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Overview of the ISOL Facility for the RISP

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The key feature of the Isotope Separation On-Line (ISOL) facility is its ability to provide high-intensity and high-quality beams of neutron-rich isotopes with masses in the range of 80 − 160 by means of a 70-MeV proton beam directly impinging on uranium-carbide thin-disc targets to perform forefront research in nuclear structure, nuclear astrophysics, reaction dynamics and interdisciplinary fields like medical, biological and material sciences. The technical design of the 10-kW and the 35-kW direct fission targets with in-target fission rates of up to 10^{14} fissions/s has been finished, and for the development of the ISOL fission-target chemistry an initial effort has been made to produce porous lanthanum-carbide (LaCx) discs as a benchmark for the final production of porous UCx discs. For the production of various beams, three classes of ion sources are under development at RISP (Rare Isotope Science Project), the surface ion source, the plasma ion source (FEBIAD), the laser ion source, and the engineering design of the FEBIAD is in progress for prototype fabrication. The engineering design of the ISOL target/ion source front-end system is also in progress, and a prototype will be used for an off-line test facility in front of the pre-separator. The technical designs of other basic elements at the ISOL facility, such as the RF-cooler, the high-resolution mass separator, and the A/q separator, have been finished, and the results, along with the future plans, are introduced.

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I. INTRODUCTION

In the past few years, production and delivery of a high-purity intense of rare isotope beam (RIB) have been major concern, as a novel research tool for various fields, including fundamental research fields such as astrophysics and nuclear physics and applied research fields such as material and bio-medical science. The development of a RIB production facility has just passed its primary stage, so immediate establishment of this facility is expected to lead us to a pioneering position in research fields using rare nuclides. Moving away from the valley of stability, the production of exotic nuclei, however, is usually confronted with the difficulties that stem from the

- very low production cross sections,
- very intense production of unwanted species in the same target,
- very short half-lives of the nuclei of interest.

In general, two complementary ways are available for producing good-quality beams of exotic nuclei: the in-flight fragmentation (IF) separation technique and the ISOL technique [1–3]. The technology to produce & separate rare isotopes by using the ISOL method has been consistently developed over the past 50 years. The ultimate aim of ISOL systems is the production of exotic nuclei that are abundant, pure, of good ion-optical quality, and variable in energy from low (a few tens of keV/nucleon) to intermediate energies (a few hundreds of MeV/nucleon). This method utilizes reactions between protons, neutrons, gamma-rays or ions bombarding a thick target. Particularly, neutron-rich rare isotopes are produced by nuclear fission reactions of uranium target nuclei by bombarding them with intense ion beams. Rare isotopes are produced by nuclear reactions in the target and are thermalized in a catcher consisting of a solid, liquid or gas material (often the target and the catcher are the same object). These radioactive isotopes are then transported from the target/catcher to the ion source and ionized. The extracted ions are then selected and analyzed using a high-resolution mass separation system, and multiple charge-state ions passing through a charge breeder are subsequently accelerated to the required energy.

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Table 1. Characteristics of the main ISOL facilities [4].

Facility		Driver	Primary beam target	Power on rate (#/s)	Fission @lab. (pps)	^{132}Sn rate 1st RIB	State or
TRIAC, KEK		Tandem	30 MeV, 3 μA	0.09 kW	$\sim 10^{11}$	3×10^5	closed
HRIBF, ORNL		Cyclotron	40 MeV, 10 μA	0.4 kW	4×10^{11}	2×10^5	closed
ISOLDE, CERN	REX	Linac	$1 \sim 1.4$ GeV, 2 μA	2 kW	$\sim 10^{12}$	$\sim 10^7$	upgraded to HIE
	HIE		$1 \sim 1.4$ GeV	10 kW	$\sim 10^{13}$	$\sim 10^8$	2015
ISAC, TRIUMF		Cyclotron	450 MeV, 70 μA	17 kW	5×10^{13}		in operation
SPI4RAL2, GANIL		Linac	40 MeV d, 5 mA (converter)	200 kW	$\sim 10^{14}$	$(0.3 \sim 2) \times 10^9$	2015
SPES, INFN		Cyclotron	40 MeV, 0.2 mA	8 kW	$\sim 10^{13}$	3×10^7	2017
iThemba LABS	phase-1	Cyclotron	70 MeV, 0.115 mA	8 kW	$\sim 10^{13}$	$(0.2 \sim 1) \times 10^8$	2020
	Phase-2		70 MeV, 0.5 mA	35 kW	5×10^{13}	$(0.8 \sim 4) \times 10^8$	
RISP, IBS	RISP	Cyclotron	70 MeV, 0.143 mA	10 kW	1.6×10^{13}	$(2 \sim 4) \times 10^7$	2019
			70 MeV, 0.5 mA	35 kW	7×10^{13}	$(0.5 \sim 1.2) \times 10^8$	> 2020
	Post-RISP	Linac	660 MeV, 0.6 mA	400 kW			

