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Study of neutron-rich isotopes near N=152 shell closure using Timepix type detectors integrated into the mass separator MASHA

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Abstract: The MASHA facility [1–3] was developed as a high precision mass-spectrometer for heavy and super heavy elements with masses up to 450 a.m.u. It uses ISOL (Isotope Separation On-Line) method. Its unique properties opens great prospective for the investigation of neutron-rich nuclei produced in multinucleon transfer reactions. Mainly nuclei near the neutron N = 126 and N = 152 shell closures are of great interest. This region of nuclei is not so far thoroughly enough investigated while its research has direct relation to the synthesis of super heavy elements. As is known the island of stability close to super heavy elements (Z = 112–118) exists due to the shell effects in nuclei. More detailed investigation of these shell effects can greatly help in the synthesis of next super heavy elements.

Heavy neutron rich radon isotopes were produced in the multinucleon transfer reaction ^{40}Ar + ^{232}Th at Flerov Laboratory of Nuclear Reactions, Dubna. Radon isotopes with given masses

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were detected using two types of detectors: a multi-strip well-type detector (made in Canberra) and a position-sensitive quantum counting hybrid pixel detector of the Timepix type [4]. The latter detector has an array of 256×256 square pixels each with a pitch size of 55 μm for the full sensitive area 14×14 mm^2. Radon isotopes implanted into the detector emit then alpha and beta particles until they reach the stable or long-lived isotopes at the end of their decay chains. The positions of radon isotopes, the tracks, times and energies of the beta particles were measured and analyzed. New software for the particle recognition and data analysis of the results obtained from the experiment was developed and used. It has been proven that MASHA + Timepix setup is a powerful instrument for investigation of neutron-rich isotopes far from stability limits.

KEYWORDS: Particle identification methods; Particle tracking detectors; Data processing methods; Data acquisition concepts

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1 Experimental setup

The mass separator MASHA (figure 1) can measure, with a high precision, the mass of any nucleus beginning from helium up to nuclei with masses A~450. Fission fragments, alpha particles and beta particles are detected at the focal plane with a high efficiency. It opens up great prospect for the investigation of neutron-rich and neutron-deficit nuclei produced in mutinucleon transfer reactions.

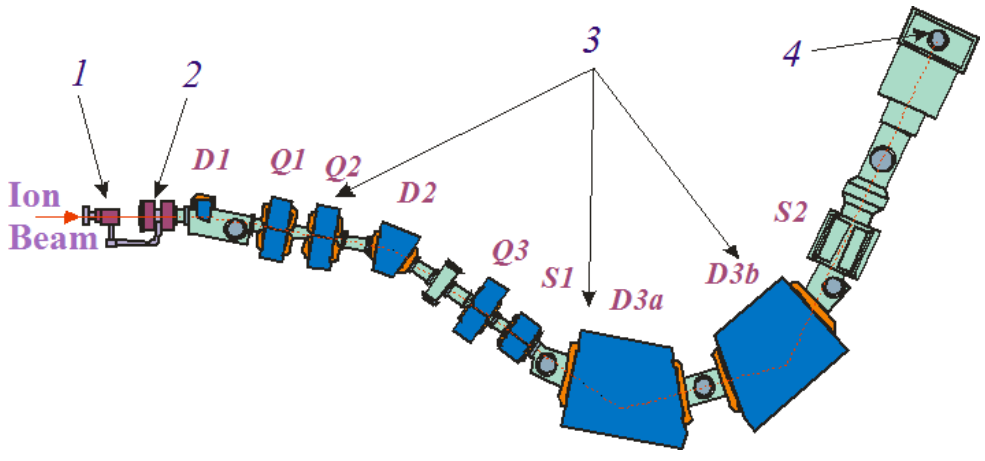

Figure 1. Scheme of the mass separator MASHA: 1 — target block with hot catcher; 2 — ion source; 3 — D1, D2, D3a, D3b – Q1-Q3 and S1, S2 are magnetic dipole, quadrupole and sextupole optical elements, respectively; 4 — the focal plane where Timepix and multi-strip detectors are installed.

