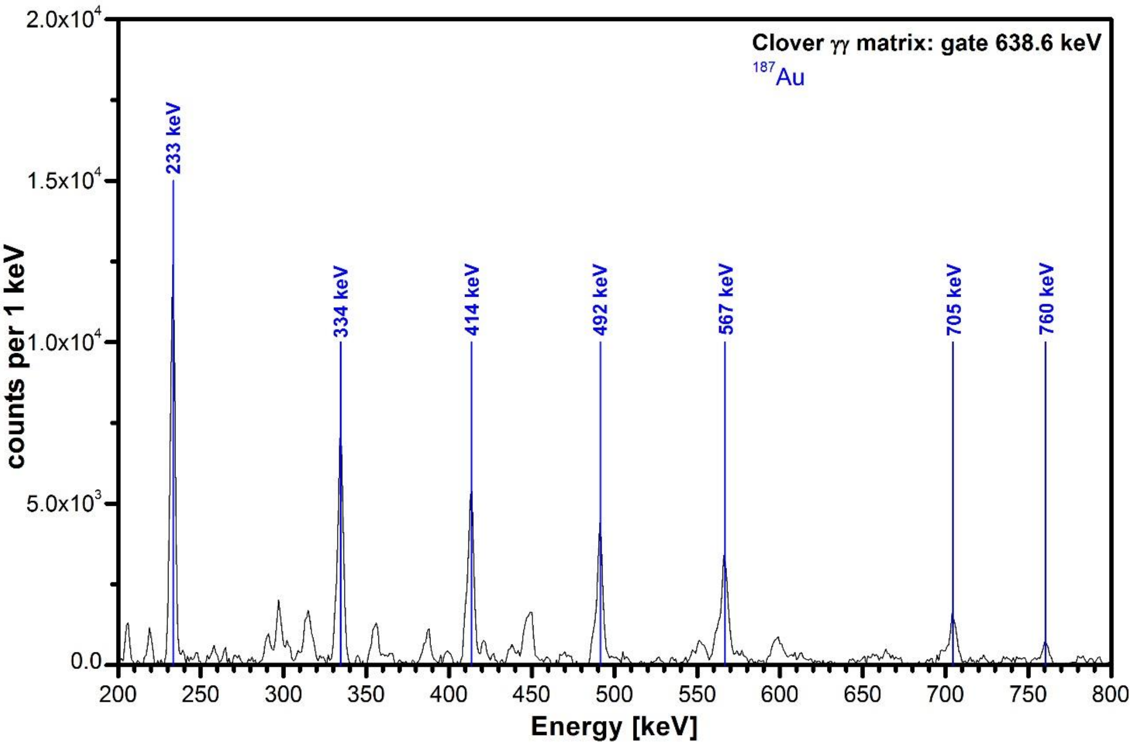


Figure 6: Energy spectrum of Clover detectors gated at 638.6 keV.

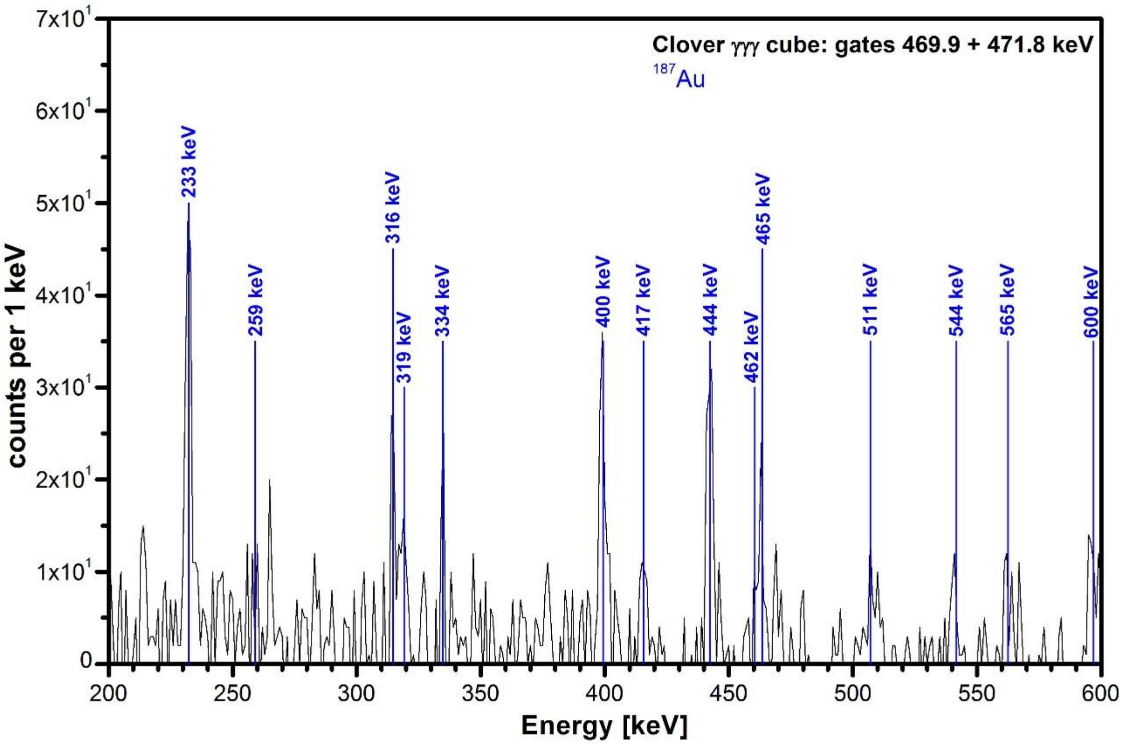


Figure 7: Energy spectrum of Clover detectors gated at both 469.9 keV and 471.8 keV.

