New isomer and decay half-life of ^{115}Ru

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Exotic, neutron-rich nuclei of mass $A = 115$ produced in proton-induced fission of ^{238}U were extracted using the IGISOL mass separator. The beam of isobars was transferred to the JYFLTRAP Penning trap system for further separation to the isotopic level. Monoisotopic samples of ^{115}Ru nuclei were used for γ and β coincidence spectroscopy. In ^{115}Ru we have observed excited levels, including an isomer with a half-life of 76(6) ms and $(7/2^-)$ spin and parity. The first excited 61.7-keV level in ^{115}Ru with spins and parity $(3/2^+)$ may correspond to an *oblate* $3/2^+[431]$ Nilsson orbital. A half-life of 318(19) ms for the β^- decay of the $(1/2^+)$ ground state in ^{115}Ru has been firmly established in two independent measurements, a value which is significantly shorter than that previously reported.

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I. INTRODUCTION

The structure of neutron-rich nuclei from the mass $A \sim 110$ region is of particular interest for modeling the nucleosynthesis process of rapid neutron capture, the r process [1]. As discussed in a recent theoretical work [2] one of the reasons is the rapid change of nuclear shapes in this region, first from spherical to strongly prolate deformed, and then, at higher neutron numbers, to a triaxial and possibly to an oblate shape, predicted in this region some time ago [3]. It is now suggested that instead of a pure oblate deformation, prolate and oblate shapes may compete in very neutron-rich nuclei of this region [2]. Such information as well as other data, including β^- decay half-lives and the existence of long-lived isomers, are crucial for calculations of the r-process path. However, the experimental data are scarce and theoretical estimates are used as inputs for calculations at large neutron excess. Therefore, experimental studies of these nuclei are of great importance.

Due to recent advances in experimental techniques, we have undertaken systematic studies of nuclei in the $A \sim 110$ region, starting with reinvestigation of less neutron-rich nuclei, where we have improved previous results significantly [4–6], and moving toward more neutron-rich isotopes [7–11]. These studies provide reliable systematics of excited nuclear levels in the region [12], which are useful in planning further experiments and help to understand the nuclear structure. They also are, at present, the main tool to search for signatures of oblate configurations, as discussed in Refs. [9,10,12].

Our recent work [8] suggests that a long-lived isomeric state may be present in the very neutron-rich nucleus ^{115}Ru, where no excited levels are known to date. Based on this prediction (see Fig. 5 in Ref. [8]) and better understanding of the nature of excited levels in odd-N nuclei in the region [12], we prepared a systematics figure of bandhead levels in odd-A Ru isotopes, drawn relative to the $11/2^-$ level, which is shown in Fig. 1.

In odd-A Ru isotopes we see a pattern which is similar to that observed for bandheads in odd-A Pd isotopes [12] for both positive- and negative-parity levels. In particular, at neutron numbers $N = 67$ and 69 the odd neutron populates the $7/2^-[523]$ orbital. Figure 1 suggests that this $7/2^-$ level will be close to the $1/2^+$ ground state also at $N = 71$. It is important that in ^{115}Ru the $5/2^+$ excitation is expected above the $7/2^-$ level. This would permit the presence of a long-lived isomer in ^{115}Ru. We note that the $3/2^+$ level, which most likely corresponds to the $3/2^+[411]$ *prolate* configuration, may also be above the $7/2^-$ at $N = 71$. However, in the $N = 71$ isotone, ^{117}Pd, the ground state has spin and parity $3/2^+$ [16], which is unexpected and may be due to an *oblate* structure [12]. It is of a great interest to search for such a $3/2^+$ level below the expected $7/2^-$ isomer in ^{115}Ru.

In the first observation of β^- decay of ^{115}Ru [17], performed at the Ion Guide Isotope Separator On-Line (IGISOL) mass separator [18], one transition with an energy of 292 keV was assigned to the ^{115}Ru decay. The half-life corresponding to the β^- decay of the ground state of ^{115}Ru, specified as the half-life of the 292-keV γ transition fed in this decay was first reported as 400(100) ms [19] and later increased to 740(80) ms [17]. The measurement was made over a time base of 2.0 s. The β-decay half-lives at the border of known nuclei are very important input parameters for nuclear structure as well as astrophysical r-process calculations. Therefore, it is crucial to verify the reported half-lives.

