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First Observation of New Isotopes in the Fragmentation of ^{198}Pt at FRIB

O. B. Tarasov,[1,*] A. Gade,[1,2] K. Fukushima,[1] M. Hausmann,[1] E. Kwan,[1] M. Portillo,[1] M. Smith,[1] D. S. Ahn,[3] D. Bazin,[1,2] R. Chyzh,[1] S. Giraud,[1] K. Haak,[1,2] T. Kubo,[4] D. J. Morrissey,[1,5] P. N. Ostroumov,[1,2] I. Richardson,[1,2] B. M. Sherrill,[1,2] A. Stolz,[1] S. Watters,[1,2] D. Weisshaar,[1] and T. Zhang[1]

[1]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[3]*Center for Exotic Nuclear Studies, Institute for Basic Science, Daejeon 34126, Republic of Korea*
[4]*RIKEN Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[5]*Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA*

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Five previously unknown isotopes (^{182,183}Tm, ^{186,187}Yb, ^{190}Lu) were produced, separated, and identified for the first time at the Facility for Rare Isotope Beams (FRIB) using the Advanced Rare Isotope Separator (ARIS). The new isotopes were formed through the interaction of a ^{198}Pt beam with a carbon target at an energy of 186 MeV/u and with a primary beam power of 1.5 kW. Event-by-event particle identification of A, Z, and q for the reaction products was performed by combining measurements of the energy loss, time of flight, magnetic rigidity $B\rho$, and total kinetic energy. The ARIS separator has a novel two-stage design with high resolving power to strongly suppress contaminant beams. This successful new isotope search was performed less than one year after FRIB operations began and demonstrates the discovery potential of the facility which will ultimately provide 400 kW of primary beam power.

Introduction.— Neutron-rich nuclei in the region of the nuclear chart below ^{208}Pb have long posed a challenge for experimental study due to their small production cross sections and difficulty to uniquely identify individual nuclides. This barely explored territory, that extends up to and beyond the magic neutron number $N = 126$, plays an important role in r-process nucleosynthesis [1]. The r-process is responsible for the production of about half of the heavy elements in the Universe and the influence of neutron magic numbers away from stability is critical to its operation. While the presence of an $N = 126$ shell closure is predicted to shape the r-process pathway and abundance patterns [2, 3], its exploration in nuclei far from stability can also provide critical insight into the evolution of nuclear shells [4] and nuclear isomerism [5] in heavy neutron-rich nuclei. Only four $N = 126$ isotones of elements lighter than Pb have been produced and recently identified [6–9]. New isotopes were discovered in this hard-to-reach region by the in-flight fragmentation of ^{238}U [9] and ^{208}Pb [10] beams on beryllium targets at energies of approximately 1 GeV/u and, most recently, in the fragmentation of an 85-MeV/u ^{198}Pt beam on a beryllium target [11].

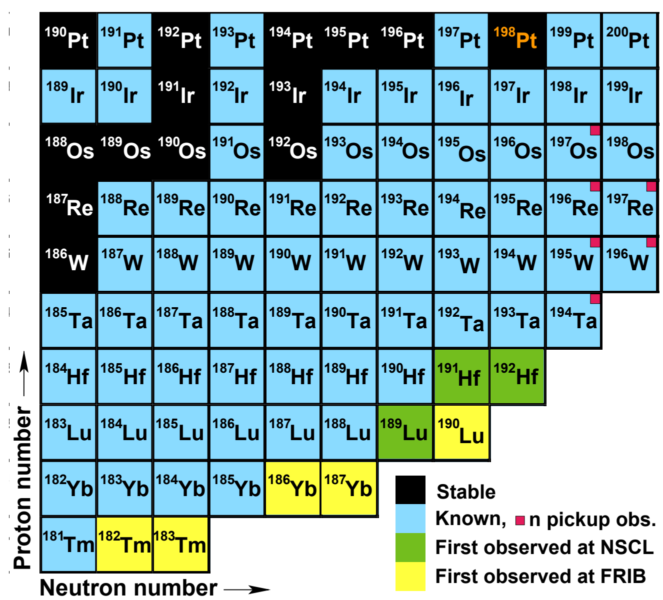

FIG. 1: Region of the nuclear chart, $69 \leq Z \leq 78$ and $112 \leq N \leq 122$, showing the known nuclei and the eight nuclides that were recently discovered at NSCL [11] and FRIB (present work) by the fragmentation of ^{198}Pt beams. Previously known isotopes observed in the present work whose formation involved one- and two-neutron pickup relative to the projectile are marked.

