様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　２ 年　 ６ 月 １７ 日現在

機関番号：８２４０１

研究種目：若手研究

研究期間：2018～2019

課題番号：１８Ｋ１３５７３

研究課題名（和文）Development of a cryogenic multipole ion trap for isomeric separation with MRToF mass spectrometry

研究課題名（英文）Development of a cryogenic multipole ion trap for isomeric separation with MRToF mass spectrometry

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：新しいアイデアに基づくミクロ多重極トラップの開発に着手し、ガスキャッチャーセルからのイオン引き出しに使用するトラップ装置を利用してその実現可能性を実験的に検証した。更に、既存のPaulトラップの極低温での駆動試験を様々なオンライン実験で実施した。最終目的であるミクロ多重極トラップと質量分析器との接続は未完結であるが、存装置を用いた試験により、達成できる見通しを既立てることができた。これまでのところ、プリント電極基板を使ったトラップが最も有望であると考えている。微小電極による微小領域内トラップによりイオンの空間的広がりを制限することで、質量分析器へ問題なく接続できることが期待される。

研究成果の学術的意義や社会的意義
Nuclear isomers separated by their mass offer unique opportunities to precisely study masses of superheavy elements on the search for the island of stability. This research project is focused on the realization of very high resolving powers of fast mass spectrometers to enable isomeric resolution.

研究成果の概要（英文）：In this research project, new concepts towards microscopic multipole traps have been investigated and several possibilities have been tested in the experiment. We accomplished several tests of small trapping systems as used for extraction of ions from a gas-catcher cell. Experience has also been obtained for the cryogenic operation of a previously existing Paul trap during various on-line experiments over the period of the grant.
The final goal of an independent microscopic multipole trap coupled to a mass spectrometer is further pending, but can be accomplished using the existing devices. By the experience obtained up to date, planar trap designs (i.e. printed electrodes on an insulating board) are most promising for the realization of the trapping structures. Trapping systems with smaller volumes are necessary and can be realized by more narrow electrode boundaries, so that the motional space of the ions is restricted to enable a meaningful combination with a mass spectrometer.

研究分野：Experimental Nuclear Physics

キーワード：ion traps　small ion traps　mass spectrometry　multi-reflection devices　precision physics

１．研究開始当初の背景

In superheavy element (SHE) research the knowledge of nuclear masses is still very scarce and experiments become more challenging by low production rates [1]. The nuclear mass is one of the most important input parameters to reliably confirm the physical properties of SHE and, as an ultimate goal, to predict and verify the position of the presently hypothetical "island of stability". Facing also the problem of the expected long half-lives of SHE and the reoccurrence of beta decay, precise mass measurements are independent of the decay and thus very desirable as a verification of the nuclide's identity and for the exploration of ground state and excited state energies. At present, excited states in heavy atomic nuclei and SHE still cause a particular challenge for the study of heavy isotope and SHE masses (see e.g. [2]), as the separation of ground states and excited states of nuclei by their mass difference requires mass spectrometers with particularly high resolving power. As from alpha decay spectroscopy exclusively the energy difference between initial and final state can be revealed, the ability to resolve isomeric states by mass is a key to disentangle the puzzles of energy states from decay spectroscopy and precisely obtain the masses of SHE higher in the decay chain. In that way, the existing spectroscopy data can be applied in an unambiguous way. New mass data of presently unknown SHE is of utmost importance to benchmark and improve theoretical models and to tighten the boundaries of the island of stability and to predict its position in the nuclear chart. Furthermore, the production of new SHE depends on precisely matching the correct collision energies to maximize the cross section for the rare events. These energies must be predicted from theory first and require accurate input data from the nuclei known so far.

[1] Morita et al. J. Phys. Soc. Jpn. 81 (2012)
[2] M. Rosenbusch et al. Phys. Rev. C 97, 064306 (2018)

２．研究の目的

The purpose of this research project is to improve multi-reflection time-of-flight mass spectrometry (MRTOF-MS) for the capability to resolve low-lying isomeric states of heavy nuclei. This requires by far higher resolving powers as compared to the performance of present systems. The project concentrates on the initial phase-space conditions, to which the ions are cooled prior to the injection into the mass spectrometer. Present systems are using very reliable quadrupole ion traps to store, cool, and eject ions for the mass measurement. The field shape in quadrupole traps allows only for a limited cooling performance by unwanted heating of the stored ion cloud via the radio-frequency (RF) field in a gas filled trap (usually Helium). As a consequence, for a background gas at a certain temperature, the temperature of the stored ions converges already at multiples of the gas temperature in usual quadrupole cooler traps.

In this project, the general idea is to allow for the use of multipole traps for the cooling and preparation procedure of the ions. Multipole traps consist of a larger number of radio-frequency electrodes enabling a RF field of different order, as for example octupole fields, dodecapole fields, or fields of higher order. By the electric shielding effect, these traps are nearly field-free in the center, where the extension of the field-free region increases with the order of the field. The ion cloud is confined in this region and the ions can move freely and cool to low temperatures by collisions with gas atoms at low pressure. These traps are presently widely used to produce cold molecules and atomic clusters.