The placement and order of the individual transitions in the bands was based on intensity calculations from RadWare. The scheme itself is constructed from the Clover γ-γ matrix data, but correction have also been made based on γ-γ-γ cube data. The double gated spectra have lower count rates but are much more accurate since a lot of contaminations and statistical coincidences have been eliminated. We also used the γ-γ matrix data from LEPS detectors. Since these detectors have a high efficiency for lower energies, their spectra were used to resolve low lying transitions and observe the characteristic X-rays, which proved valuable in determining the contaminating isotopes in the data.

The main goal of the experiment PR235 was the identification of rotational band structures built upon *intruder states*. No such transitions were observed in our data. These expected transitions could have been obscured by the contaminants present in our data or simply they are not present. One example is the $11/2^{-}$ intruder state identified in the beta-decay study [4], seen in Fig. 1 and 8 [15]. The transition was not visible in the singles data and in the spectrum gated on 104 keV (see Fig. 9), where it would have to be observed if present in our data (based on Fig. 5 and 8). Similarly, predicted positive parity states from Fig. 2 were not observed. Even with contaminations, we found no trace of new transitions and can declare that they are not present in our data. This, the main conclusion from our study, suggests that the structure in ^{187}Au differs from the one predicted by the systematics of odd mass Au isotopes. The rotational bands must have a structure that requires a different a different type of experimental approach. Fig. 8 supports this suggestion, as we can see that there are differences in how the pair of $11/2^{-}$ states behave in ^{177}Au and ^{187}Au.

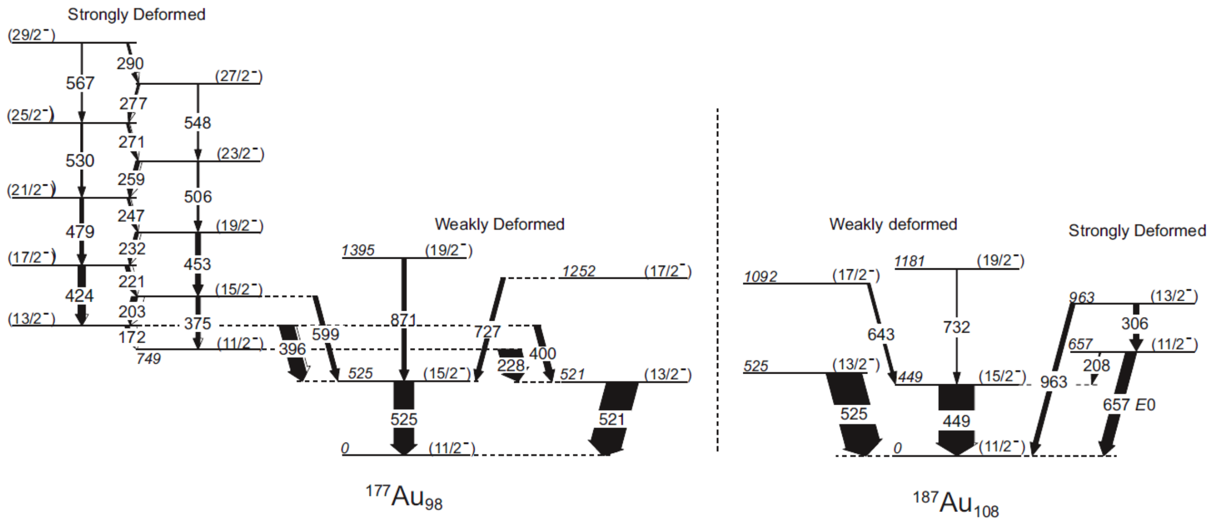


Figure 8: 11/2^{-} intruder state configurations in ^{177}Au and ^{187}Au, taken from [15].

