RI BEAM FACTORY PROJECT AT RIKEN

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Abstract

The world-top-class radioactive-isotope-beam (RIB) facility, which is called “RI beam factory (RIBF)”, is under construction at RIKEN. This facility is based on the so-called “in-flight RI beam separation” scheme. Commissioning of a new high-power heavy-ion booster system consisting of a cascade of three ring cyclotrons with K=570 MeV (fixed frequency, fRC), 980 MeV (Intermediate stage, IRC) and 2500 MeV (superconducting, SRC), respectively, is scheduled for late in 2006. This new ring-cyclotron cascade system boosts energies of the output beams from the existing K540-MeV ring cyclotron up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions. These energetic heavy-ion beams are converted into intense RI beams via the projectile fragmentation of stable ions or in-flight fission of uranium ions by a superconducting isotope separator, BigRIPS. The combination of the SRC and the BigRIPS will expand our nuclear world into presently unreachable region. Major experimental installations are under priority discussion as the second-phase program of the RIBF project. Construction of the second phase is expected to start in 2006.

OVERVIEW

The advent of a radioactive isotope (RI) beam in the last half of 1980’s has opened up a new fascinating discipline in the nuclear science and technology. To further develop this new promising field, the RIKEN Accelerator Research Facility (RARF) has undertaken construction of an "RI Beam Factory,” or simply “RIBF” since April 1997 aiming to realize a next generation facility that is capable of providing the world’s most intense RI beams at energies of several hundreds MeV/nucleon over the whole range of atomic masses.

Figure 1 shows a schematic layout of the existing facility and the RIBF under construction. At present, the RARF has the world-class heavy-ion accelerator complex consisting of a K540-MeV ring cyclotron (RRC) [1] and a couple of different types of the injectors: a variable-frequency heavy-ion linac (RILAC) [2] and a K70-MeV AVF cyclotron (AVF) [3]. Moreover, its projectile-fragment separator (RIPS) [4] provides the world’s most intense light-atomic-mass (less than nearly 60) RI beams.

The RIBF will add new dimensions to the RARF’s present capabilities: a new high-power heavy-ion booster system consisting of three ring cyclotrons with K=570 MeV (fixed frequency, fRC [5]), 980 MeV (Intermediate stage, IRC[6]) and 2500 MeV (superconducting, SRC [7]), respectively, will boost energies of the output beams from the RRC up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions. An 880 MeV polarized deuteron beam will also be available. The goal of the available intensity is set to be 1 pμA, which is limited due to presently planned radiation shielding power around a primary-beam dump. These energetic heavy-ion beams will be converted into intense RI beams via the projectile