The Facility for Rare Isotope Beams (FRIB) [12, 13] that presently provides beam energies of approximately 200 MeV/u is poised to offer access to the most neutron-rich unexplored nuclei on the nuclear chart once the design primary-beam power of 400 kW is reached. A key question for the ability to delineate the details of the r-process is how far from the known isotopes will FRIB provide nuclei for study in the $N = 126$ region. The challenge is that, at beam energies significantly below 1 GeV/u, the separation and identification of fragments with high atomic numbers become increasingly difficult. This is due to the fact that the fragments emerge from the production target with several atomic charge states. This necessitates the determination of each fragment's charge state, q, in addition to its mass number, A, and proton number, Z, on an event-by-event basis with sufficient resolution in all quantities. In the present work, we report the first observation of the previously unknown isotopes ^{182,183}Tm, ^{186,187}Yb, and ^{190}Lu produced in the

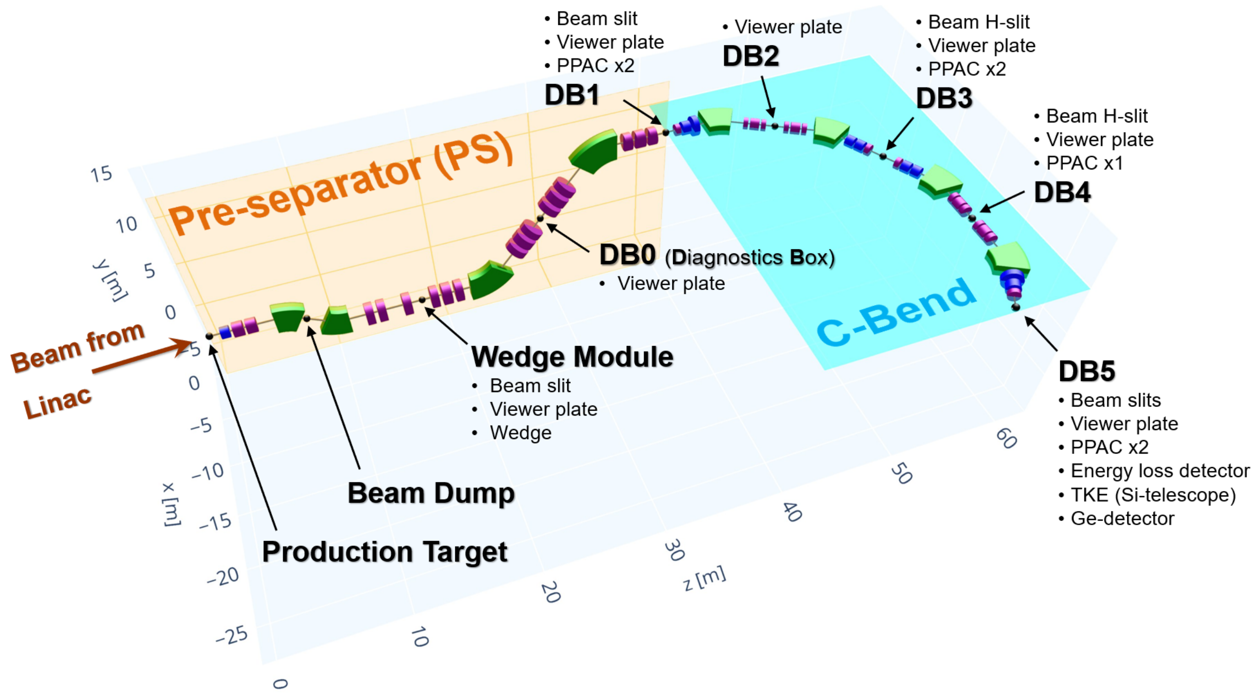

FIG. 2: Schematic view of the experimental setup used in the current work. A ^{198}Pt beam was accelerated by the FRIB linear accelerator and fragmented in a carbon target at the start of the ARIS fragment separator. Fragments were transported to the last diagnostic block (DB5) of the separator and stopped in a silicon detector telescope. The positions of various diagnostic devices are shown.

fragmentation of a 186-MeV/u ^{198}Pt$_{120}$ beam with an intensity of 2.5×10^{11} pps on a carbon target in the Advanced Rare Isotope Separator (ARIS) [14, 15] at FRIB. This intensity corresponds to only 1/270 of FRIB's ultimate primary-beam power.