II. EXPERIMENT

The light-particle induced fission of U or Th, used in Refs. [17,19], produces nuclei of interest together with a vast background of less exotic isotopes. The isobaric beam delivered by IGISOL always contains a large amount of activity coming from the less exotic isobars, which makes γ and β spectroscopy rather difficult. An improved β-decay spectroscopy of ^{115}Ru was possible only after the JYFLTRAP Penning trap system [20], coupled to the upgraded IGISOL

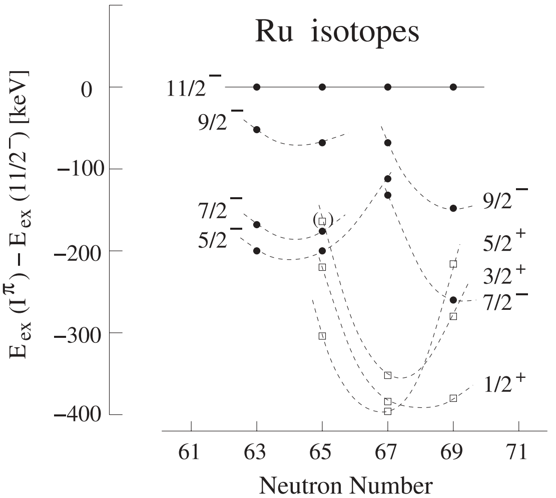

FIG. 1. Low-energy levels in odd $^{107-113}$Ru isotopes shown relative to the $11/2^-$ level. The data are taken from Refs. [7,13–15]. The open (full) symbols are for positive- (negative-) parity states.

mass separator [21], was applied to prepare monoisotopic samples for β-γ spectroscopy, providing a very effective system for the production of extremely exotic neutron-rich nuclei of refractory elements. The use of this setup for making clean samples of ^{115}Ru is described in Ref. [8] and more details on the isotopic purification technique can be found in Refs. [22,23].

In the present work we report on the recent trap-assisted measurements of ^{115}Ru β decay, one devoted to detailed spectroscopy studies of both ^{115}Ru and ^{115}Rh and the other to a precise measurement of the half-life of the ground state of ^{115}Ru. The results of the measurements have been partly reported in conference proceedings [11].

In our measurements the nuclei of interest were produced in fission of ^{238}U induced by 25-MeV protons from the K-130 cyclotron. Fission fragments of mass $A = 115$ were separated on-line using the IGISOL mass separator. The isobaric beam was directed to the Penning ion trap system for mass separation to the isotopic level. The monoisotopic ion samples of ^{115}Ru released from the trap were either detected with a microchannel plate (MCP) detector to measure ion-beam intensity (mass scans) or implanted onto a movable plastic tape for β-decay spectroscopy. In the best conditions the yield of ^{115}Ru ions measured after the trap with the MCP was about 50 ions per second for a 13-μA proton beam.

Our spectroscopy setup, located around the implantation point, consisted of two high-purity coaxial Ge detectors for γ rays, one Ge detector of LOAX type for low-energy γs, and a 2-mm-thick plastic scintillator surrounding the implantation point for detecting β particles. The collection tape was periodically moved to transport away long-lived decay products.

III. RESULTS

Mass scans obtained for $A = 115$ isobars are shown in Fig. 1 of Ref. [11]. The exotic nucleus ^{115}Ru, is well separated from other isobars, providing very clean samples for β and

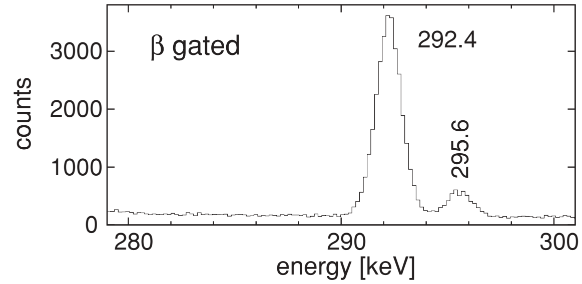

FIG. 2. Fragment of a γ spectrum around the dominating 292.4-keV line, observed in the present trap-assisted measurement, to be compared with Fig. 2 in Ref. [17].