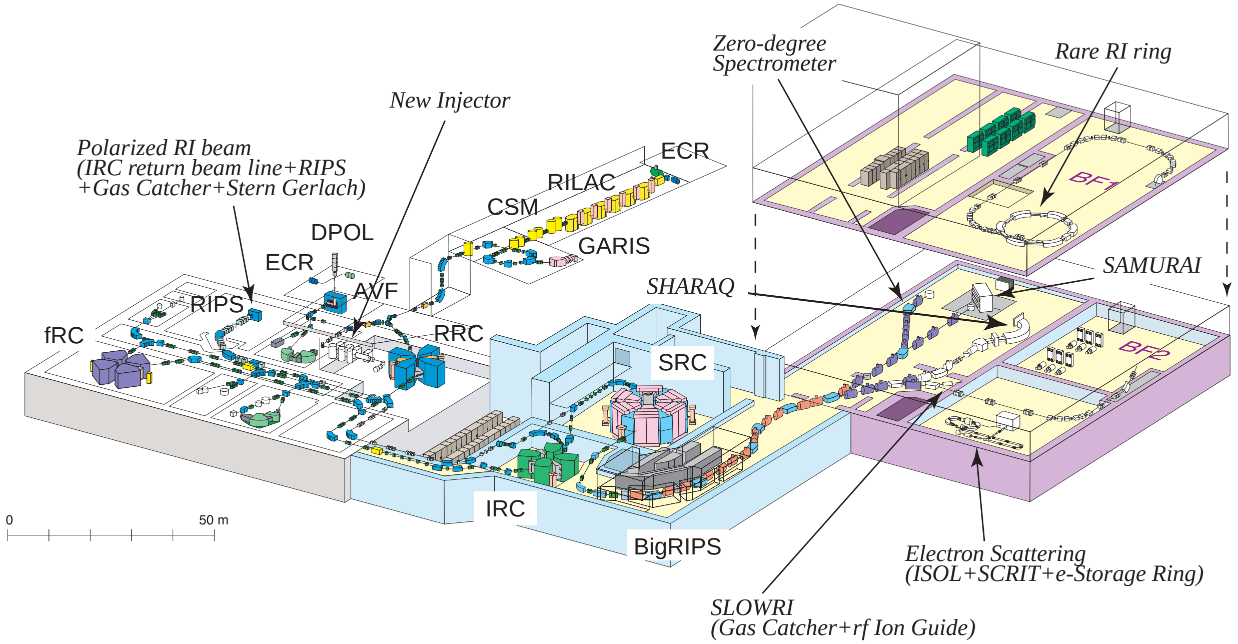

Figure 1: A schematic bird’s-eye view of the existing facility (left-hand side) and the RIBF under construction (right-hand side). The arrows indicate major experimental installations planned in the second-phase program of the RIBF project. The experimental installations other than the zero-degree spectrometer have not been approved yet.

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fragmentation of stable ions or the in-flight fission of uranium ions by the superconducting isotope separator, BigRIPS [8]. The combination of the SRC and the BigRIPS will expand our nuclear world on the nuclear chart into presently unreachable region.

Now (as of October 1 2004) the assembling of the SRC, the IRC and the BigRIPS is under way at their respective sites in the RIBF accelerator building completed in April 2003. The fRC is being fabricated in the factory. The construction of the RIBF experimental building will be finished in May 2005. The first beam (a 350 MeV/nucleon uranium beam with nearly ten pnA) is scheduled for late 2006. The routine operation for the users will begin in April 2007.

The details of each machine are described in the respective references.

The RIBF project is divided into the phase I already approved and the phase II not yet approved. In the phase I, the booster ring cyclotrons, the BigRIPS and, in addition, a zero-degree forward spectrometer will be completed. Major experimental installations planned to be constructed in the phase II are under priority discussion. They are: a large acceptance superconducting spectrometer (SAMURAI), a gamma-ray detector array, a facility utilizing very slow RIBs provided via a gas-catcher and rf ion guide system (SLOWRI), a low-to-medium energy polarized RIB facility consisting of a gas catcher and a Stern-Gerlach separator at the RIPS (Polarized RI beams), an high-resolution RI-beam spectrometer (SHARAQ), a rare RI precision mass measurement apparatus consisting an isochronous storage ring and an individual injection system (Rare RI ring), and an electron-scattering experimental apparatus consisting of a self-confining RI-ion target (SCRIT) in an electron storage ring and a uranium-photo-fission ISOL system. A new additional injector linac to the RRC to make it possible to concurrently conduct RIBF experiments and super-heavy-element experiments is also planned. It is our hope that the phase II will be approved and the construction will be undertaken in 2006.

The details of each planned experimental installation are described in Ref. [9].

ACCELERATION MODES AND PERFORMANCE

Figure 2 shows a schematic diagram of the RIBF heavy-ion accelerator system. In this diagram, a K-value and a velocity gain factor of each cyclotron are shown. The RILAC has an injector of a variable-frequency RFQ linac (FCRFQ) equipped with an 18 GHz ECRIS and an 18 GHz superconducting ECRIS and a booster linac (CSM). The AVF has a 14.5 GHz ECRIS, a 10 GHz ECRIS and a polarized deuteron source. Several acceleration modes will be available. Mode (1): RILAC+ RRC+ (stripper2) [10]+ fRC+ (stripper3)+ IRC+ SRC is used for the RI-beam generation at 350 MeV/nucleon (fixed energy). 115 MeV/nucleon output beams from the IRC can be transferred to the existing RIPS in the phase II. Mode (2): RILAC+ (stripper1) [11] + RRC+ (stripper3)+ IRC+ SRC is used for variable energy experiments. Mode (3): AVF+ RRC+ SRC is used for polarized deuteron beam generation at 880 MeV in the phase II. The harmonic numbers for respective operation modes are also shown. Figure 3 summarizes the acceleration performance of the RIBF.