The region of the chart of nuclides investigated in the present work is shown in Fig. 1. It should be noted that six previously known nuclides produced in this measurement involved the pickup of one or two neutrons relative to the neutron number $N = 120$ of ^{198}Pt. Also, in our previous study [11], three neutron pickup examples were found to have production cross sections more than those expected from the latest empirical parameterizations based on high-energy data, implemented in the $\texttt{LISE}^{++}_{cute}$ code [16, 17]. This underscores the potential to produce nuclei with more neutrons than the projectile at high beam energies in quantities useful for experiments. One may speculate that the availability of high-ℓ neutron orbitals in heavy nuclei beyond $N = 120$ lessens the negative effect of the orbital angular momentum mismatch for pickup reactions at these high beam energies (see Fig. 2 of Ref. [18]). These results provide an important demonstration that FRIB will enable discovery and study of important nuclides near $N = 126$.

Experiment.— A primary beam of ^{198}Pt nuclei was accelerated through the three segments of the FRIB linear accelerator to a final energy of 186 MeV/u and impinged on a rotating 3.54 mm thick carbon target wheel (ρ = 1.89 g/cm^3). Three Pt charge states, 66$^+$, 67$^+$, 68$^+$, were simultaneously delivered by the accelerator, which increased the beam intensity by more than a factor of two as compared to a single-charge-state primary beam [19]. The presence of multiple charge states of the beam and reaction products exiting the production target is a major concern for experiments conducted at intermediate or low beam energies and various methods have been employed to prevent the primary-beam in various charge states from reaching the detectors in these inverse kinematics experiments, e.g., [11]. In a recent measurement at NSCL using ^{198}Pt (at 85 MeV/u), the separator used a limited momentum acceptance and thin targets to observe fragmentation products between a series of primary-beam charge states. In the present work, however, a relatively thick target (comprising approximately 70% of the range of the primary beam) was employed to enhance the yields of neutron-rich isotopes and to shift the momenta of the unreacted primary-beam ions to a lower-$B\rho$ region compared to the ions of interest by the differential energy loss between those fragments and the primary-beam nuclei.

The versatile ion optics of ARIS was used to separate and identify the rare isotopes resulting from the fragmentation of the ^{198}Pt beam. ARIS was primarily designed to operate in momentum-compression mode [14]. Here, to accommodate the important requirement to produce a broad spectrum of neutron-rich isotopes, the ARIS ion optics were configured in a new "non-compression" dispersive mode. Additionally, a thin homogeneous 50 μm