The MASHA facility (presented above) is a combination of the so-called ISOL method of synthesis and separation of radioactive nuclei with the classical method of mass analysis, allowing mass identification of the synthesized nuclides in a wide range of masses.

2 Exploitation of Timepix particle tracking detectors

2.1 Upgrade of the detection system

Super heavy nuclei in the region N = 126 and N = 152 decay mainly by emitting β^-, β^+ or by electron capture. By measuring the mass, lifetime and energy spectra of beta particles and taking into account the position sensitivity of the focal plane detector one can identify these nuclei with a high accuracy. However, this raises a strict demand on high-resolution particle tracking detector.

Working capability of the multi-strip detector in the place of the beta particle identification is limited. The position-sensitive quantum counting hybrid pixel detectors of the Timepix type well satisfy the requirements by providing a high spatial resolution and single-quantum detection. These devices have an array of 256×256 square pixels each with a pitch size of 55 µm for a full sensitive area of 14×14 mm^2. Each individual pixel is able to operate independently and perform a measurement according to its configuration mode (i.e. TOT — Time Over Threshold mode for measurement of deposited energy, TOA — Time Of Arrival mode for measurement of particle interaction time, and Medipix mode for recording a particle hit count).

The Timepix detector was placed in the position of the multi-strip detector at the focal plane (as shown in figure 2). The direct ion decay observation method [11] has been adapted for use at the mass separator MASHA.

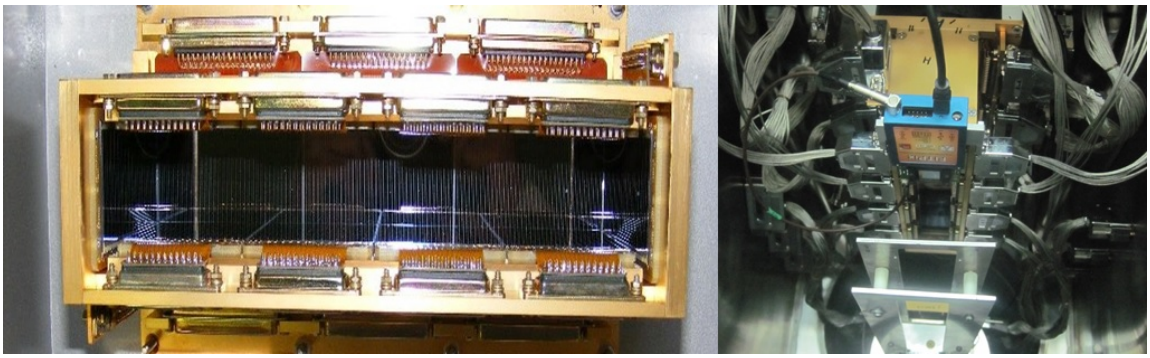

Figure 2. Front view of the multi-strip detector (left side) and Timepix & FITPix read-out system installed close to this detector (right side).

Different Timepix read-out solutions were used during development of the MASHA & Timepix set-up. Initially, an ordinary FITPix [6] with a Timepix chipboard was used. However, later on, to meet better specific requirements of the application it was replaced by the FITPix COMBO [7] system (figure 3). The latter is a type of the read-out interface with an integrated common electrode signal analysis functionality.

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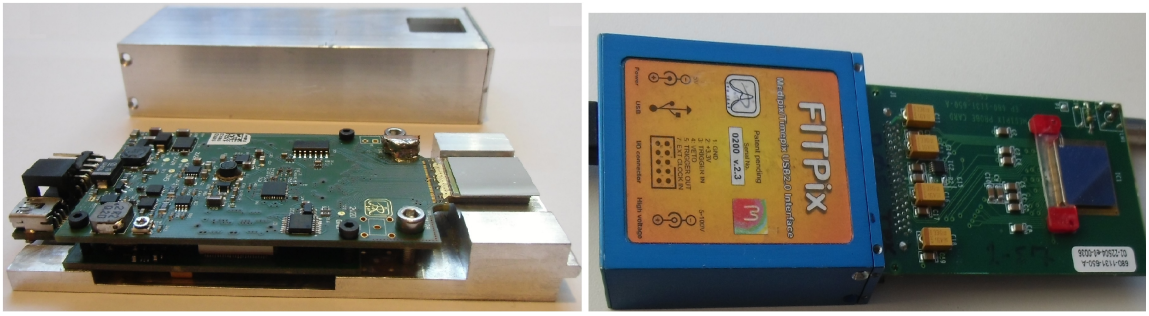

Figure 3. Disassembled FITPix COMBO read-out interface with an integrated Timepix detector is on the left, Standard FITPix read-out interface + Timepix chipboard is on the right.