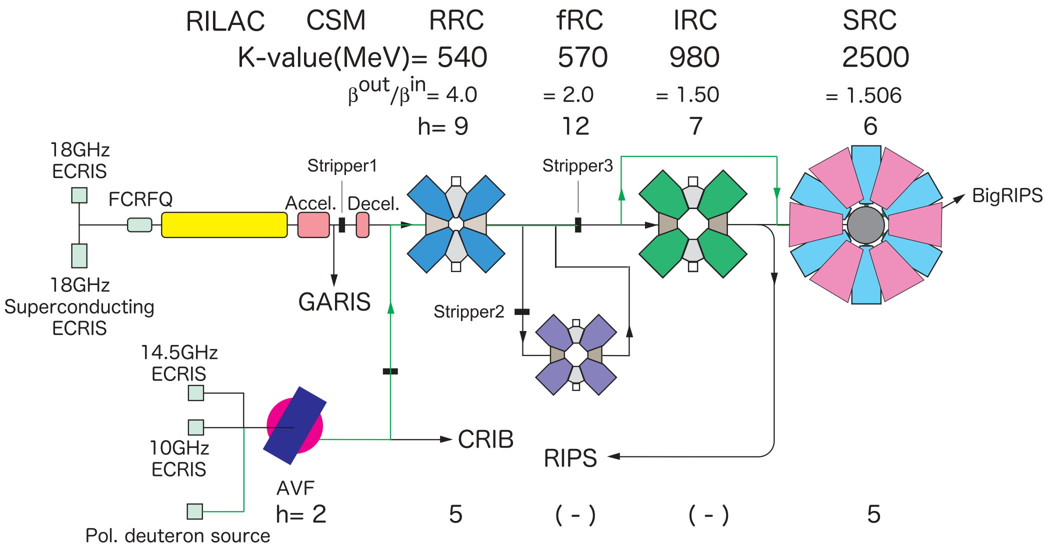

Figure 2: A schematic diagram of the RIBF heavy-ion accelerator system.

EXPECTED PRIMARY BEAM INTENSITIES: ESTIMATION

At present, the beam transmission efficiency through the RILAC (between the exit of the mass-to-charge analyzing slit for the beam extracted from the 18GHz ECRIS and the injection point to the RRC) and that through the RRC (between the injection point to the RRC and the extraction point from the RRC) are nearly 70% and also nearly 70%, respectively.

We conjecture that the former unsatisfactory efficiency is attributed mainly to: (1) the emittance broadening of the ECRIS beams caused by the strong space-charge effect and (2) the optical astigmatism due to the nonlinear aberration in the analyzer magnet section, and that the latter one is attributed mainly to: (3) the insufficient longitudinal focusing power of the present rebuncher system between the RILAC and the RRC.

Nevertheless, assuming that the 100% transmission efficiency can be realized for all of the fRC, the IRC and the SRC, 1 pμA beam will be achieved, for example, for ^{48}Ca, ^{86}Kr, ^{136}Xe beams at 350 MeV/nucleon as shown in Table 1. And also nearly 10pnA is expected for ^{238}U beam at 350 MeV/nucleon without use of the 1st charge stripper (between the RILAC and the RRC) when 8eμA of U^{35+} beam estimated may be obtained from the present 18GHz ECRIS [12].

In the near future, we plan to remedy the respective problems (1)-(3) listed above to improve the present unsatisfactory transmission efficiencies by taking the following measures: (1) We will raise the extraction voltage a few times higher to reduce the emittance growth and implement the neutralizing solenoid just after the exit of the ECRIS to reduce the space charge force; (2) We will modify the analyzing dipole magnet to have an appropriate sextupole field to compensate the non-linear optics; and (3) We will install a new double-rebuncher system between the RILAC and the RRC to produce an enough focusing power in the longitudinal direction and will modify the present sinusoidal rf system of the RRC into a flat-top acceleration system.