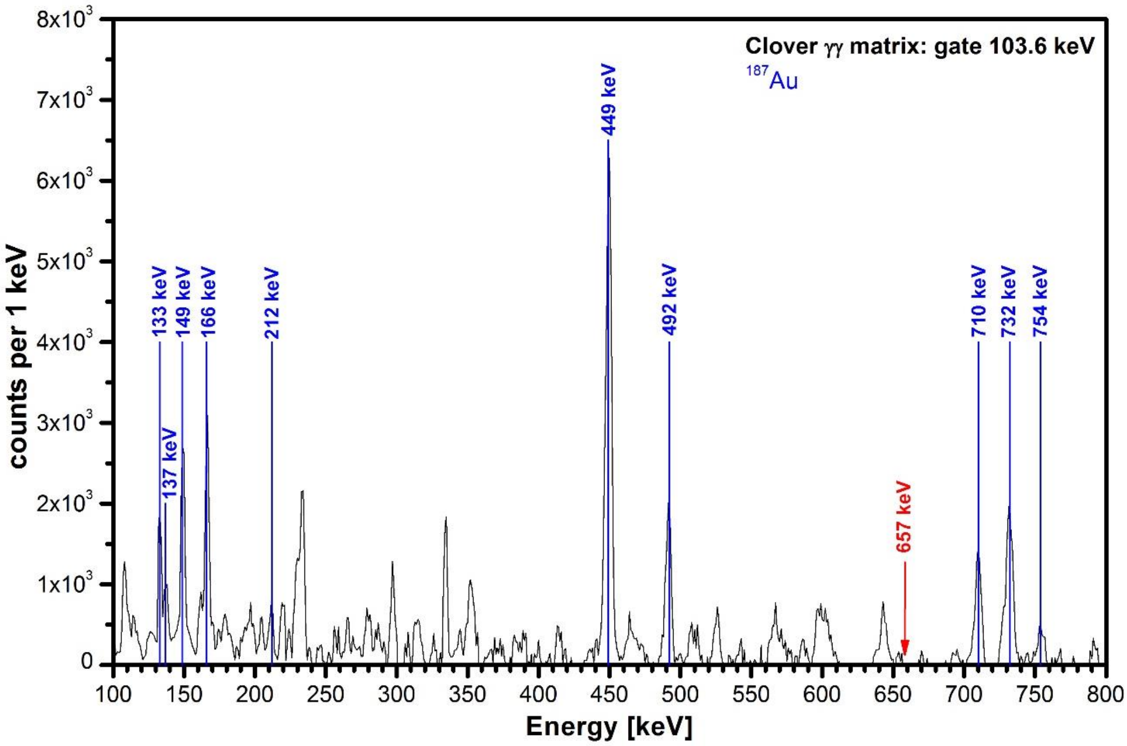


Figure 9: Energy spectrum of Clover detectors gated at 103.6 keV.

Contaminations

During the data analysis, we observed contaminating transitions from other isotopes, that were also created in the fusion-evaporation reaction and the subsequent de-excitation and decay. Several of these contaminants have been identified, some with a very high count rate and intensity of transitions. To calculate the intensities of the ^{187}Au transitions with RadWare, all the transitions from these contaminants had to be identified and appropriately placed in their respective level schemes.

The most abundant contaminant is the ^{188}Au isotope, where many transitions have high intensities that match those of ^{187}Au. The two most intensive transitions from ^{187}Au in the spectrum had intensities only few percent higher than the two most intensive transitions in ^{188}Au. Even in γ-γ-γ data, ^{188}Au is still observed in similar intensities than the studied isotope. The conclusion on the presence on ^{188}Au is, that its intensity and abundance is very nearly on the same level as the studied ^{187}Au, which makes it extremely difficult to make a new observation in the data and declare that it is part of ^{187}Au. Another problem is the fact, that the contaminant is an isotope of the same chemical element, which ruled out using characteristic X-rays to sort the data. Furthermore, some transitions in ^{188}Au have very similar energies to the ones in ^{187}Au. Some examples (listed for ^{187}Au first) are 133.6 keV and 132.9 keV, 508.8 keV and 509.0 keV, 732.3 keV and 731.8 keV. Fig. 10 shows the spectrum gated at 731.8 keV, where transitions from both gold isotopes are clearly observed. Other contaminating isotopes in our data were ^{181}Ta (target element), ^{187}Pt and ^{188}Pt (decay products of ^{187}Au and ^{188}Au respectively), and ^{185}Ir. All of these isotopes were confirmed by the presence of their respective characteristic X-rays. Fig. 11 shows the single spectrum of all the Clover detectors, where the most intensive peaks are labelled with different colours, representing the isotopes from which they originate. Transitions with similar energies are highlighted at one position. The colour of the line represents the isotope that has the most intensive transition in this case of conjoined labels. As we can see from this figure, the spectrum is very complicated, with many transitions from different isotopes having same energies.