2.2 Implantation and detection of ions in Timepix detectors

The process of ion implantation and its decay detection is demonstrated by the sketch shown in figure 4. The super heavy ion under investigation is implanted into the surface layer of the Timepix sensor at time t_0. Its initial position cannot be directly determined because its energy is too low (~ 40 keV) to penetrate through the detector dead layer. Nevertheless this can be done by measuring the origin of a particular beta track if detected. The first evidence of the implanted ion presence is its decay at time t_1 with creating a track registered in the pixel matrix of Timepix. The other subsequent decays follow one by one at times t_2, t_3, ... up to t_n (the number of decays is determined by the isotope studied). Not all events in the decay chain get registered due to beta-particle escape. Only half of the beta-particles can be detected in the sensor since they are emitted isotropically. Some beta particles leave only small fraction of their energy before they escape out of the sensor volume. In this case the registered track cannot be clearly recognized from background ones. Therefore the efficiency of detection of the events from the full decay chain can be low, especially for isotopes with a lot of decay steps in the chain.

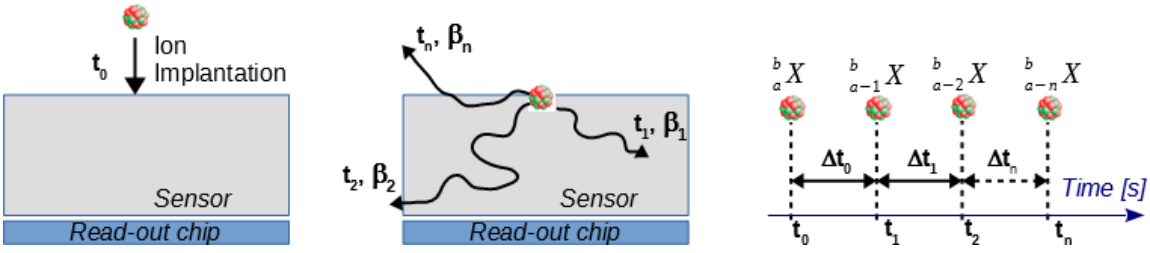

Figure 4. Ion implantation in the surface layer of the Timepix sensor (left side); Emission and registration of beta particles within the sensor originating from the previously implanted ion (center); Process of successive decay of the implanted ion and its progeny where t_0 stands for time point when the ion was implanted into the sensor, t_1 to t_n stand for time points of decay occurrence, Δt_0 stands for period from ion implantation to the first detectable beta decay, Δt_1 to Δt_n stand for life times of the daughter products (right side).

3 Experimental results

3.1 Investigated isotopes

Neutron-rich radon isotopes (A = 227–232) were produced in the mutinucleon transfer reaction ^{48}Ca + ^{232}Th. An intense ^{48}Ca beam (~5 μA) with an energy of 7.3 AMeV was delivered by the U-400M Cyclotron, FLNR, JINR, Dubna. Since radon is a noble gas, we expected to get a high efficiency. Nuclei in this region decay mainly by β^-. Typically, 2–4 beta particles are emitted before accessing the final long-lived isotopes. The tracks of these beta particles have the same starting point, namely, the one where Rn isotope was before implanted into the Timepix sensor. A case of the decay that are of great interest regarding the experimental study is shown in figure 5.