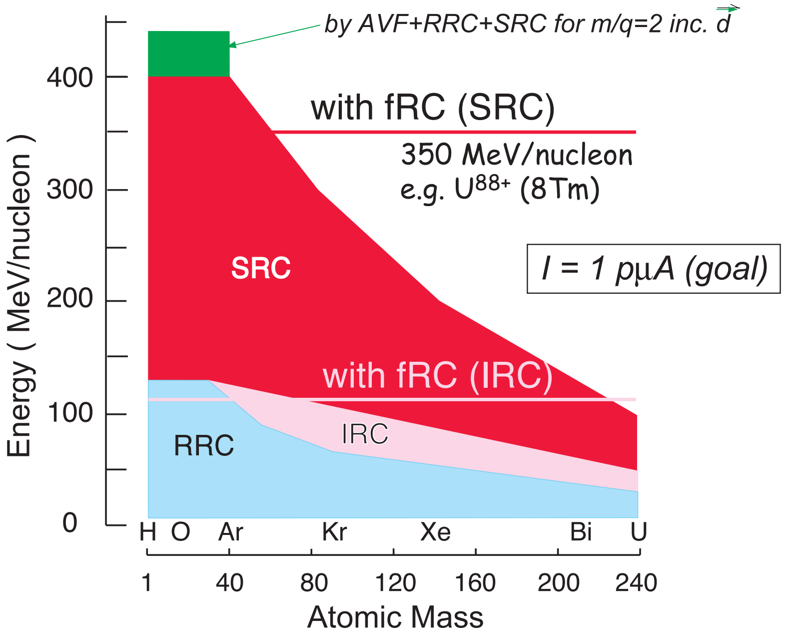

Figure 3: A diagram of the RIBF acceleration performance (MeV/nucleon) for each atomic mass.

Table 1. Expected intensities (pμA) of primary beams ^{48}Ca, ^{86}Kr, ^{136}Xe and ^{238}U at the exits of the 18 GHz ECRIS, the RILAC, the RRC, the fRC, the IRC, the SRC when these beams are finally accelerated by the SRC to 350 MeV/nucleon. Both of the transmission efficiencies through the RILAC and through the RRC are assumed to be 70%. As for the fractions of the charge state after the charge strippers, see Ref. 13. The expected intensity of ^{238}U beam from the 28 GHz ECRIS under the conceptual design is given in Ref. 12.

	18GHz ECRIS	RILAC	RRC	Charge Stripper2	fRC	Charge Stripper3	IRC	SRC
^{48}Ca (pμA)	8+ 10	8+ 7.0	8+ 4.9	19+ 2.0	19+ 2.0		19+ 2.0	19+ 2.0
^{86}Kr	14+ 10	14+ 7.0	14+ 4.9	33+ 2.0	33+ 2.0		33+ 2.0	33+ 2.0
^{136}Xe	20+ 15	20+ 10.5	20+ 7.3	44+ 2.2	44+ 2.2	52+ 0.97	52+ 0.97	52+ 0.97
^{238}U 18GHz> Super >	35+ 0.23 16	35+ 0.16 11.2	35+ 0.11 7.8	72+ 0.021 1.5	72+ 0.021 1.5	88+ 0.007 0.51	88+ 0.007 0.51	88+ 0.007 0.51

In order to realize the 1 pμA uranium beam at 350 MeV/nucleon, in addition to these remedies, we will have to develop the new 28 GHz superconducting ECRIS [12].

Expected intensities of ^{48}Ca, ^{86}Kr, ^{136}Xe and ^{238}U beams at 350 MeV/nucleon for production of intense RI beams are listed in Table 1.

BIGRIPS

The BigRIPS is designed to be of a two-stage RI beam separation scheme as shown in Fig. 4. The first stage from the production target to the F2 focus comprises a two-bend achromatic spectrometer, consisting of four superconducting quadrupole triplets (STQs) and two room-temperature dipoles (RTDs). This first stage serves to produce and separate RI beams. The in-flight fission of a uranium beam as well as the projectile fragmentation of various heavy ion beams are used to produce RI beams. A wedge-shaped degrader is inserted at the momentum-dispersive focus F1 to make achromatic isotopic separation based on the so-called dispersion matching technique. A high-power beam dump is placed inside of the gap of the first dipole to stop 100 kW primary beams. Thick concrete blocks of about 9,000 tons surround the first stage to shield neutron radiation from the target and beam dump. The second stage from the F3 focus to the F7 focus consists of eight STQs and four RTDs, comprising a four-bend achromatic spectrometer. Since our energy domain is not so high, the purity of RI beams is expected to be poor due to the nature of energy loss as well as the mixture of charge state. Several isotopes are mixed in an RI beam. To overcome this difficulty, the second stage is employed to identify RI-beam species (the atomic number, the mass-to-charge ratio and the momentum) in an event-by-event mode, making it possible to deliver tagged RI beams to experimental setups placed downstream of the BigRIPS.