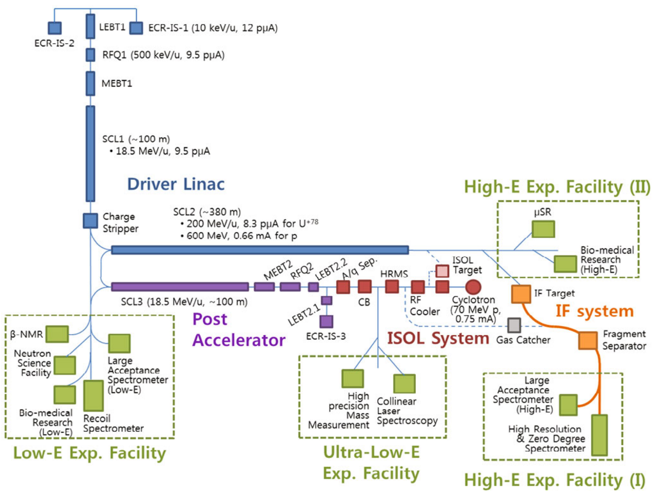

Fig. 1. (Color online) Layout of the RISP accelerator complex, RAON.

Table 1 introduces representative worldwide ISOL facilities, that utilize nuclear fission targets. The ISOL system for RAON is the first RI facility in Korea dedicated to providing intense high-quality neutron-rich rare-isotope beams of medium mass ($A = 80 \sim 160$) to experimental facilities by employing high-power direct-fission targets. Beam intensities of up to 10^8 pps are expected to be available for ^{132}Sn, a doubly magic isotope, with a purity over 90%. One of the most unique and innovative ideas in RAON is a combined scheme of the ISOL and the IF methods, which has the potential to generate more exotic rare isotopes that cannot be reached by using only the ISOL or the IF method. This new production method for a rare-isotope beam is expected to significantly broaden the map of rare isotopes and to open new opportunities for basic sciences. Figure 1 shows the layout of the accelerator complex, RAON.

II. ISOL FOR RISP

Figure 2 shows the preliminary design layout of the ISOL system. A uniform 70-MeV proton beam with a maximum current of 500 μA, which is delivered from a cyclotron driver, will impinge on a uranium-carbide target, and neutron-rich isotopes will be produced as fission fragments at a rate of maximum 7×10^{13} fission/s. Because the technology for a high-power (> 10 kW) direct ISOL target has not yet been well established, the uranium-carbide targets will be developed in stages from a low-power (10 kW) target of a disk-type to the unique concept of a high-power (35 kW) target of a cone type or a combination of multiple targets that can overcome the power limitations of existing targets. The high-power target is expected to represent a technical innovation in terms of its capability to sustain an elevated beam power. The RI beam production & separation system based on ISOL consists of a primary beam driver, a target-ion source (TIS) system, and an isotope separation and charge breeding system, and the different steps involved in the ISOL system include

1) production of radioactive isotopes mainly from UCx targets,

2) ionization and extraction from the target-ion source (TIS) system,

3) RF-cooling and high-resolution mass separation (with a working resolving power of 10,000),