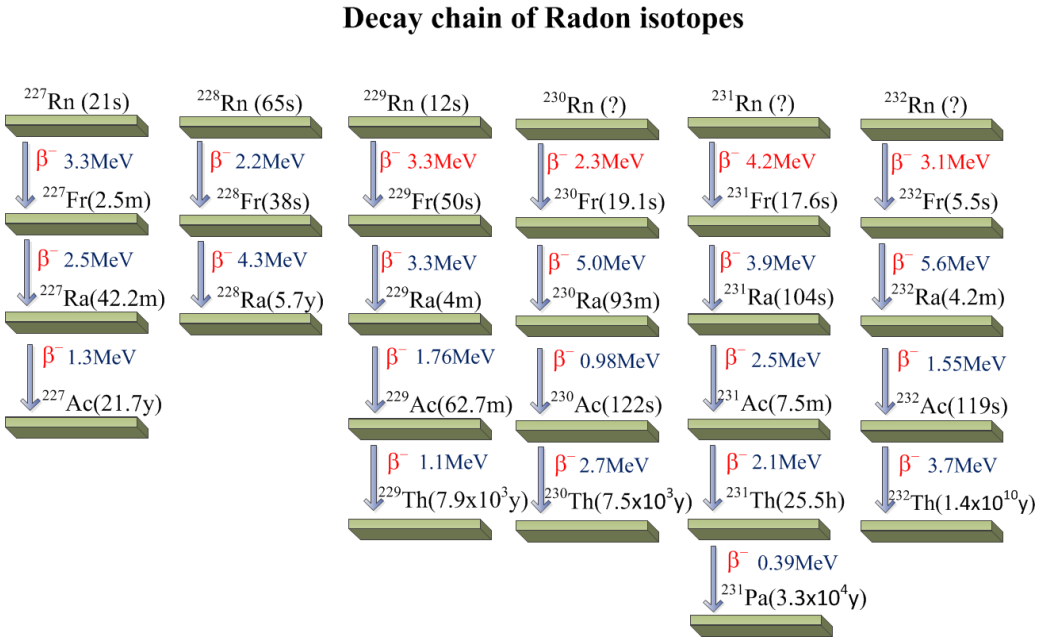

Figure 5. Beta decay chains of some selected radon isotopes (experimentally studied ones are marked by red).

3.2 Experiment run and event acquisition process

Study of each isotope of interest was done in the following way. First, the mass calibration of MASHA + Timepix setup was carried out by alpha particles from decay of ^{220}Rn isotope (see figure 6). All other radon isotopes were implanted approximately at the very same position of the Timepix sensor.

Mass setting in the focal plane of mass separator is carried out by control software calibrated for multi-strip detector. The frontal detector part covers a 240×35 mm area of the focal plane and consists of 192 strips with a pitch of 1.25 mm. In the case of radon isotopes a set of peaks (masses) with the step of 15 strips is seen [1–3]. When the MASHA + Timepix setup is used in the experiment, one part of multi-strip detector is replaced with Timepix detector, so it is quite easy to set roughly the given mass on Timepix sensor. After that more precise tuning is done to set the mass in the centre of Timepix detector. The magnetic field is than measured for dipoles D3a and D3b by using the Hall and NMR senzors. Since the isotopes are ionized to charge state $Q = +1$ the

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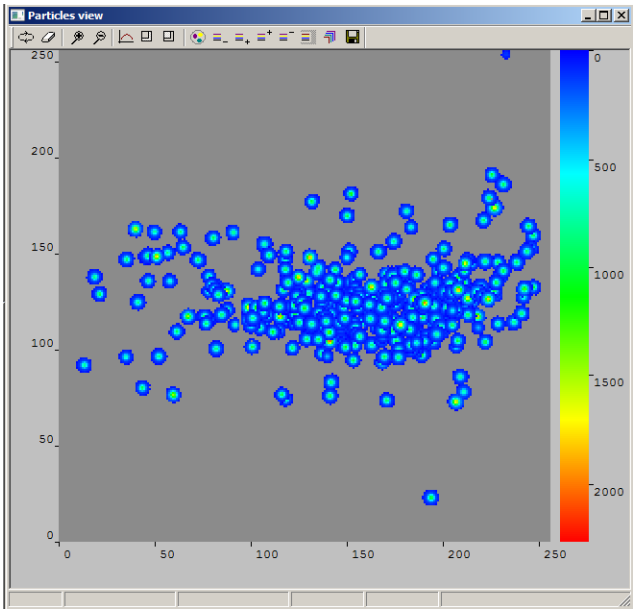

Figure 6. Mass calibration of MASHA + Timepix setup by using the alpha decay of ^{220}Rn (integral image composed of individual alpha tracks showing the focusing and scattering of implanted ions).

next radon masses are set by changing the magnetic field for dipoles D3a and D3b. The Timepix detector is two coordinate detector compared to multi-strip one. In this case a more precise tuning of our magneto-optical system is carried out.