γ spectroscopy. Figure 2 in Ref. [17] shows a β-gated γ-ray spectrum for mass $A = 115$ near the 292-keV peak, which is the most intense transition fed by ^{115}Ru β decay. The spectrum is dominated by a γ line of about 296 keV ascribed earlier to the ^{115}Rh β^- decay [24]. In an analogous fragment of a β-gated γ-ray spectrum following the trap-assisted measurement of ^{115}Ru β^- decay, shown in Fig. 2, the strongest γ peak is at 292 keV thanks to the use of monoisotopic clean samples (see also Fig. 2 in Ref. [11], which shows the high resolving power of $\beta\gamma$ and $\gamma\gamma$ coincidence measurements of monoisotopic ion samples of ^{115}Ru).

We also note a remarkable increase in the ^{115}Ru yield after the Penning trap as compared to our test experiment [8], which was possible due to further tuning of the IGISOL-JYFLTRAP system. An example of a coincidence γ spectrum gated by the 292.4-keV line is shown in Fig. 3. The comparison with the spectrum gated by the same transition in the previous run (see the top picture in Fig. 3 in Ref. [8]) shows a clear increase in statistics. A schematic drawing of ^{115}Ru β decay is shown in Fig. 4. A detailed scheme of excited levels in ^{115}Rh fed by ^{115}Ru β^- decay will be published elsewhere [25]. In our first study of ^{115}Ru decay [8] we have assigned spins and parities to levels in ^{115}Rh as shown in Fig. 4. The present work does not change these assignments. Somewhat surprising is the lack of transitions from the 499.1- to the 372.3-keV level, although this probably could be explained as due to differences in level structures.

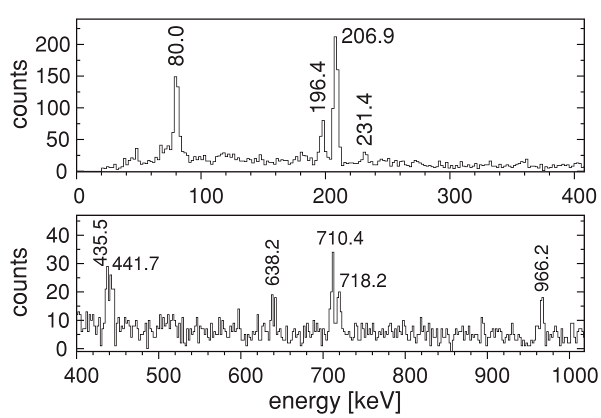

FIG. 3. Coincidence γ spectra gated on the 292.4-keV transition which is the one most intensively populated in ^{115}Ru β decay.

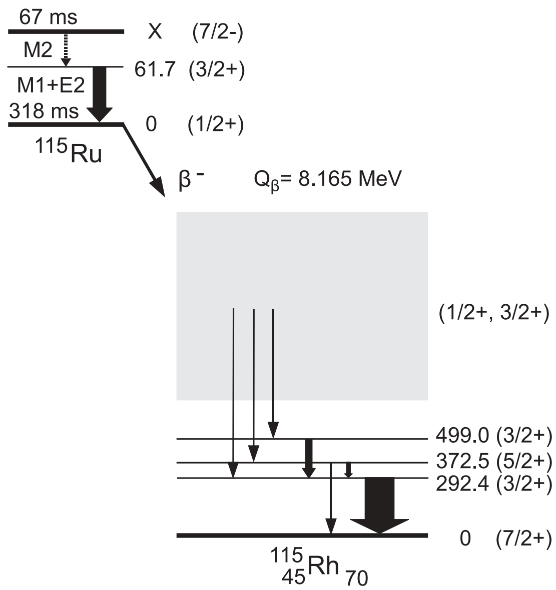

FIG. 4. Decay of the isomer and the ground state in ^{115}Ru.