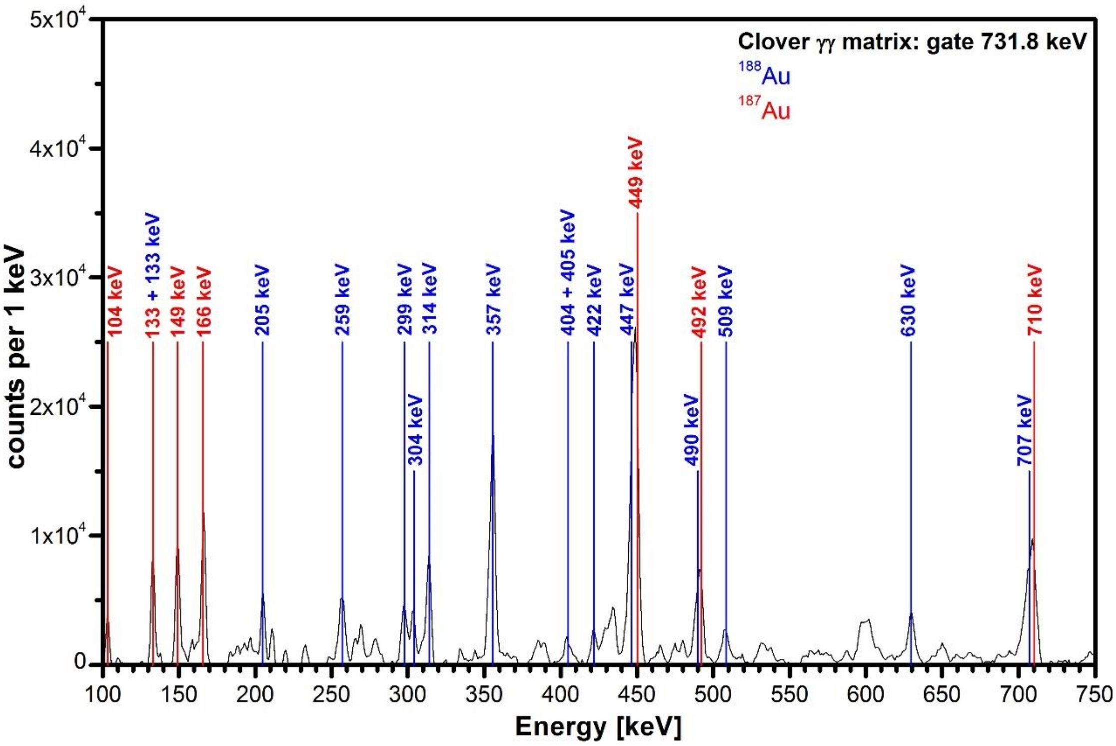


Figure 10: Energy spectrum of Clover detectors gated at 731.8 keV.

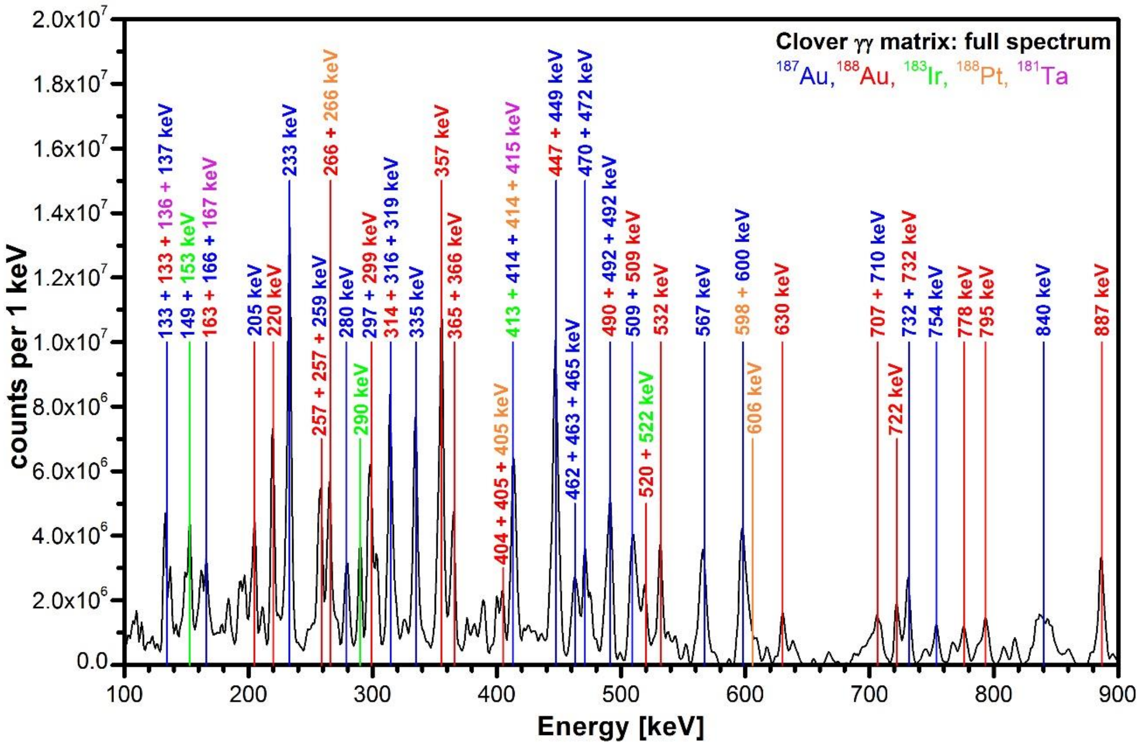


Figure 11: Full Clover spectrum of our experimental data.

New transitions in ^{187}Au

During the data analysis and the writing of the present work, a new publication about ^{187}Au came out [16]. In this article, new transitions and even a new band structure, which is supposedly from ^{187}Au, has been identified in the data from an in-beam gamma-ray spectroscopy experiment. ^{187}Au was produced at the Argonne National Laboratory in the reaction ^{19}F + ^{174}Yb, very similar to the one used in [6, 7]. The Gammasphere array was used to collect the data and only three and higher coincidences have been written. The data was analysed using RadWare. Fig. 12 shows the level scheme from the article, where new transitions are marked by an asterisk. Bands 1 and 2 (Yrast and LW) correspond to the same two bands in our data, band 3 (SP) is the new band.