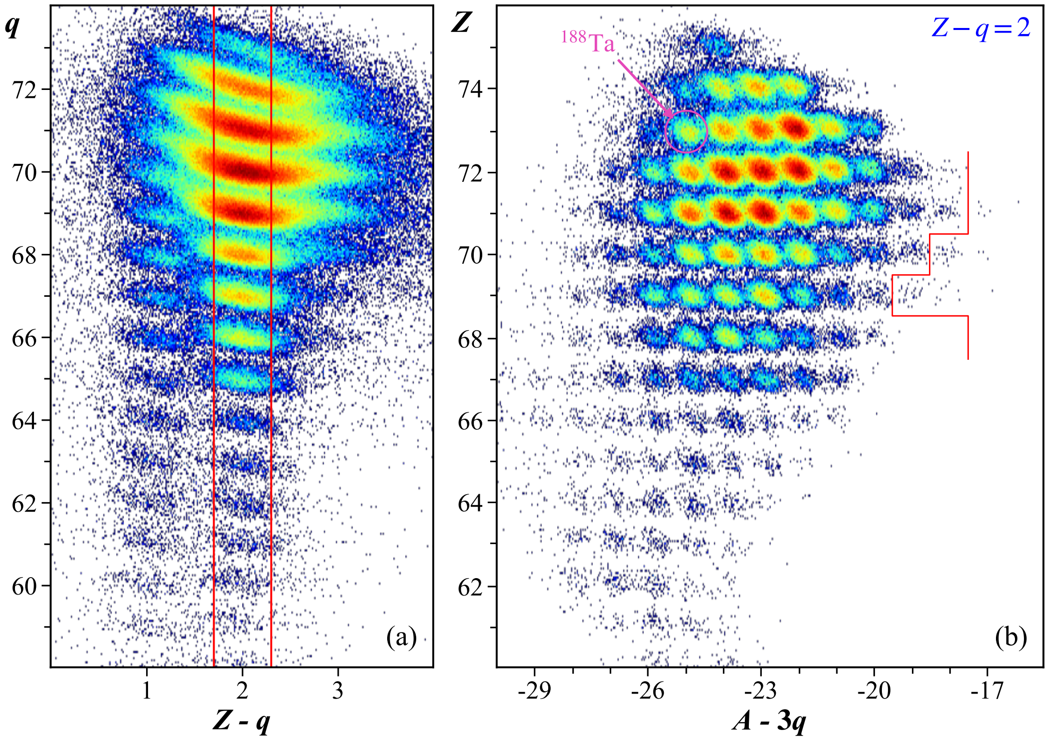

FIG. 3: (a) The separation of charge states is demonstrated in the q vs. $Z-q$ spectrum of a setting optimized to observe $^{186}_{70}Yb^{68+}$ ions, in which the helium-like charge states were most prominent. A charge-state selection gate [1.7 to 2.3] on the helium-like ions was applied to obtain the spectrum in (b), with the Z distribution of the helium-like ions as a function of $(A/q-3)\times q$, where the mass-to-charge ratio, A/q, was constructed from ToF and $B\rho$ measurements. This PID plot, labeled as Z vs. $A-3q$, demonstrates the quality of the mass, charge, and elemental separation. The limit of previously observed nuclei is indicated by the solid red line. A γ-ray spectrum observed in coincidence with the labeled $^{188}Ta^{71+}$ ions was used to confirm its identification (see text).

Al-degrader was positioned at the dispersive plane of the preseparator to suppress light particles using acceptance slits at the DB1 position. The experimental setup is sketched in Fig. 2. The C-Bend section of ARIS (DB1-DB5) served as a single, high-resolution analysis stage, enabling effective particle separation in the high-Z region. This section was operated with a horizontal dispersion of 67.4 mm/% at the midpoint of the C-Bend (DB3).

The particles of interest were stopped at the DB5 location shown in Fig. 2 in a silicon PIN diode telescope consisting of six silicon detectors (each 50×50 mm^2) with thicknesses of 505, 307, 496, and three detectors of 998 μm, in that sequence. The Si detector thicknesses were chosen to stop the fragments of interest in the middle of the 4^{th} detector, while the subsequent detectors served to veto reactions occurring in the preceding detectors, they enabled the identification of intermediate-mass fragments. The event-by-event identification of each heavy ion in this study involved the combined measurement of the magnetic-rigidity ($B\rho$), time of flight (ToF), energy losses (ΔE_i), and total kinetic energy (TKE). The method for heavy-ion identification using this approach has been thoroughly described in the appendix of Ref. [20] and more recently in [11].

The magnetic rigidity and length of the fragment's trajectory were reconstructed from the position and angle measurements at the DB1, DB3, and DB5 focal points using pairs of delay-line position-sensitive parallel plate avalanche counters (PPACs) at these locations. The velocity resolution was enhanced by averaging the results from three different combinations of timing signals from the DB3 PPACs and the DB5 detectors (PPACs and PIN1). The positions of all of these devices are shown schematically along the beam path in Fig. 2.