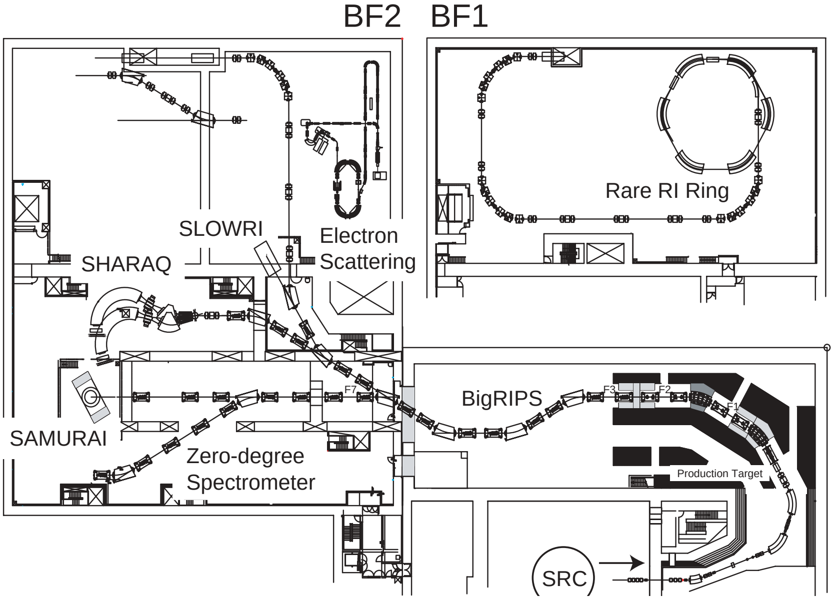

Figure 4: Layout of the BigRIPS and the major experimental installations planned in the second phase.

The angular acceptances of the BigRIPS are designed to be 80 mrad horizontally and 100 mrad vertically, while the momentum acceptance to be 6 %. The maximum bending power is 9 Tm. The total length is 77 m. The angular and momentum spreads of fission fragments at 350 MeV/nucleon uranium ions are estimated to be about 100 mrad and 10 %, respectively. The acceptances of BigRIPS are comparable to those values, allowing one to achieve high collection efficiency for the in-flight fission fragments: almost half of the produced fission fragments may be accepted. These high acceptances are made possible by the use of superconducting quadrupoles with large apertures and room-temperature dipoles with large gaps.

The beam-line spectrometer called the zero-degree spectrometer will be constructed. This spectrometer is specified for inclusive and semi-exclusive measurements equipped with gamma detectors around secondary targets.

EXPANSION OF THE NUCLEAR WORLD IN THE RIBF: ESTIMATION

The expected yields of RI beam have been estimated assuming the primary beam current and energy of 1pμA and 350 MeV/nucleon, respectively. The EPAX2 has been employed to obtain the production yields of unstable nuclei of interest, taking into account the BigRIPS angular- and momentum- acceptances.

The region on the nuclear chart where the production rate exceeding 1 particle/day, which will be enough to confirm the existence, can be obtained is indicated in Fig. 5 for the projectile fragmentation of appropriate stable nuclei and the in-flight fission of a uranium beam.

The expected intensity of doubly magic nuclei ^{78}Ni is found to be 10 particles/sec, which enables the detailed internal structure studies of this intriguing nucleus.