The drawback of multipole traps, and the reason why their applications in time-of-flight mass spectrometry (see [1] for a design study) is yet rare, is a too wide space in which the ion cloud can spread. This causes an unwanted expansion of the possible initial position of the ions and will limit the mass resolution by ion optical aberrations of the MRTOF-MS. Furthermore, cutting the phase space of the beam at another stage in the apparatus (like skimming) leads to losses and is not applicable for experiments with rare ions.

The main idea to overcome this problem is to decrease the size of the multipole trap, so that the maximum expansion of the ion cloud is limited to a desirable volume. In that way, the cooling can be achieved without the unwanted expansion of the ion cloud, which leads to high resolving powers of the subsequent mass spectrometry. To succeed in producing such initial conditions, the anticipated expansion of the field-free region must be in the order of a few hundred micrometers, which poses a particular challenge for this project.

[3] U. J. Lorenz & T. R. Rizzo, Anal. Chem. 83, 20, 7895 (2011)

３．研究の方法

In the present on-line setup, atomic nuclei of interest are produced at the RIBF facility of RIKEN by fusion-evaporation reactions upon the impact of a primary beam taken typically from RIKEN's RRC accelerator on a thin target. The produced fusion-evaporation residues are separated from the primary beam using the GARIS-II separator and transported to a gas stopping cell via thin beam energy degraders to pre-adjust the kinetic energy. The gas stopping cell is filled with helium at about 100 mBar pressure in order to decelerate the produced exotic ions by ion-atom collisions from accelerator energies down to lower energies until a thermal equilibrium with the gas atoms is achieved. By use of radio-frequency carpets the stopped ions are kept away from touching the walls and are guided to a small extraction orifice into a Paul-trap system. After passing a linear quadrupole the ions are transferred to a preparation Paul with a planar geometry and are stored in a helium buffer gas at low pressure for several milliseconds until an equilibrium state is achieved. The cooled ions are ejected and transported into the MRTOF device. Capture of ions is achieved by switching the mirror voltages and enabling a potential well exceeding the kinetic energy of the ions. In that way, reflections forth and back between the two concentric ion mirrors are achieved. For the detection of the ions' time-of-flight, the mirror at the exit side of the MRTOF device is opened and the ions can reach the detector where their TOF signal is recorded [4,5].
Various general aspects of the research project are:
- Molecular dynamics simulations (including the commercial software SIMION) for feasibility studies
- Radio-frequency technology above 10MHz
- Technology of radio-frequency carpets
- Design of ion traps from printed circuit boards
- Vacuum technology, ion sources, ion detection techniques (measurement of low currents and also single-particle detection), control systems, and TOF mass spectrometry

[4] P. Schury et al., Nucl. Instr. Meth. B 335, 39 (2014)
[5] Y. Ito et al., Phys. Rev. Lett. 120, 152501 (2018)

４．研究成果

In this research project, new concepts for microscopic multipole traps have been investigated. Initially a 3-dimensional design was proposed but has been discarded later due to difficulties to accurately manufacture a system with a trapping region of less than 1 mm size. As an alternative, planar electrode structures as applied for radio-frequency carpet technology in gas stopping cells come into question and have been further investigated for this purpose. Molecular dynamics simulations have been performed to verify various geometries and parameters allowing for storage conditions of ions with different atomic masses. These studies revealed the feasibility of planar designs, but also that the concept is challenging for the tight restrictions of the trapping volume. Upon the small size and distances of the RF electrodes (on the order of 100 micrometers and less), frequencies higher than 10MHz and high signal amplitudes are necessary to safely enable ion storage, especially when hot ions are injected into the trap. For this purpose, high-frequency devices to enable guiding fields with frequencies of up to 50 MHz have been purchased and tested.
Aligned with other developments of a novel type of RF carpets, first tests of linear and planar RF electrodes for ion storage and transport could be performed with success [1]. Ion transport with different trapping parameters allowing for the extraction of ions from the novel gas-catcher cell have been demonstrated. Furthermore, at the present MRTOF setup the planar quadrupole trap has been investigated for the feasibility of cryogenic operation. To this end the trap was cooled to cryogenic temperatures and heated back to room temperature during full operation of the mass spectrometer, without any incidents. By the experience obtained up to date, planar trap designs with printed electrodes are most promising for the realization of the trapping structure. Trapping systems with smaller volumes are necessary and can be realized by narrow electrode boundaries for the confinement, so that the motional space of the ions is restricted enough to enable a meaningful combination with a TOF mass spectrometer. However, the goal to test an independent microscopic multipole trap system coupled to a mass spectrometer is further pending.

[6] A. Takamine et al., RIKEN Accel. Prog. Rep. 52 (2019)

５．主な発表論文等

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２．論文標題 Improving wide-band mass measurements in a multi-reflection time-of-flight mass spectrograph by usage of a concomitant measurement scheme	５．発行年 2018年
３．雑誌名 Int. J. Mass Spectrom.	６．最初と最後の頁 40-46
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ijms.2018.08.007	査読の有無 有
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３．雑誌名 Phys. Rev. C	６．最初と最後の頁 64306
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3．雑誌名 Review of Scientific Instruments	6．最初と最後の頁 014702～014702
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1063/1.5104292	査読の有無 無
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掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1016/j.nima.2019.163198	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1093/ptep/ptz120	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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