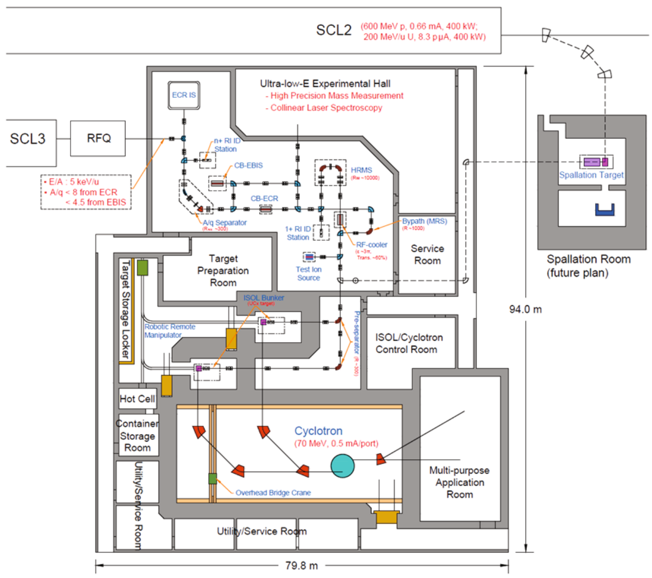

Fig. 2. (Color online) Layout of the ISOL facility.

4) charge-state breeding (EBIS or ECRIS) and A/q separation (with a resolving power of 300), and

5) post-acceleration.

In this process, the physical (*e.g.*, production cross-section, decay half-life, ionization potential, *etc.*) and chemical (*e.g.*, volatility, molecular formation probability, *etc.*) properties of the isotope and the element of interest are essential and are used to tailor the set-up in order to optimize the figures of merit given above [1]. High-energy beams, up to 18.5A MeV (SCL3) at the low-energy experimental room or higher than 200A MeV (SCL3 + SCL2) at the high-energy experimental room, are provided by post-accelerators.

The ISOL/RISP project is in progress for the design (technical & engineering) and development of a domestic ISOL facility, and outside expertise and periodic reviewing of the project seem to be essential for favorable progress on the project. Also, active contacts are underway to establish collaborations for the development of some delicate elements with global pioneering ISOL groups such as ISOLDE (EU), GANIL/LPC CAEN (France), CENBG (France), SPES (Italy), and TRIUMF (Canada). Table 2 shows the development goal of the ISOL facility in this project.

Target/Ion Source (TIS): The TIS system is the heart of an ISOL system and consists of a target (and catcher material), a transfer line and an ion source, and these components have to be carefully designed and optimized in order to obtain the desired high production rate of RIs. As a first step, we are developing a 10-kW ISOL target system, which consists of 1.3-mm-thick uranium-carbide multi-disks and a cylindrical tantalum heater, similar to the ISOL target of SPES [2, 5]. The overall size of the target and the disk spacing were optimized

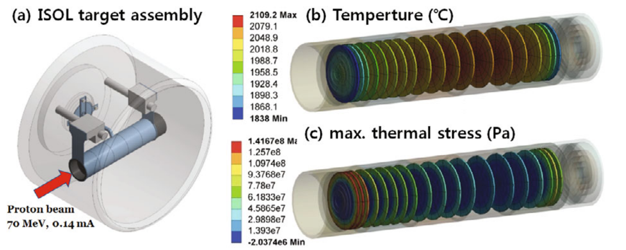

Fig. 3. (Color online) (a) Schematic view of the 10-kW ISOL target design. (b) Temperature and (c) thermal stress are calculated by using the ANSYS code.

to maximize the release rate at a temperature of about 2000 °C without Joule heating. The temperature and the thermal stress of the target were calculated by using the finite-element model code ANSYS (ver.14.5.0) combined with the MCNPX code (ver.2.6.0) [6], as shown in Figs. 3(b) and (c), and the optimized 10-kW target consists of nineteen, 50-mm-diameter, 1.3-mm-thick, coaxial disks appropriately spaced in a graphite tube. In the final thermal analysis, the incident proton beam size was optimized to be 45 mm in diameter in order to ensure that the maximum thermal stress was under the fracture stress of 200 MPa for UCx disks. Figure 3(a) shows the schematic view of 10-kW ISOL target's design. The proton-induced fission rate in the target is estimated to be about 1.6×10^{13}/s by using the Oak Ridge National Laboratory (ORNL) fission model [7] and the MCNPX code for a 10-kW proton beam. The isotope distribution of the fission products is shown in Fig. 4. The ^{132}Sn isotope, being a doubly-magic nucleus, is one of the benchmark isotopes in the ISOL research field, and the in-target production yield of the isotope is estimated to be about 2.2×10^9 s^{-1}.