A very interesting new feature observed in the ^{115}Ru trap-assisted study is the presence of a 61.7-keV γ line, which is seen in a single γ spectrum [Fig. 5(b)] but is not present in a β-gated γ spectrum [Fig. 5(a)]. The half-life corresponding to the 61.7-keV γ decay was measured by gating on the 61.7-keV peak and projecting on the TDC spectrum correlated with the activity-decay cycle, yielding a value of 76(14) ms [11]. In the present study the decay period was divided into 10 time bins and counts in the 61.7-keV line were obtained by a Gaussian fit in each of the time bins. The result is shown in Fig. 6 and provides a half-life value of 76(6) ms. A γ transition of 61.7 keV has not been reported either in any of the less exotic members of the $A = 115$ isobaric chain or in possible oxidation impurities and is also not present in the laboratory background. Comparison of the spectra in Figs. 5(a) and 5(b) reveals also a clear correlation of the presence of the 61.7-keV line and the 19.2-keV K_α x-ray line of ruthenium.

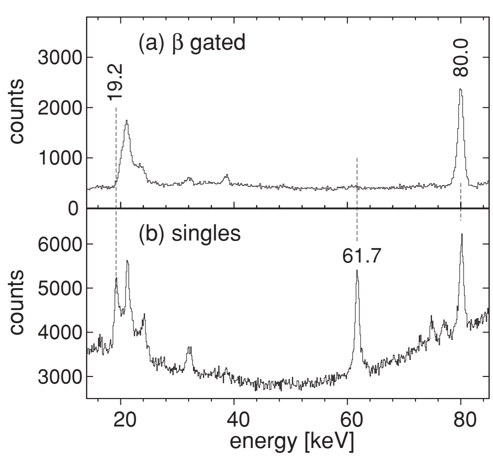

FIG. 5. β-gated and single γ spectra following the β decay of ^{115}Ru are shown in (a) and (b), respectively. The 19.2-keV peak is a K_α x-ray of Ru.

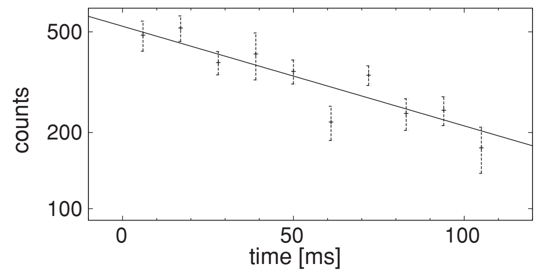

FIG. 6. Decay spectrum corresponding to the 61.7-keV line. Its half-life has been estimated as 76(6) ms in accord with the preliminary value in Ref. [11].

The experimental estimate of the α_K internal conversion coefficient for the 61.7-keV line gives a value of 2.7 ± 0.6. Theoretical values of the α_K coefficients for a 61.7-keV transition are 1.1 for $M1$ and 4.9 for $E2$ multipolarity; the other α_K values are 16.2 for $M2$, 267 for $M3$, 0.48 for $E1$, and 41 for $E3$ [26]. Therefore, our experimental α_K value indicates a mixed $M1$ and $E2$ character for the 61.7-keV line. Based on the above findings we propose that the 61.7-keV γ line corresponds to a transition in a cascade deexciting an isomer in ^{115}Ru populated directly in fission. A similar isomer is known to exist in ^{113}Ru [27]. Our experimental estimate for the ratio of the isomer to the ground-state production, found as the ratio of the 62- to 292-keV transition intensities, is 0.5. The intensity of the 62-keV transition includes its experimental internal conversion.

Our test trap-assisted measurement of ^{115}Ru β decay [8] provided a half-life of 270(38) ms for the ground state of ^{115}Ru [11], which differs significantly from the previous value [17]. However, this measurement was done with a rather short time base of 111 ms and had low statistics. Therefore, in the present work a dedicated measurement of the ^{115}Ru decay half-life was performed. In this measurement the spectroscopy setup consisted of two Ge segmented clover detectors, one LOAX type Ge detector, and a 2-mm-thick plastic scintillator. The monoisotopic samples of ^{115}Ru were implanted onto the collection tape for 1 s and then implantation of ions was blocked for a 1-s-long decay period. The collection tape was moved after three implantation and decay periods. In this run an analog data acquisition system was used in parallel with a digital system based on Digital Gamma Finder modules (XIA). The results are presented in Figs. 7(a) and 7(b). In both figures the decay of the 292-keV line is compared to the decay of the sum of 125.6- and 127.9-keV transitions fed in the β decay of ^{115}Rh. The half-lives measured with the analog and the digital data acquisition systems of 318(29) ms and 343(28) ms, respectively, are the same within their error bars, represented here by statistical uncertainty. As the final value for the half-life of the ground state of ^{115}Ru, we propose $T_{1/2} = 318(19)$ ms, the weighted average of the values found in this work, and the value from Ref. [11].