None of these transitions have been observed in the previous in-beam data [6, 7]. The employed Gammasphere array has better efficiency than the previously used detecting systems. As explained earlier, the thickness of the arrow in a RadWare constructed level scheme depends on the intensity of the transition. Based on this, we can observe, that the two new transitions, 265.3 keV and 404.5 keV, have intensities on the same level as the 567.0 keV transition, which has certainly high intensity, even in γ-γ-γ data. We would expect that transitions with the same level of intensity would by clearly visible in the data, even with lower detecting efficiency. Even more than with in-beam data, it seems strange that no trace of this band was observed. The newly observed band has a transition crossing to band 1, where it populates the 13/2$^-$ state. This transition with an energy of 436.5 keV is therefore in coincidence with the 233 keV, the strongest transition in ^{187}Au. If present, this transition should have been visible in the data. The PTRM calculations performed for ^{187}Au do not predict an 11/2$^-$ band-head at this energy. Fig. 13 shows the PTRM calculations, compared with the experimental data [4]. There are three 11/2⁻ states predicted in these calculations and all three were observed at energies similar to the expected energies from the model. Furthermore, the experimental data in [4] have very high sensitivity. Peaks with relative intensities as low as 0.3 % of the most intensive transition have been identified and placed in the level scheme. Therefore, we can presume that these new transitions are not present in the beta-decay study of ^{187}Au [4].

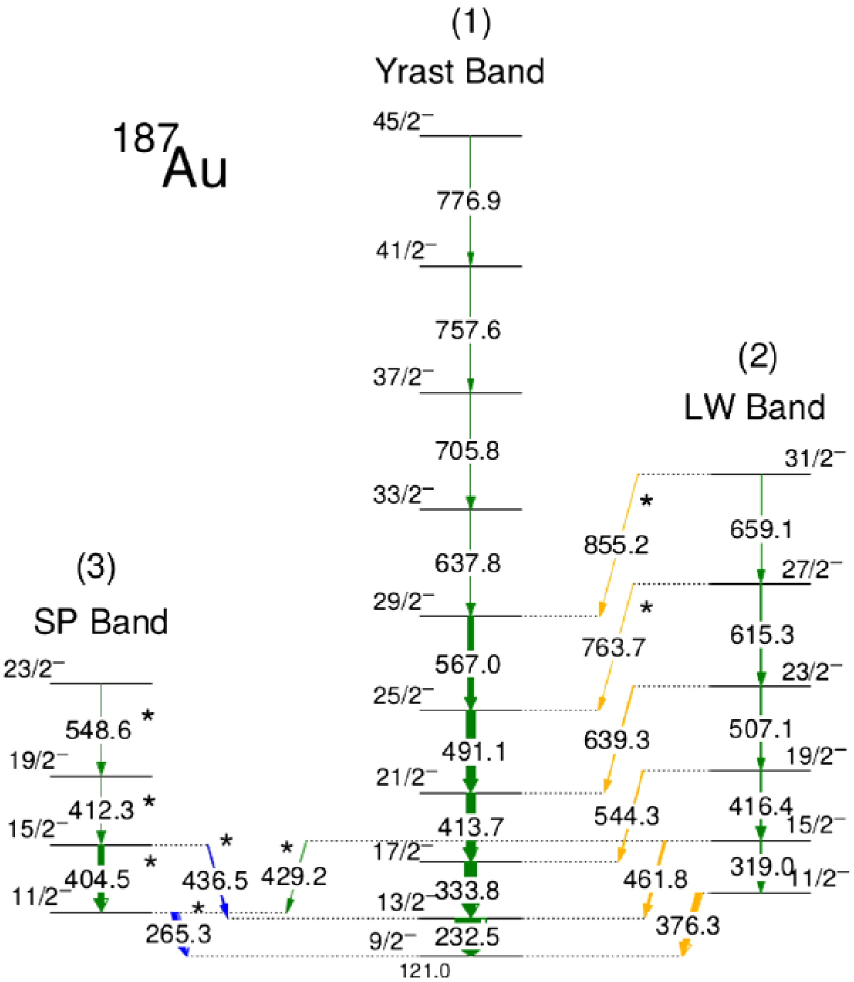
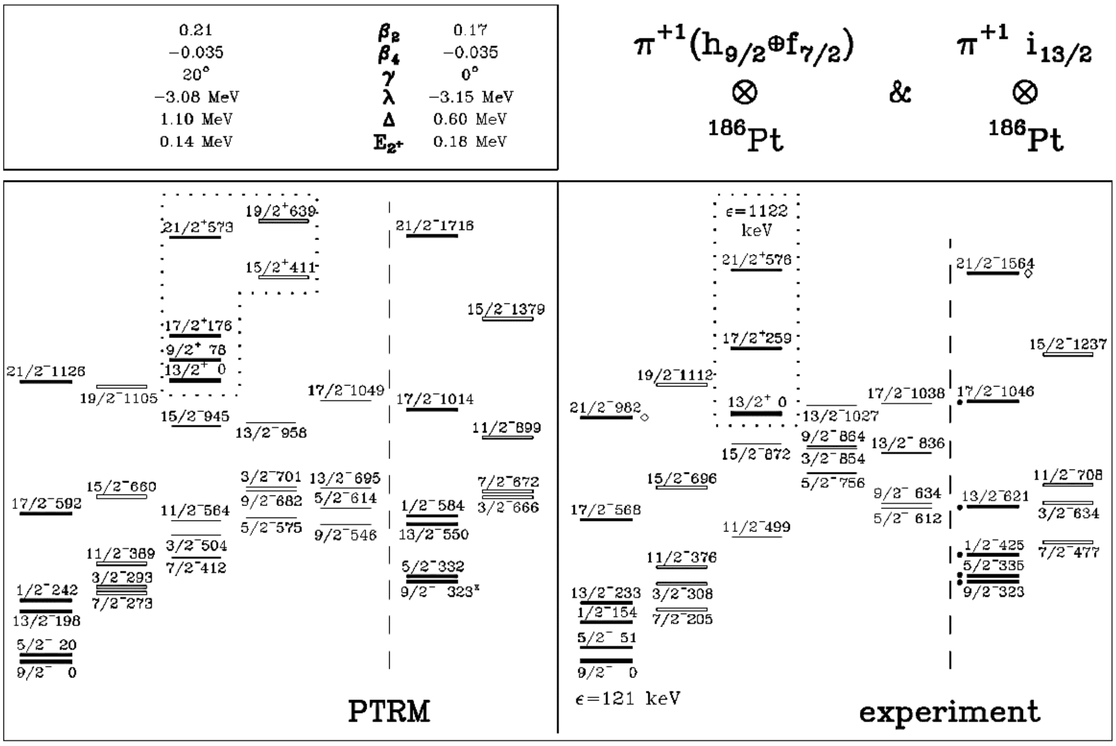