Three different types of ion sources will be used selectively depending on the elements, as shown in Fig. 4: the surface ionization (SI) type for alkali and alkaline-earth elements, the FEBIAD (forced-electron-beam-induced arc-discharge) plasma type for gaseous and volatile elements, and the resonance-ionization laser-type for post-transition metals [8]. For the ion source's R&D program, an off-line version of the ISOL's front-end is in the engineering-design stage (see Fig. 5) and is expected to be fully operational at the end of 2014. The apparatus designed is an evolution of the Front-end 6 developed at ISOLDE (CERN) [9]. It will permit the production of stable ion beams as well as their transport to the diagnostic instrumentation where the characteristics are measured. A beam profiler is used to detect the beam shape, a Faraday cup is used to measure the beam current, and the ion source emittance is measured using an emittance meter. These instruments will enable us not only to perform ion source efficiency and emittance studies in order to characterize and improve the instruments, but also to characterize the RI beam monitoring devices during the development phase.

Table 2. Development goal of the ISOL facility at RISP.

System	Components	Development goal
Proton driver	Cyclotron	• 70 MeV, 0.5 mA/port
ISOL target	UCx fission target (10 kW / 35 kW)	• Fission rate (#/s): 1.6×10^{13} / 7.3×10^{13} ^{132}Sn production rate (#/s): 2.3×10^{9} / 9.7×10^{9}
Ion sources	RILIS, Cavity SIS, FEBIAD (Plasma) IS	• efficient, selective and reliable ionization of most elements
RFQ cooler	RF quadrupole	• CW & pulsed • Beam current: up to 1 μA • Emittance: $\sim$3 π mm mrad • ΔE/E $< 5 \times 10^{-5}$ • $\varepsilon_{trans.} > 60\%$ (CW)
HRMS	dipole + multipole + dipole	• R_w (working) $\sim$ 10,000 • D > 34 cm/%
Charge breeder	EBIS / ECR	• efficiency: (4 $\sim$ 30%) / (1 $\sim$ 18%) • A/q: (2 $\sim$ 4) / (4 $\sim$ 8) • E spread (eV/q): $\sim$50 / (1 $\sim$ 10) • E/A: 5 keV/u
Charge state separator post-accelerator	(E + B) combination Super-conducting LINAC (SCL3, SCL3 + SCL2)	• $R_{a/q} \sim 300$ • (0.4 $\sim$ 18.5 $\sim$ 200)A MeV • ^{132}Sn @lab. (pps): (0.4 $\sim$ 1) $\times 10^{8}$

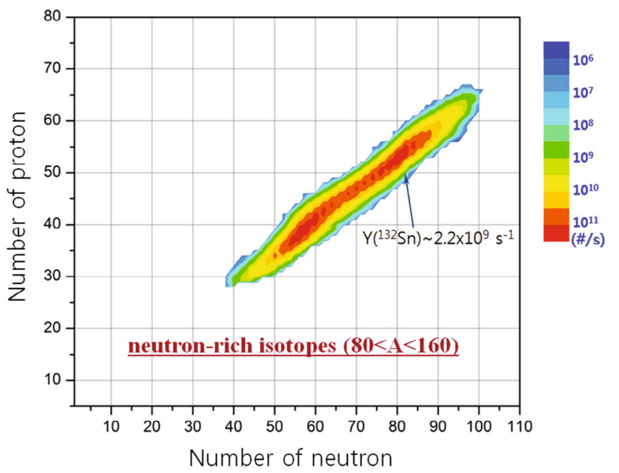

Fig. 4. (Color online) RI production yield from a 10-kW UCx ISOL target.