IV. DISCUSSION

The striking feature of the ^{115}Ru β-decay scheme is the lack of transitions to the ground state, which is in clear contrast to

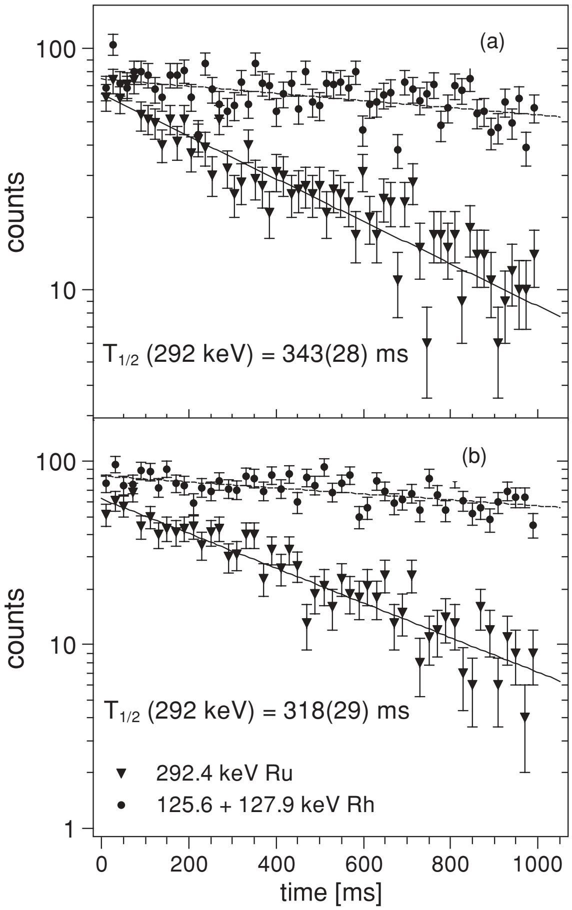

FIG. 7. Decay pattern of the 292.4-keV line fed in ^{115}Ru β decay. For comparison, the decay of the sum of the two most intense transitions in ^{115}Rh β decay is shown. Note that ^{115}Rh is solely produced in the decay of ^{115}Ru mother, thus its apparent half-life is longer than the value measured in Ref. [24]. The data in the upper picture and $T_{1/2} = 343(28)$ ms were measured with the digital acquisition system. The lower picture and $T_{1/2} = 318(29)$ ms come from the analog system.

the β-decay scheme of the neighboring ^{113}Ru [28]. It is known that the ground state in ^{113}Rh and ^{115}Rh has spin and parity $7/2^+$. Therefore, the observed difference in the decay pattern indicates a difference in spins of β-decaying levels in both nuclei. In ^{113}Ru the $7/2^-$ isomeric level decays to $9/2^-$ levels in ^{113}Rh, which can decay to the $7/2^+$ ground state [8,27,28]. The lack of analogous decays in ^{115}Rh indicates that the newly found isomer in ^{115}Ru deexcites mainly by electromagnetic transitions, while the β-decaying ground state of ^{115}Ru has a rather low spin. The decay of the ground state populates only low-spin levels in ^{115}Rh, which cannot decay directly to the $7/2^+$ ground state of ^{115}Rh.

In the previous trap-assisted investigation of ^{115}Ru β decay we tentatively proposed $1/2^+$ spin and parity for the ground state of ^{115}Ru [8], following a similar assignment for the ground state in ^{113}Ru [7]. This is supported by the systematic trend in Fig. 1. Calculations performed for analogous $1/2^+$ states in ^{111}Ru [29] and ^{113}Ru [7] indicate that these states have a complicated structure, involving four single- particle orbitals as well as collective excitations.

For the 76-ms isomeric state in ^{115}Ru we propose spin and parity $7/2^-$, as observed in ^{113}Ru [7]. This isomer can be due to the 71st neutron occupying the $7/2^-[523]$ prolate state originating from the $h_{11/2}$ intruder orbital. Such a solution is also supported by the systematics trend seen in Fig. 1. However, in the case of a $7/2^-$ isomer located above the $1/2^+$ ground state, the isomeric transition would be of $E3$ character. Such multipolarity of the isomeric transition is in variance with our experimental estimation of the internal conversion coefficient for the 61.7-keV transition. Moreover, the 76-ms half-life is about three orders of magnitude shorter than a Weisskopf estimate for a 61.7-keV $E3$ transition.