Figure 12: Partial level scheme of ^{187}Au, taken from [16].

We looked at our data, if we can see these new transitions or some traces of them. Giving the nature of our data, with several contaminants present, it would be hard to confirm the existence of these transitions unless very clearly visible in all the possible coincidences. Like in the article, we used Clover γ-γ-γ data to investigate the presence of these transitions. The new 429.2 keV transition crosses from *Band 2* to the new band and should not be in coincidence with a *Band 1* transition. A spectrum gated at 506.8 keV and 416.8 keV, shown in Fig. 14, shows that this transition is not present in our data. To observe the presence of the 436.5 keV crossing transition, a spectrum gated at 233 keV and 412.3 keV was generated. Once again, there was no evidence in our data to confirm this transition or the 548.6 keV transition. There are similar transitions present in our data, 404.5 keV and 265.3 keV are present in ^{188}Au, although not in coincidence with each other. Besides *Band* 1 in ^{187}Au, 413.0

keV is also a very strong transition in ^{185}Ir. However, the most significant contaminant in this case is ^{188}Pt.



^{x} the calculated band head energy is adjusted to the value of 323 keV

Figure 13: PTRM calculations and experimental data for ^{187}Au states, taken from [4].

^{188}Pt contains similar transitions to all of the transitions from the new band and they are even in coincidence.

New band in ^{187}Au: 265.3 - 404.5 - 412.3 - 548.6

Transitions in ^{188}Pt: 265.7 - 405.5 - (513.6) - (583.8) - 411.6 - (523.5) - 548.6

265.7 - 405.5 - 413.8 - 551.0

All the listed transitions from ^{188}Pt are shown in Fig. 15. Based on this, we cannot confirm the presence of the new band in our experimental data. Considering the fact, that no previous study of ^{187}Au has observed these new transitions, it is far more likely that they are not present in our data. Furthermore, it creates some scepticism as to whether the new transitions and band in [16] were assigned correctly or if they originate from ^{187}Au. Granting them the benefit of doubt, if these new transitions and band are indeed part of the ^{187}Au structure, it would be something that has not been observed previously. Not only in ^{187}Au, but in all of the studied odd-mass Au isotopes.