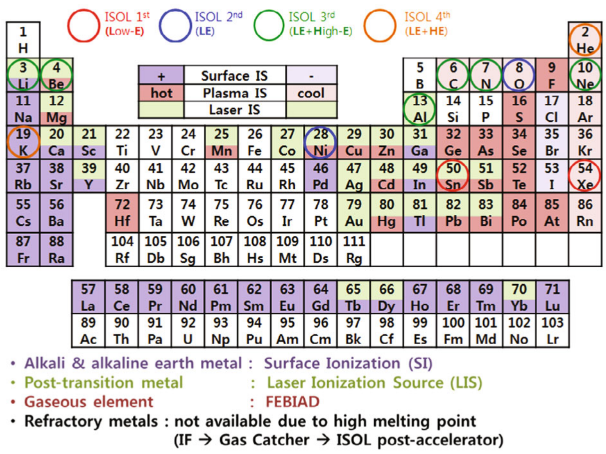

Fig. 5. (Color online) Periodic table of elements considered at RISP.

Beam Transport and Purification: In order to reduce activation along the beam transport line by unwanted ions extracted from the ion source, we will use a 90-degree dipole magnet with a mass resolving power of 300 as a pre-separator. A high-resolution mass separator (HRMS) is required to provide mass (isobar)-purified beams of exotic nuclides from the TIS station. The design goal of the HRMS is that the working resolution be higher than 10000 with a transmission of > 90% and an input beam emittance of 3π-mm-mrad. The small input emittance can be achieved using an RFQ-cooler in front of the separator. The configuration is symmetric with respect to the mid-plane in order to minimize higher-order aberrations [10]. The HRMS consists of two dipole magnets with a 90-degree bending angle, six electrostatic quadrupoles, two electrostatic sextupoles, and an electrostatic multipole. The theoretical mass resolution is estimated to be about 34000 for a 2π-mm-mrad beam emittance, however, the working resolution may be substantially lower in real operation due to some systematic uncertainties. Because the design and the construction

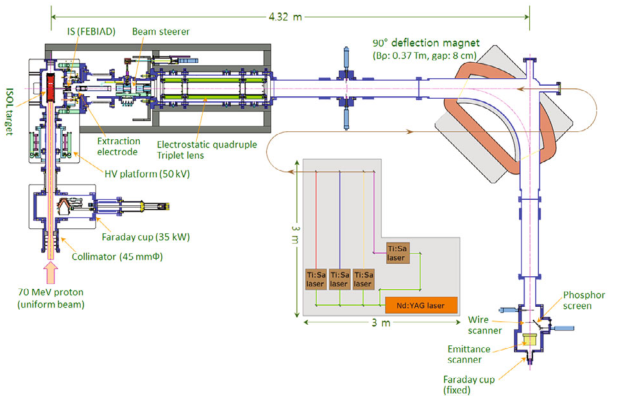

Fig. 6. (Color online) Layout of the off-line ISOL front-end complex.

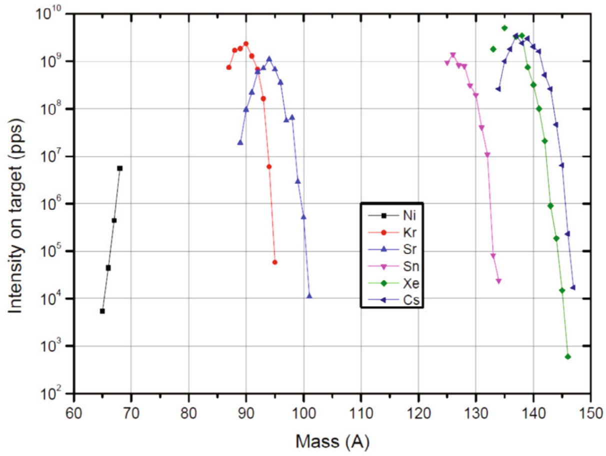

Fig. 7. (Color online) Expected on-target intensities of neutron-rich isotopes calculated by considering transmission, ionization and acceleration efficiencies for different isotopes generated from a 10-kW ISOL target.

Table 3. Primary RI beam species from the ISOL facility at RISP.

Isotope	Half-life	Science	Lab. Yield (pps)
^{66}Ni	2.28 d	Pigmy	4×10^5
^{68}Ni	21 s	Symmetry	5×10^6
^{132}Sn	39.7 s	r-process, pigmy	1×10^7
$^{130-135}$Sn	3.7 min $\sim$ 0.5 s	Fine structure, Precision mass	$10^8 \sim 10^4$
^{140}Xe	13.6 s	Symmetry	3×10^8
^{144}Xe	0.4 s	Symmetry	1×10^5

of a HRMS having such a high resolving power requires a long period of R&D, we propose to build a copy of the SPIRAL2 version with the collaboration of the HRS (High-Resolution Separator) team in CENBG (Center for Nuclear Research of Bordeaux Gradignan, France).