The energy signals from the Si telescope detectors were used for the energy-loss and total-kinetic-energy measurements. The particle identification (PID) procedure was calibrated by passing a low-intensity charge state

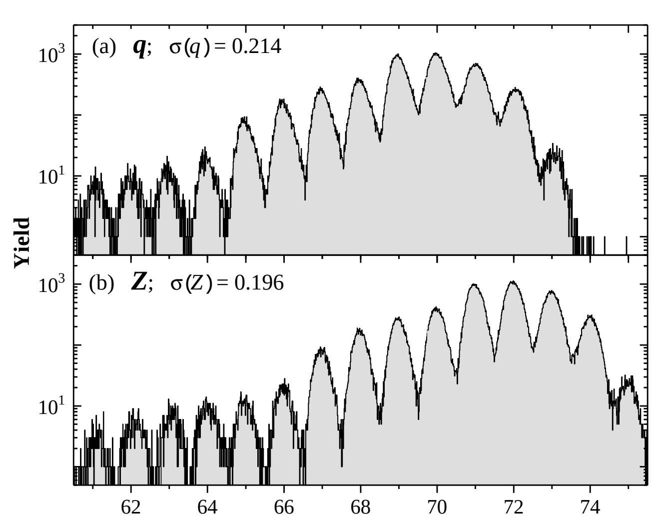

FIG. 4: The ionic, q (a), and elemental, Z (b), spectra obtained for fragments that stopped in the fourth detector of the Si telescope during the data taking for the new-isotope search. The spectra were gated to select the helium-like ions as described in the caption of Fig. 3.

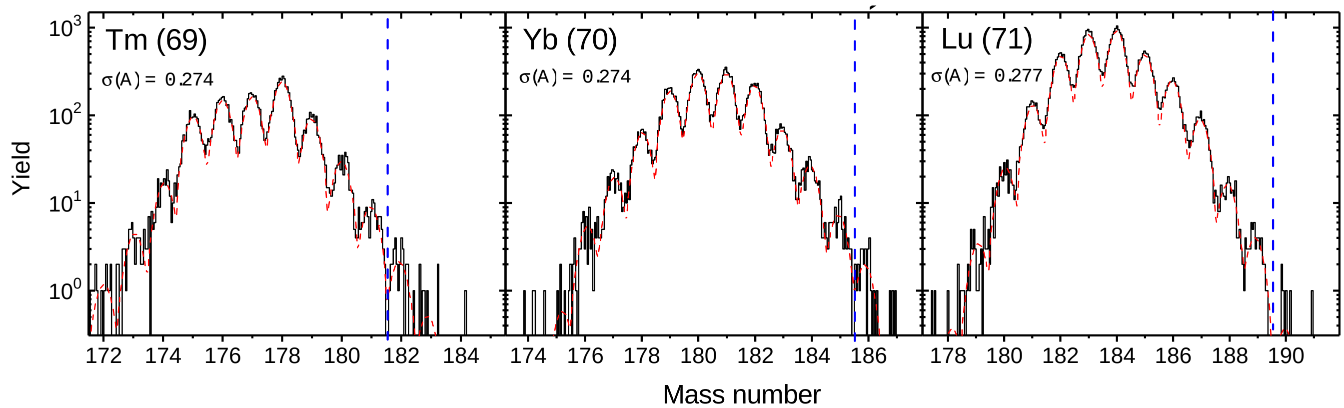

FIG. 5: Mass spectra of elements with atomic numbers ranging from 69 to 71 obtained with the new-isotope-search settings of the separator. A gate condition on Z with a width [Z-0.3, Z+0.3] was applied to generate these spectra in addition to the selection of the helium-like charge state (see Fig. 3). The standard deviation obtained for Gaussian functions having a constant width (dashed red lines) are indicated for each element. The dashed blue line marks the limit of known isotopes for each element.

of the primary beam through the system. Additionally, a germanium γ-ray detector was placed in close proximity to the Si telescope to provide an independent verification of the isotope identification by observing the known, short-lived decay of ^{188}Ta ($T_{1/2} = 3.7$ μs, $E_\gamma = 292.4$ keV) reaction products in the so-called microsecond isomer-tagging technique.

During the isomer-tagging measurements, the separator was tuned to optimize production of the $^{190}_{72}\mathrm{Hf}^{70+}$ ion based on calculations with the $\mathtt{LISE}^{++}_{cute}$ code [16, 17]. Four isotopes with more neutrons than the primary beam, including $^{197}\mathrm{Re}_{122}$, were observed in this short run. During the production of the new, more exotic fragments, different tunes were employed to specifically optimize observation of the $^{186}_{70}\mathrm{Yb}^{68+}$ and $^{180}_{67}\mathrm{Ho}^{65+}$ ions.