To explain the experimental observations we propose a $3/2^+$ level located 61.7 keV above the $1/2^+$ ground state of ^{115}Ru and the $7/2^-$ isomeric state located about 20 keV above the $3/2^+$ level. In this scenario the $7/2^-$ isomeric level deexcites by a $M2$ transition, which has energy below the K-shell electron binding energy in Ru. Therefore it is not K converted and does not contribute to the K x-ray line seen in Fig. 5. The $3/2^+$ level populated by the isomeric decay deexcites further via a mixed $M1$+$E2$, 61.7-keV transition to the $1/2^+$ ground state. In that scenario, the observed 61.7-keV γ line is due to the $M2$ isomeric transition, which is reasonably close to the Weisskopf estimate for a 61.7-keV, $M2$ transition. We note that in ^{113}Pd there is a $(9/2^-)$ isomer of 0.3 s, which deexcites by a $M2$ transition of 81.3 keV and in ^{117}Pd an $(11/2^-)$ isomer of 19.1 ms, which deexcites by 168.6- and 71.5-keV transitions of $M2$ character [30]; see Fig. 8. The 76-ms half-life of the 61.7-keV γ ray is between the half-lives of isomeric transitions in ^{113}Pd and ^{117}Pd.

The $3/2^+$ level in ^{115}Ru might be interpreted as due to the $3/2^+[402]$ prolate Nilsson orbital. Such a configuration is observed in ^{111}Ru 215 keV below the $7/2^-$ level. In ^{113}Ru its energy increases and it is located just below the $7/2^-$ level. If this increasing trend continues in ^{115}Ru, then the $3/2^+[402]$ prolate orbital should appear above $7/2^-$ in ^{115}Ru, as suggested by Fig. 1, which is contrary to the scenario proposed above.

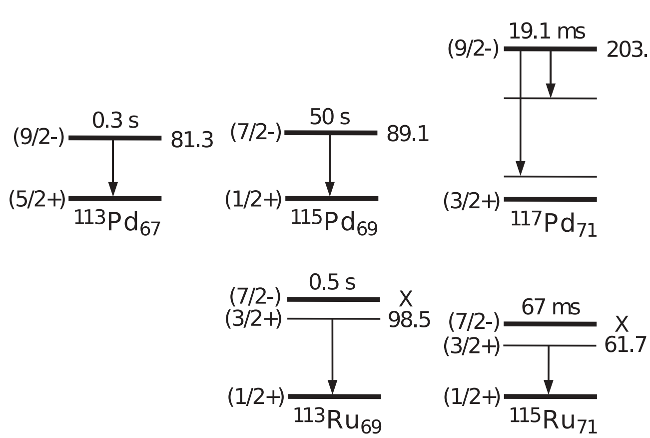

FIG. 8. The levels, spin, and parities in ruthenium and their palladium isotones relevant for discussion of the isomeric state in ^{115}Ru. The data for ^{113}Pd come from Ref. [30], for ^{115,117}Pd from Ref. [16], and for ^{113}Ru from Ref. [7].

A possible way to have a $3/2^+$ level below the $7/2^-$ isomer is to employ the $3/2^+[431]$ orbital on the oblate side of Nilsson diagram. As already mentioned an analogous "unexpected" $3/2^+$ level appears low in energy in the $N = 71$ isotone ^{117}Pd where it forms the ground state [16]. As discussed in Ref. [12] this level may be due to an oblate configuration. The $(3/2^+)$ level at 61.7 keV in ^{115}Ru could be the second case. At present the arguments based on systematics of excited states is as much as we can say about the presence of oblate configurations in the very neutron-rich nuclei of the $A \sim 110$ region, predicted here theoretically [3]. Furthermore, as pointed out in another recent work [2], it may be that there is no well-developed oblate minimum in the potential in nuclei of this region and that both prolate and oblate configurations compete. Our observations seem to favor this latter scenario. Obviously more work is needed to reach firm conclusions on this subject.

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