EXPERIMENTAL INSTALLATIONS IN THE PHASE II

The large-acceptance multi particle spectrometer (SAMURAI) is proposed. The main part of the spectrometer system is a large-gap superconducting magnet with 7 Tm of bending power for momentum analysis of heavy projectile fragments and projectile-rapidity protons with large angular and momentum acceptance. The large gap also enables measurements of projectile-rapidity neutrons with large angular acceptance in coincidence

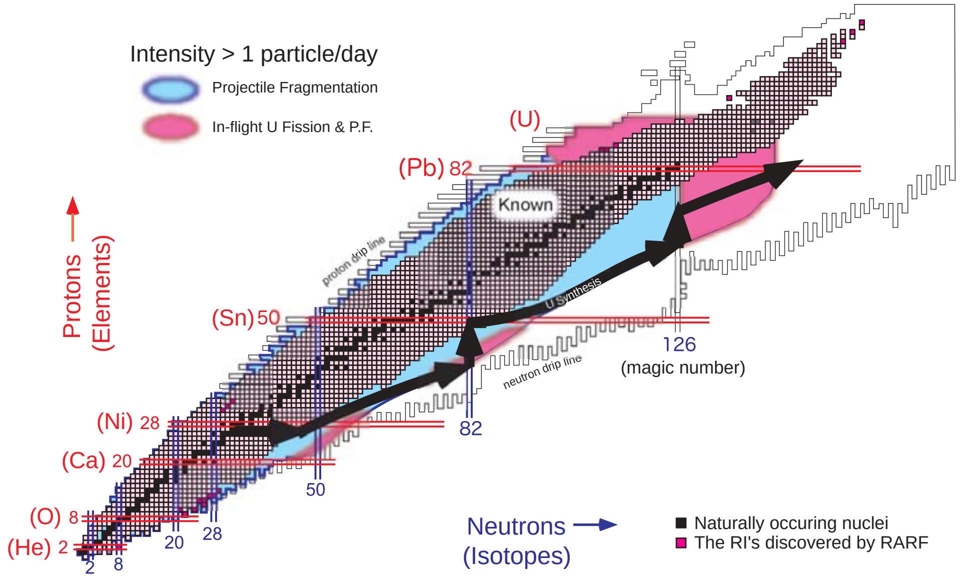

Figure 5: Great expansion of the nuclear world on the nuclear chart by the RIBF. The new region to be expanded will cover the hypothetical pathway to uranium synthesis in the supernova explosion.

with heavy projectile fragments.

The high-resolution RI-beam spectrometer (SHARAQ) with momentum resolution of 15000 is proposed.

The slow RI-beam facility (SLOWRI) is proposed aiming to provide universal slow or trapped RI of high purity by combining the BigRIPS and a gas-catcher system utilizing the so-called the RF ion-guide technique. This will allow a unique opportunity to perform precision atomic spectroscopy for a wide variety of RI, not available in so far existing facilities worldwide.

The new system of electron scattering experiment for unstable nuclei using the SCRTI is proposed. The SCRIT (Self-Confining Radioactive Ion Target) is the trapped-ion cloud formed at local position in an electron storage ring. Ions are three-dimensionally confined in the transverse potential well produced by the projectile electron beam itself and additionally applied longitudinal mirror potential. RI ions are injected into the potential well from outside. Therefore we need slow RI ion source like an ISOL. In our numerical calculation, the luminosity of e-RI collision is achievable to be more than 10^{28} $s^{-1}cm^{-2}$, which is enough to determine the charge distribution of unstable nuclei.

The new precision mass measurement system (Rare RI ring) consisting of individual injection and a precisely tuned isochronous ring is proposed for energetic rare RI beams. In the scheme, we measure a time-of-flight of a particle in the ring and its velocity before injected into the ring (on the long transport line) by combining individual injection. The accuracy of the mass measurement can be achieved at the order of 10^{-6} for the momentum acceptance of the order of 10^{-2}. Individual injection also allows us to identify the mass-measured RI particles event-by-event.

The recent great success of the discovery of the new super heavy element (SHE), ^{278}113 [14] using the RILAC, the CSM and the GARIS strongly encourages us to further pursue the heavier SHE search and to more extensively study nuclear physical and chemical properties of the SHEs. This compels us to provide a longer machine time for these experiments. However, this SHE research and the RIBF research are incompatible with each other, because both of these two researches use the RILAC. Thus, we propose to construct a new additional injector linac to the RRC which is planned to place in the RRC vault. The new injector will be used exclusively to produce the 350 MeV/nucleon primary beams (It is operated at the fixed frequency like the fRC.) This linac will make it possible to concurrently conduct the SHE and the RIBF researches.

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