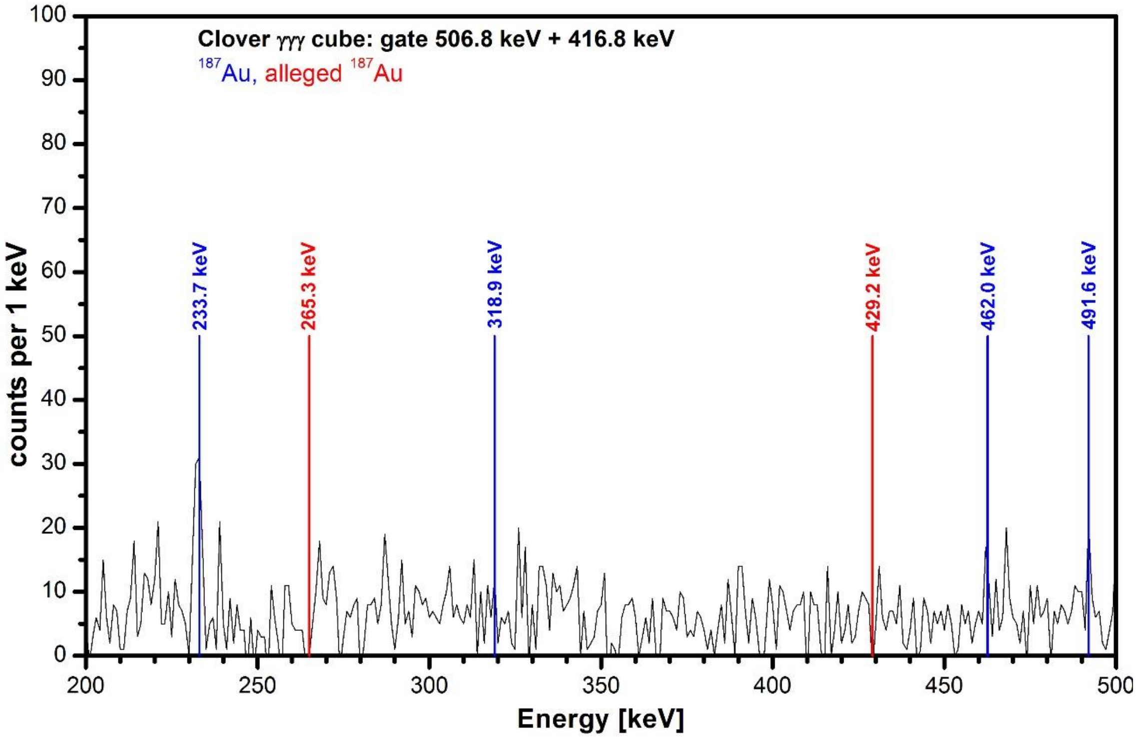


Figure 14: Energy spectrum of Clover detectors gated at 506.8 keV and 416.8 keV.

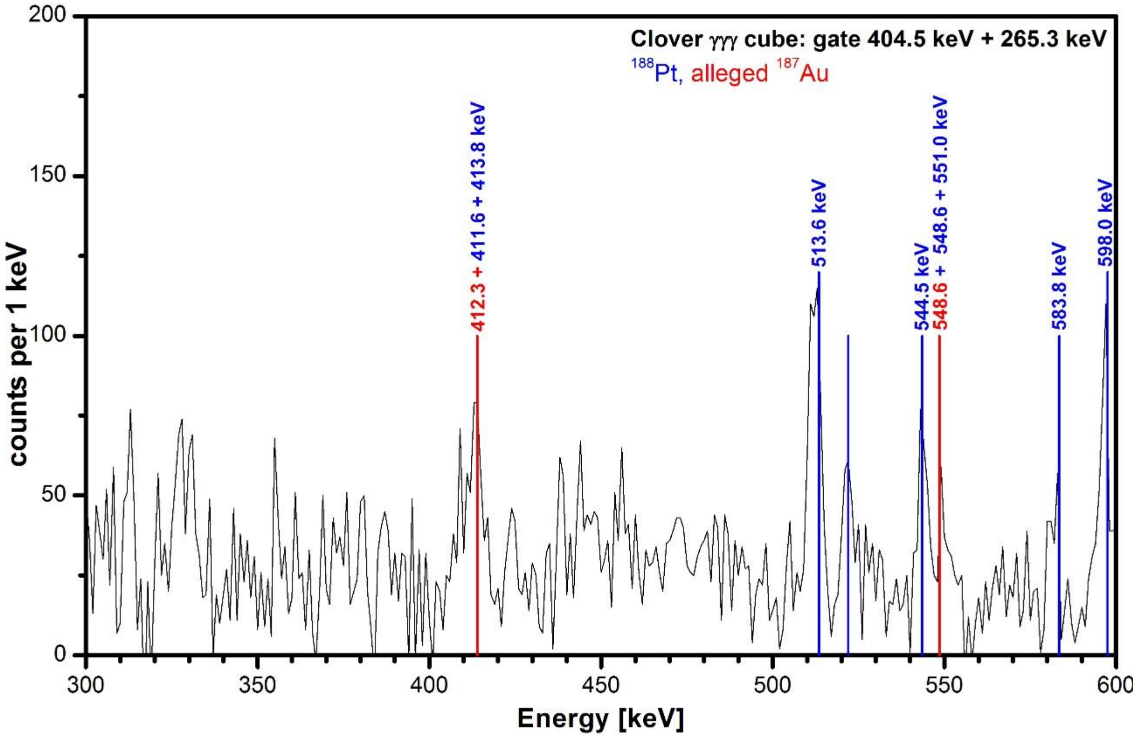


Figure 15: Energy spectrum of Clover detectors gated at 404.5 keV and 265.3 keV.

References

[1] BOHR, A. and B. R. MOTTELSON, *Collective and Individual-particle aspects of Nuclear Structure*, In Mat. Fys. Medd. K. Dan. Vidensk. Selsk., **Vol. 27**, No. 16, p. 1-174 (1953).

[2] HEYDE, K. and J. L. WOOD, *Shape Coexistence in atomic nuclei*, In Rev. Mod. Phys., **Vol. 83**, Is. 4, p. 1467-1521 (2011). DOI: 10.1103/RevModPhys.83.1467.

[3] WOOD, J. L. *et al*., *Symmetry between particle and hole level systems in* ^{189}Au, In Phys. Rev. C, **Vol. 14**, Is. 2, p. 682-4 (1976). DOI: 10.1103/PhysRevC.14.682.

[4] RUPNIK, D. *et al.*, *Levels of* ^{187}Au*: A detailed study of shape coexistence in an odd-mass nucleus*, In Phys. Rev. C, **Vol. 58**, Is. 2, p. 771-95 (1998). DOI: 10.1103/PhysRevC.58.771.

[5] PAPANICOLOPOULOS, C. D. *et al.*, *Very Converted Transitions and Particle-Core Coupling in Neutron-Deficient Odd-Mass Au Isotopes*, In Z. Phys. A, **Vol. 330**, Is. 4, p. 371-6 (1988). DOI: 10.1007/BF01290122.

