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研究課題名（和文）不安定核のためのイオンサーフィングガスセルの開発研究

研究課題名（英文）Construction of an ion surfing gas cell for unstable nuclei

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研究成果の概要（和文）：安定核イオン源によるオフラインと不安定核イオンによるオンラインの両方において、イオンサーフィン型RFカーペットの性能テスト行った。K+、Cs+によるオフライン実験では、一般的なガス圧100mbarより高圧下においてもなお100%近い効率を達成した。これを元に開発されるガスセルは低エネルギー不安定核実験の根幹となり、より高圧で動作することでより高効率を得ることにつながる。これらの結果は昨年誌上発表した。
またこれを基に核融合反応による高エネルギー不安定核を用いたオンライン実験においても実装され、205Frを用いた測定で約30%の停止・引出し効率を得た。オンライン実験の結果は近々誌上発表予定である。

研究成果の概要（英文）：We have successfully tested the use of ion surfing rf-carpet, both online and offline. The initial offline results were published last year. Newer offline results have been published in the Master Thesis of Arai Fumiya at University of Tsukuba. These newer results have shown that we can use higher pressure than expected in a large gas cell to be used online at RIKEN. The large gas cell will be the basis of a low-energy nuclear physics facility and higher pressure will mean higher efficiency.
The new rf-carpet has been used in online commissioning of a small gas cell for fusion-evaporation reactions products. The goal of this facility is to measure trans-Uranium elements, eventually providing anchor points for hot-fusion reactions which will aid in precise determination of new super-heavy elements.
The new rf-carpet tested online more than 30% efficiency while providing good differential pumping. Initial results will be published in scientific journals soon.

研究分野：数物系科学

キーワード：ガスセル　rfカーペット　イオンサーフィング　原子核質量測定

１．研究開始当初の背景

The gas cell is an important tool in nuclear physics. The most exotic nuclei are created by in-flight fission and fragmentation or by fusion-evaporation reactions. In both cases, the resultant nuclei are produced as high-energy ions that are incompatible with precision ion trap-based experiments. By stopping these ions in the gas cell, extracting them and transferring the ions into high-vacuum it is possible to use these highly exotic nuclei in ion trap experiments.

Gas cells have two drawbacks. The first is that in order to achieve maximum stopping efficiency, a high-pressure He gas environment is required. This lead to a need for an expensive differential system to connect the gas cell with high-vacuum. The second is that the transport speed for ions is generally limited by high-voltage breakdown in the He gas environment.

We initially intended to build and test a surfing-mode rf-carpet for fast extraction of ions from a gas cell. The surfing mode allows for faster ion transport without worry of high-voltage breakdown. We desired to make as small of a pitch for the rf-carpet as possible to allow minimal need for expensive pumps needed for differential pumping to allow ions extracted from gas cell to be transported into high-vacuum.

２．研究の目的

The project originally had three goals:

(1) Development of a substrate-free rf-carpet, using wire-chamber techniques.

Ions, especially unstopped high-energy ions, may strike the substrate and cause it to charge up. This reduces the efficacy of the carpet and can lead to failure of the carpet. To eliminate the risk of rf-carpet charge-up from ions striking the substrate, we hoped to build a linear rf-carpet without substrate by using thin wires stretched across a frame.

(2) Development of a carpet which could operate at high-pressure.

As mentioned previously, higher pressure in the gas cell leads to higher stopping efficiency for the energetic ions. However, at higher pressures the rf-carpet requires higher rf amplitude; it has been difficult to operate rf-carpets successfully at high pressures as there has been a tendency for the rf voltage to breakdown in the He environment. However, by working with sufficiently fine carpet structures, the breakdown voltage should become mitigated by a combined increase in the rf field repulsive strength (proportional to r^{-3}) and an increase in the Paschen limit at sufficiently small distances. At the same time, a fine structure would allow for a very small exit orifice, providing an excellent pumping barrier and reducing the need for large and expensive pumps.

(3) Development of fast transport of ions by rf-carpet.

Many of the exotic nuclei that would be most interesting to study have short half-lives, often 10 ms or less. For this reason it is important to extract ions as quickly as possible from the gas cell. Typically this is done with static electric fields. However, particularly for large gas cells, this leads to unreasonably large DC voltages resulting in discharges. The ion surfing method should circumvent the discharge problem and allow very fast extraction of ions from the gas cell.

３．研究の方法

A pair of medium-sized gas cells were constructed – one strictly for offline studies and a second for online and offline studies.