Charge Breeding and A/q Separation: Post-acceleration of a multiple-charge-state ion beam is preferred as the simplicity, efficiency and cost of the post-accelerator is directly related to the charge-state of the ions. Multiply-charged ions can be produced directly from the ion source or by using a charge-state breeder. We are planning to introduce an 18-GHz ECR (electron cyclotron resonance) ion source at another laboratory and initially to use it for the charge breeding of radioactive ions. A more complex EBIS (electron beam ion source) may be installed some time later, considering the result of an on-going development project at the RISP.

An ECR charge breeder has a higher intensity acceptance and beam acceptance, and it works in the pulsed mode as well in the continuous mode [11, 12]. On the contrary, light ions are more efficiently bred by using an EBIS, and the ion beam's quality is higher regarding emittance and superposition of impurities [13]. The A/q separator, which consists of magnetic and electric benders, plays a role in removing contaminants coming from the charge breeders, thereby improves the purity of the multiple-charge-state ion beam before its being injecting into the post-accelerator. An A/q separator was preliminarily designed for a mass resolution of 300 in terms of ion optics; however, it should be further optimized and designed separately, depending on the type of charge breeding.

III. RI BEAM YIELD

The RI beam extracted from the charge breeder is accelerated by the superconducting linac, SCL3 and is finally delivered to the low-energy experimental hall with a variable energy up to 18.5A MeV. The intensity at the experimental hall can be expressed by the following relation:

$$Y = \Phi \cdot \sigma \cdot N \cdot \varepsilon_r \cdot \varepsilon_i \cdot \varepsilon_{cooler} \cdot \varepsilon_{ms} \cdot \varepsilon_{cb} \cdot \varepsilon_{aq} \cdot \varepsilon_{tr} \cdot \varepsilon_{acc}, \quad (1)$$

where σ is the formation cross-section for the nuclear reactions of interest, Φ is the primary-beam's intensity, N is the target thickness, ε_r is the release efficiency from the ISOL target, ε_i is the ionization efficiency, ε_{cooler} is the ion cooling efficiency, ε_{ms} is the mass separation efficiency, ε_{cb} is the charge breeding efficiency, ε_{aq} is the a/q separation efficiency, ε_{tr} is the ion-transport efficiency through the beam transport line, and ε_{acc} is the post-accelerator transport efficiency. The intensity losses caused by the decay of the isotope in the ISOL target coupled with the ion source should be taken into account, especially for short half-life isotopes. Figure 7 and Table 3 show the expected isotopic intensities at the experimental target for some typical elements: Sn, Xe, Ni, Kr and Sr. For each of these elements, individual ionization efficiencies of 30, 20, 10, 12, and 20% respectively, and charge breeding efficiencies of 4, 10, 4, 10 and 4% were assumed. The overall efficiency, which is case dependent, was in the range of $0.01 \sim 1\%$. As shown in the figure, beam intensities of certain isotopes dramatically decreases with increasing mass due to relatively short half-lives, so reducing the release time of such short-lived isotopes is critical if their final yields are to be increased. Currently, we already have a conceptual design for a cone-shaped high-power ISOL target up to 70 kW. For efficient delivery of short-lived isotopes, especially from a high-power target ($>$ 10 kW), however, developing an innovative target geometry, like the multi-body, multiple-transfer line unit proposed at the EURISOL project [14], seems to be essential.

IV. CONCLUSION

A general overview of the ISOL/RISP project is presented. The ISOL project at the RISP is a challenging project in this field, and as newcomers, we are practically crossing the technical design stage. The detailed designs of the facilities are in the Technical Design Report, which will be published by the end of 2013. The R&D on the ISOL target chemistry has been on-going since July 2013, and ion sources are being made one by one. The off-line test facility of the TIS front-end system is at the final engineering design stage. Extensive & active collaboration with advanced foreign institutes seems to be essential, in particular, for the successful development of the RF-cooler, HRMS, charge breeder and A/q separator. The first exotic beam from the ISOL at RISP is expected in early 2019.

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