The Timepix detector was continually operated during the measurement runs and all events registered in the pixel detector were acquired and saved for the future post processing. Meanwhile, the ions of the selected isotopes were continuously being implanted into the sensor (with a rate ranging from several ions per hour up to several ions per second depending on the isotope studied). The minimal reasonable measurement period is determined by the lifetime of the selected isotope and by ones of all the daughter products in the decay chain till reaching stable or long lived nucleus. Before beginning the next isotope study some waiting delay is necessary to reduce the activity from previously implanted ions and daughter products. The same measurement procedure was repeated for all isotopes studied.

3.3 Data analysis and searching for related decay events

A software tool dedicated to analysis of decay events was developed to process acquired data. Particle tracks were recognized in pixel matrices while their properties (time of detection; deposited energy; track shape-roundness, length; end point coordinates; etc. . .) were evaluated and saved in a database forming a catalogue of all registered decays.

Next, correlated events belonging to a decay chain sequence of the isotope of interest was being searched on base of a selection criteria (i.e. lifetime, point of interaction, track energy, etc.). After filtration, a list of corresponding event sets was composed. The figure 7 demonstrates the dedicated tool and output obtained after processing and evaluation of data presented in figure 8.

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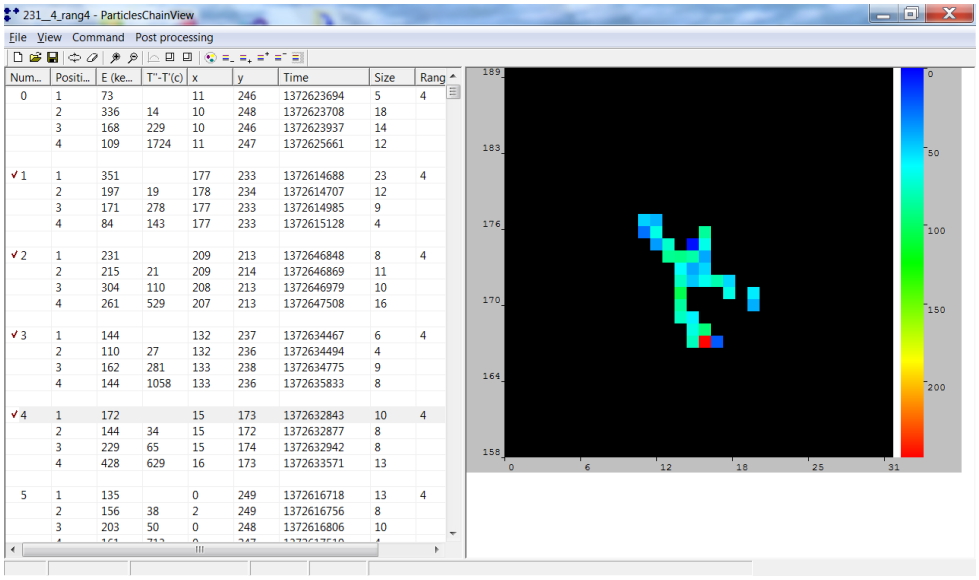

Figure 7. Data processing & event filtration tool GUI — Output display window (an example of obtained results with a list of event set matching to applied criteria).