Results.— A resolution of the mass-to-charge ratio, $\sigma(A/q)$, of 0.001 was achieved during the initial calibration stage of the experiment by employing a low primary-beam current and utilizing timing signals from both DB1 and DB5 PPACs, mentioned above. However, as the primary beam current was increased to the highest level for the production and separation of new isotopes, the use of the DB1 PPACs became impractical due to high background rates. This situation is similar to that encountered in the recent new-isotope searches at RIKEN [21, 22], which were successfully carried out by introducing a 450-mm-thick iron collimator at the exit of the first stage of the BigRIPS separator. Installation of such a device was not feasible for this measurement. Nonetheless, the present data analysis was able to effectively distinguish the fragments of interest from the background. The standard deviations of the other PID parameters during the production runs were $\sigma(q) = 0.214$ for the ionic charge, $\sigma(Z) = 0.196$ for the element number, $\sigma(A/q) = 0.0024$, for the mass-to-charge ratio, and $\sigma(A-3q) = 0.27$ for the deduced mass number from A/q and q values, respectively, using the detectors located at DB3 and DB5.

The effectiveness of the TKE measurement to separate charge states is shown in Fig. 3(a), which contains the total distribution of charge states observed in the setting for the new-isotope search. The range of helium-like fragments is displayed as PID Z vs. $A-3q$ spectrum in Fig. 3(b). The atomic number is denoted by Z, q is the ionic charge, and $A-3q$ is a calculated quantity proportional to the ion's mass. The elemental (Z) and ionic (q) spectra obtained for helium-like ions that stopped in the fourth Si telescope are displayed in Fig. 4.

Over the course of the experiment, five new isotopes, namely ^{182}Tm (29 events), ^{183}Tm (7), ^{186}Yb (27), ^{187}Yb (3), ^{190}Lu (5), were observed for the first time. One event was found to be consistent with ^{184}Tm, and another one was found to be consistent with ^{191}Lu. The evidence for these new isotopes is shown in Fig. 5. The peaks were fitted with Gaussian distributions of constant width for each isotope and constant spacing between them. Counts to the right of the blue dashed line indicate nuclides discovered in the experiment. For comparison, ^{189}Lu was observed at a rate of 1.3 10^{-3} pps in the present study vs. 3.7 10^{-5} pps in the measurement at NSCL [11] where the first observation of this isotope from ^{198}Pt fragmentation was reported.

This work illustrates the possibility to pursue further study of nuclides in this relatively unexplored region. Future opportunities include measurement of half-lives, masses and decay modes. Exploring pickup cross sections could open the pathway to discovering even more neutron-rich isotopes. The ability to tag individual nuclides, coupled with the expected power increases at FRIB, distinctly demonstrates significant future potential.

Summary.— The present study of the fragmentation of a ^{198}Pt beam at 186 MeV/u has led to the discovery of five previously unobserved neutron-rich nuclides in a region that approaches the r-process path. The experiment was the first new-isotope search carried out at the recently completed Facility for Rare Isotope Beams and already demonstrates the impressive capabilities and new science opportunities that are and will become available as the facility evolves toward its full beam intensity of 400 kW. It also indicates that neutron pickup reactions, leading to fragments with more neutrons than the primary beam, occur in the intermediate energy regime and have the prospect to reach further into the unknown.

The unique capabilities of FRIB, including very intense primary beams at energies exceeding those that were available at NSCL, make it an ideal facility for exploring the region around neutron number $N = 126$ and beyond. Researchers at FRIB can utilize these reactions to produce, identify, and study the properties of new isotopes, contributing to advancements in nuclear physics, astrophysics, and our understanding of the fundamental properties of matter.

We would like to thank the entire operations team at FRIB for their amazing work in the beam delivery for the experiment and for all of the developments that made this measurement possible. The authors acknowledge fruitful discussions with Professors M. Thoennessen and A. V. Karpov.

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* tarasov@frib.msu.edu

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