(1) Offline studies

The performance of the rf-carpet was tested offline using a variety of ion sources and a wide range of pressures. The general experimental setup consisted of a thermal ion source offset from the center (extraction region) and set back from the rf-carpet by some centimeters, as shown in the figure below.

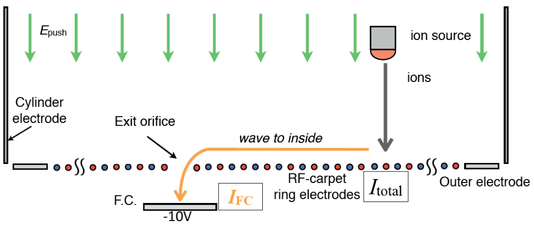


図 1: Schematic overview of rf-carpet offline test setup

Ions could be collected on the rf-carpet wires to determine the incoming ion current. Then the carpet voltages would be turned on and the current extracted could be measured on a small Faraday cup placed after the exit orifice. The rf-carpet parameters could then be optimized on the current seen at the Faraday cup. The efficiency was then determined by a ratio of the ion current seen at the Faraday cup and that seen on the rf-carpet.

This type of study was performed using three types of ions: K^+, Rb^+, and Cs^+. For each ion species, the optimal efficiency was measured for a rather wide range of pressures: 0.5 mbar ~ 300 mbar. Additionally, these studies were performed with two types of rf-carpet – one made from 80 μ m wires with 80 μ m spacing featuring an exit orifice of 320 μ m and another "rough" carpet with 2x the dimensions of the "fine" carpet. A photo of the central region of the rough carpet is shown below.

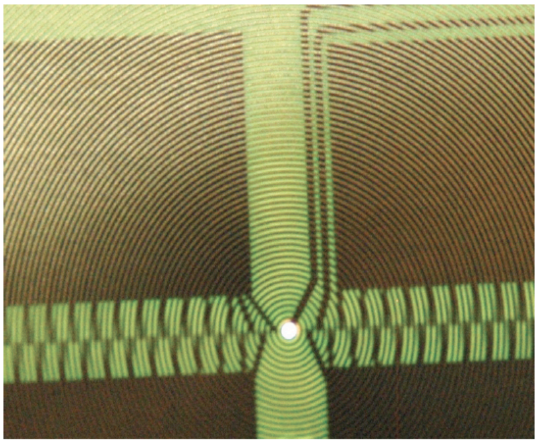


図 2: Photograph of central region of rough rf-carpet. The extraction hole has a diameter of φ 0.6 mm

(2) Online studies

Online testing was performed using a gas cell placed after the GARIS-II separator, part of the RILAC facility at RIKEN. A 138 MeV primary beam of ^{40}Ar was provide by RIKEN/RILAC linear accelerator. The beam was impinged on a rotating target made of Ta and Tm foils. The primary beam then produced ^{205}Fr, ^{216}Th and ^{217}Pa ions via fusion-evaporation reactions. These ions continued forward with total energy of ~30 MeV, and were separated from the unreacted primary beam by the GARIS-II separator.

After GARIS-II, ions pass through a rotatable Kapton foil to further degrade the ion energy to <10 MeV. The ions can then pass through a final thin Mylar film before entering the gas cell. Inside the gas cell, ions undergo ionizing collisions with He gas and eventually come to rest, mostly before striking the rf-carpet located at the end of the gas cell.

In order to determine the incoming rate of each isotope, an array of PIN diodes can be inserted in front of the gas cell. The α –decay rates are then measured to provide a normalization factor for ions entering the gas cell. A similar detector was placed after the gas cell to determine the rate of each extracted ion.

4. 研究成果

(1) Substrate-free rf-carpet

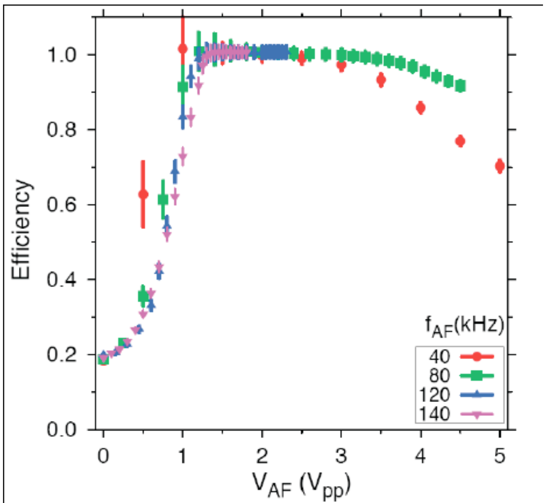
Despite many efforts, this proved untenable. We were not able to do it ourselves. A few companies said they could do it, but in the end failed. We still feel it is a valuable idea, but realization will require many technological developments.