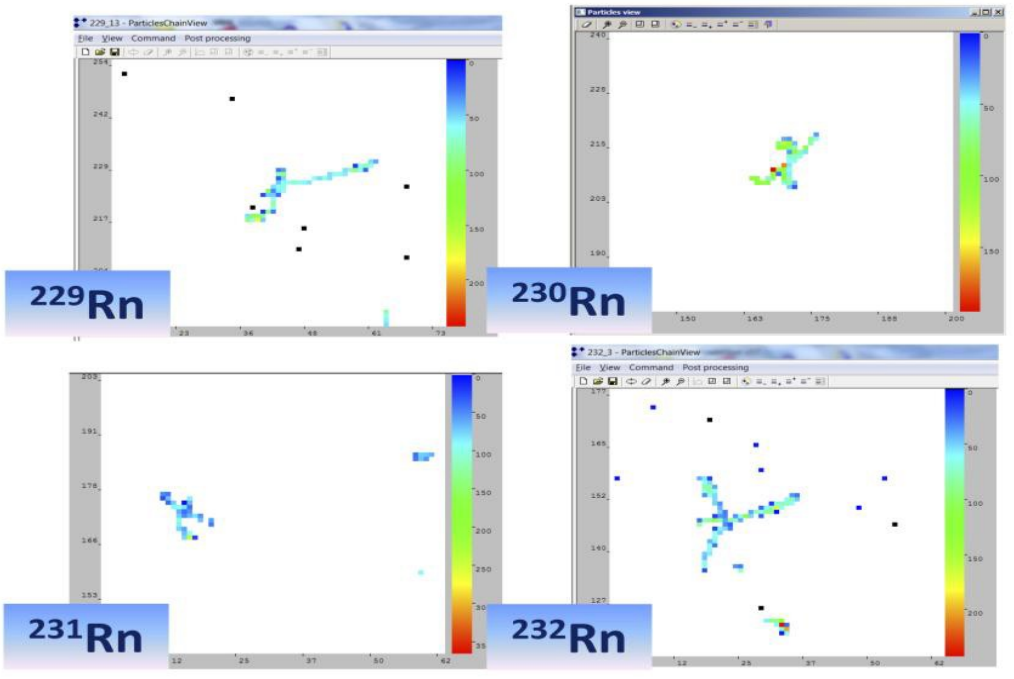

Figure 8. Data processing & event filtration tool GUI — Output display windows showing samples of fully identified ions of ^{229}Rn, ^{230}Rn, ^{231}Rn, ^{232}Rn isotopes (displaying all particular beta decay tracks composed as one image).

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3.4 Outputs obtained after processing of the measured data

Table 1 below presents an overview of fully identified ions of the studied radon isotopes (^{227}Rn, ^{229}Rn, ^{230}Rn, ^{231}Rn and ^{232}Rn) obtained after data evaluation. Only one radon isotope with given mass (A = 227–232) was implanted into the sensor and registered during a particular measurement run cycle. The Timepix detector was operated in the ToT mode with a frame acquisition time of 1 s.

Table 1. Overview of the fully identified radon ions when all partial decay stages were registered in the Timepix detector.

Isotope	Detection efficiency [%]	Number of beta particles in decay chain	Number of detected full chain events
^{227}Rn	0,654	3	75
^{229}Rn	0,187	4	46
^{230}Rn	0,149	4	28
^{231}Rn	0,223	4	12
^{232}Rn	0,2	4	3

4 Future developement

Recently, the set-up has been upgraded to the state-of-the-art pixel device Timepix3 [5] accompanied by Katherine read-out interface [8] to enhance further isotope identification. A customized Timepix3 chipboard [9] was developed to meet specific conditions of the application (operation in vacuum, solved cooling issue, common electrode signal analysis, etc.). The dedicated data analysis software tool has been integrated into the J-Pix [10] acquisition control package as a data processing plug-in. The Timepix3 detector can provide energy information as well as time of arrival information with much higher precision of about 2 ns. It can be well exploited to improve the beta particle identification by using the method [12] allowing to determine the points of the beta particle track origins.

5 Conclusions

Application of the Timepix family detectors at the mass separator MASHA possesses definitely significant enhancements in term of implanted ion identification and recognition. Especially, neutron-rich beta decaying isotopes can be clearly distinguished when comparing to performance of the former set-up based on the multi-strip detector. The pixel detector Timepix is also a powerful mean that allows very precise mass calibration providing information about the ion beam scattering and the target point.

Acknowledgments

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