[6] JOHANSSON, J. K. *et al.*, *Shape coexistence in* ^{187}Au, In Phys. Rev. C, **Vol. 40**, Is. 1, p. 132-44 (1989). DOI: 10.1103/physrevc.40.132.

[7] BOURGEOIS, C. *et al*, *Shape coexistence at high spin in* ^{187}Au, In Z. Phys. A, **Vol. 333**, Is. 1, p. 5-14 (1989). DOI: 10.1007/BF01290104.

[8] RADFORD, D. C., *ESCL8R and LEVIT8R: Software for interactive graphical analysis of HPGe coincidence data sets*, In Nucl. Instr. and Meth. A, **Vol. 361**, Is. 1-2, p. 297-306 (1995). DOI: 10.1016/0168-9002(95)00183-2.

[9] RADFORD, D. C., *Background subtraction from in-beam HPGe coincidence data sets*, In Nucl. Instr. and Meth. A, **Vol. 361**, Is. 1-2, p. 306-16 (1995). DOI:10.1016/0168-9002(95)00184-0.

[10] REISDORF, W., *Analysis of Fissionability Data at High Excitation Energies*, In Z. Phys. A, **Vol. 300**, Is. 2-3, p. 227-38 (1981). DOI: 10.1007/BF01412298.

[11] http://tlabs.ac.za/?page_id=218, accessed on January 2015.

[12] EKSTRÖM, C. *et al*., *Nuclear spins of* $^{186, 187, 188, 189, 189m}Au$, In Phys. Lett. B, **Vol. 60**, Is. 2, p. 146-48 (1976). DOI: 10.1016/0370-2693(76)90409-3.

[13] BRAGA, R. A. *et al.*, *Half-life of the* $h_{9/2}$ *shell-model intruder-state isomer* ^{187m}Au, In Nucl. Phys. A, **Vol. 410**, Is. 3, p. 441-44 (1983).

[14] BERG, V. *et al.*, *Transition rates between negative-parity states in odd-mass gold nuclei*, In Nucl. Phys. A, **Vol. 410**, Is. 3, p. 445-47 (1983). DOI: 10.1016/0375-9474(83)90637-1.

[15] VENHART, M. *et al.*, *De-excitation of the strongly coupled band in* ^{177}Au *and implications for core intruder configurations in the light Hg isotopes*, In Phys. Rev. C, **Vol. 95**, Is. 6, p. 061302 – 1-5 (2017). DOI: 10.1103/PhysRevC. 95.061302.

[16] SENSHARMA, N. *et al.*, *Longit udinal Wobbling Motion in 187Au*, In Phys. Rev. Lett., **Vol. 124**, Is. 5, p. 052501 – 1-6 (2020). DOI: 10.1103/PhysRevLett. 124.052501.

List of publications

Venhart, M., Wood, J. L., Sedlák, M., Balogh, M, Bírová, M., Boston, A. J., Cocolios, T. E., Harkness-Brennan, L. J., Herzberg, R.-D., Holub, L., Joss, D. T., Judson, D. S., Kliman, J., Klimo, J., Krupa, L., Lušnák, J., Makhathini, L., Matoušek, V., Motyčák, Š., Page, R.D., Patel, A., Petrík, K., Podshibyakin, A.V., Prajapati, P.M., Rodin, A.M., Špaček, A., Urban, R., Veselský, M. *New systematic features in the neutron-deficient Au isotopes*. Journal of Physics G: Nuclear and Particle Physics **44**, 074003 (2017).

Gillespie, S.A., Andreyev, A.N., Al Monthery, M., Barton, CH.J., Antalic, S., Auranen, K., Bardan, H., Cox, D.M., Cubiss, J.G., O'Donnell, D., Grahn, T., Greenlees, P.T., Herzáň, A., Higgins, E., Julin, R., Asztalos, S., Klimo, J., Konki, J., Leino, M., Mallaburn, M., Pakarinen, J., Papadakis, P., Partanen, J., Prajapati, P.M., Rahkila, P., Sandzelius, M., Scholey, C., Sorri, J., Stolze, S., Urban, R., Uusitalo, J., Venhart, M., Weaving, F. *Identification of a 6.6 microsecond isomeric state in* ^{175}*Ir*. Physical Review C - Nuclear Physics **99**, 064310 (2019).

Venhart, M., Balogh, M., Herzáň, A, Wood, J.L., Ali, F.A., Joss, D.T., Andreyev, A.N., Auranen, K., Carroll, R.J., Drummond, M.C., Easton, J.L., Greenlees, P.T., Grahn, T., Gredley, A., Henderson, J., Jakobsson, U., Julin, R., Asztalos, S., Konki, J., Lawrie, E., Leino, M., Matoušek, V., McPeake, CH.J., O'Donnell, D., Page, R.D., Pakarinen, J., Papadakis, P., Partanen, J., Peura, P., Rahkila, P., Ruotsalainen, P., Sandzelius, M. Sarén, J., Saygi, B., Sedlák, M., Scholey, C., Sorri, J., Stolze, S., Thornthwaite, A., Urban, R., Uusitalo, J., Veselský, M, Weaving, F. *Population of a low-spin positive-parity band from high-spin intruder states in* ^{177}*Au: The two-state mixing effect*. Physics Letters B **806**, 135488 (2020).