(2) Offline results of substrated rf-carpet

There were some great results of the rf-carpet study offline.

① Fast ion transport

As shown in the figure below, fast transport conditions with near unity efficiency were found offline for even the heavy Cs^+ ions. The figure shows results for the fine carpet, although similar results were also obtained for the rough carpet. These results are important for the ability of the rf-carpet to deliver very short-lived RI species.



f_{AF}	v_{wave} (fine RFC)	v_{wave} (rough RFC)
40 kHz	25.6 m/s	51.2 m/s
60 kHz	38.4 m/s	76.8 m/s
70 kHz	44.8 m/s	89.6 m/s
80 kHz	51.2 m/s	102.4 m/s
120 kHz	76.8 m/s	153.6 m/s
140 kHz	89.6 m/s	179.2 m/s

図 3: Result of ion extraction speed testing. The ions should travel at the same speed as the travelling wave, as shown in the table below the graph.

② Operation at high-pressure

We found surprisingly good results for operation at high-pressures. Typically, lighter ions are more difficult to transport by rf-carpet as they require higher rf amplitude to provide a given repulsive force from the carpet surface. However, we found that we were able to equally well transport K^+ and Cs^+ ions using the fine rf-carpet; the rough carpet yielded lesser results at higher pressures.

The figure below shows a comparison of maximum optimized efficiencies for K^+ and Cs^+ using both fine and rough rf-carpets. As can be seen, using the fine rf-carpet, a near unity efficiency can be achieved for both light K^+ and heavy Cs^+ ions at pressures from less than 50 mbar up to 30 mbar. These results are particularly exciting as they imply an ability to operate a large gas cell at high-pressure for optimal stopping of light RI ions produced through in-flight fission and fragmentation. They also show the importance of pushing the limits of printed circuit fabrication techniques to achieve as small of a pitch as possible.

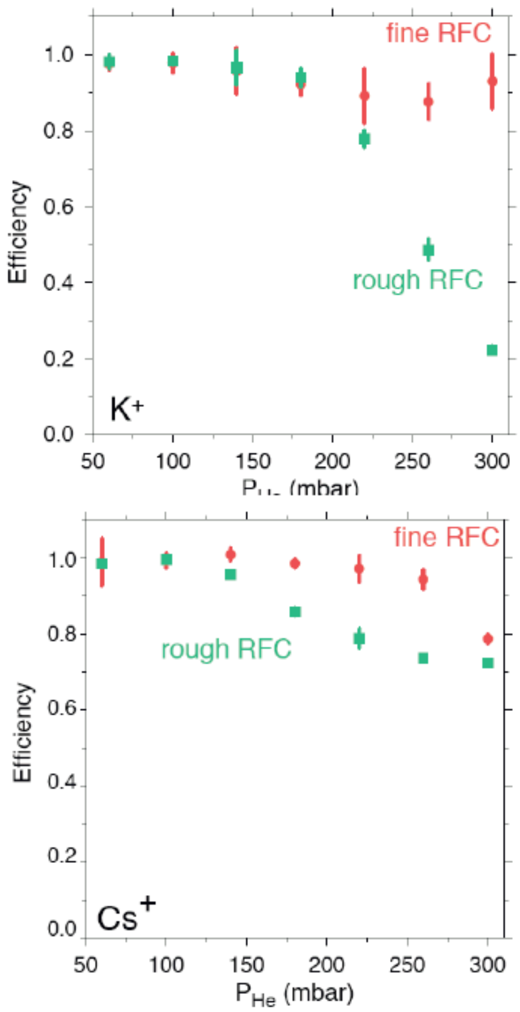


図 4: Extraction efficiency thermally produced K+ and Cs+ ions as functions of gas pressure.

③ Operation at low-pressure

Partway through this project the idea arose to use such an rf-carpet in a very low-pressure (~1 mbar) gas cell for cooling and bunching ions in a more flexible and efficient manner than the standard gas filled Paul trap. It was found that the fine carpet performed rather poorly at such low-pressures. Simulations indicated that this was do to the ions moving too quickly in the low-pressure gas and violating the assumptions of the pseudo-potential approximation. Using the rough rf-carpet, however, near unity efficiency was found for pressures as low as 0.5 mbar. This new method has now been spun off as a separately funded project at RIKEN.

(2) Online results

The online results provide the best direct evidence of the speed of ion transport by the rf-carpet. By comparing the efficiency for isotopes of varying half-lives we can indirectly confirm whether the ions are travelling quickly on the rf-carpet.

① Overall efficiency

The efficiency result achieved offline was based on a point-source of ions. In the online operation of the gas cell, however, ions within a large volume of the cell. The condition inside the gas cell is also somewhat different. In the offline studies, the ions create a uniformly charge plasma, while online condition is non-uniform plasma with regions of neutral plasma, regions of positively charged plasma and regions of negatively charged plasma. As such, we were quite pleased to measure a peak efficiency for combined stopping (most likely near unity) and extraction of ~30%, as shown below, for ^{205}Fr.

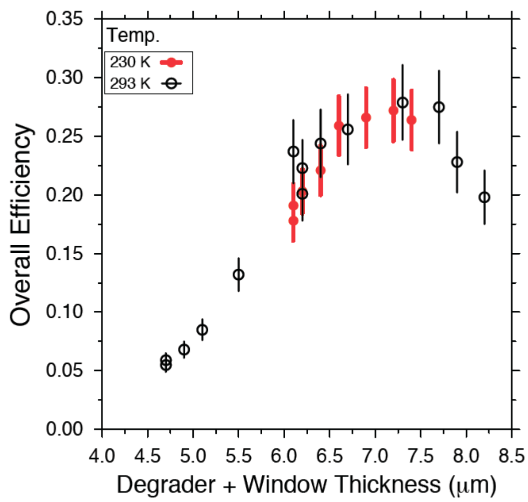


図 5: Online result, rf-carpet efficiency as function of degrader thickness

② Efficiency for isotopes of varying half-life

As stated previously, we were able to measure efficiency for a variety of half-lives. For the long-lived ^{205}Fr a peak efficiency of 30% was measured. For the short-lived ^{216}Th ($T_{1/2}$=26 ms) a peak efficiency of 12% was found. For the extremely short-lived ^{217}Pa ($T_{1/2}$=3.6 ms) a peak efficiency of 4% was observed. From this we can estimate that the extraction time must be less than 10 ms.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

① F.Arai, Y.Ito, M.Wada, P.Schury, T.Sonoda, H.Mita, "Investigation of the ion surfing transport method with a circular rf carpet" Int. J. Mass Spectrom. 362(2014)56

② 新井郁也、「超重元素の精密質量測定のためのイオンサーフィン型高周波イオンガイドガスセルの開発」修士論文 (2015) 筑波大学

〔雑誌論文〕（計　２　件）

① F.Arai, "Performance of an ion surfing rf-carpet in high gas pressure for application in high energy RI beam gas catcher" RIKEN Accel. Prog. Rep.47(2014)204

② Y.Ito, "A gas-cell ion cooler and buncher for SLOWRI" RIKEN Accel. Prog. Rep.47(2014)205

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① Y.Ito, "Gas-cell beam cooler-buncher for low-energy experiments at SLOWRI" 6th International Conference on Trapped Charges Particles and Fundamental Physics, 香川県高松市, 1 – 5 December 2014

② F.Arai, "An ion-surfing RF-carpet gas cell for transuranium nuclei study at GARIS-II" 6th International Conference on Trapped Charges Particles and Fundamental Physics, 香川県高松市, 1 – 5 December 2014

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④ F.Arai, "Performance of Ion Surfing rf-carpets for High-energy RI beam Gas Catcher" 2nd conference on Advances in Radioactive Isotope Science, 東大, 1-6 June 2014

⑤ F.Arai, "Performance of ion surfing rf-carpets for RI beam gas catcher" 4th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA 7 – 11 July 2014

⑥ Y.Ito, "A windowless gas-cell cooler-buncher at RIKEN/SLOWRI" 4th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA 7 – 11 July 2014

⑦ 新井郁也、「理研GARIS-IIにおかるイオンサーフィン型RFカーペットガスセル性能評価」日本物理学会第７０回次大会、早稲田大学、２０１５年３月21日～２０１５年３月２４日

〔図書〕（計　０　件）

〔産業財産権〕

○出願状況（計　０　件）

名称：
発明者：
権利者：
種類：
番号：
出願年月日：
国内外の別：

○取得状況（計　０　件）

名称：
発明者：
権利者：
種類：
番号：
出願年月日：
取得年月日：
国内外の別：

〔その他〕

ホームページ等

６．研究組織

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