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g FACTOR MEASUREMENTS ON RELATIVISTIC ISOMERIC BEAMS PRODUCED BY FRAGMENTATION AND U-FISSION: THE g-RISING PROJECT AT GSI*

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Within the RISING (Rare ISotope INvestigations @ GSI) Collaboration at GSI, g factor measurements have been performed on isomeric states in neutron-rich isotopes approaching ^{132}Sn and in the neutron deficient Pb-region (the g-RISING campaign). We present the experimental technique and some typical aspects related to such studies on relativistic beams selected with the FRS fragment separator. First results are presented for the $(19/2^{+})$ 4.5 μs isomeric state in ^{127}Sn, which has been produced by means of fission of a relativistic ^{238}U beam on the one hand, and by the fragmentation of a relativistic ^{136}Xe beam on the other hand. Spin-alignment has been observed in both reactions. It was the first time that spin-alignment has been established in a relativistic fission reaction.

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1. Introduction

The magnetic dipole moment, $\mu = g \cdot I$, is a very sensitive probe to investigate the single-particle configuration of a nuclear state, because nucleon g factors depend strongly on their orbital and total momentum. High-spin isomers in the region of doubly-magic nuclei often have a rather pure single-particle configuration, and then the g factor is a fingerprint of the unpaired nucleon configuration [1]. Measurements of g factors can help to assign or confirm the spin and parity of a nuclear state, especially in far-from-stability regions, where such assignments are often based on systematics and theoretical predictions.

To measure the g factor of microsecond isomeric states, the Time Differential Perturbed Angular Distribution (TDPAD) method is most suited [2]. It is based on the observation of the Larmor precession of a spin-aligned ensemble of isomers implanted in a suitable stopper that is placed in a static magnetic field. Spin-aligned isomers are produced in most nuclear reactions, such as fusion-evaporation [3], projectile fragmentation [4–6] or spontaneous fission [7]. If the isomers are produced and stopped in the production target, they maintain their spin-alignment if a large enough magnetic field is applied and if the target material has suitable properties. In such case, one can investigate their g factor "in-beam" [2]. However, to study isomers in exotic isotopes, one often needs to select the isomers of interest with an in-flight fragment separator [8]. The spin-alignment in an isomeric beam is then preserved during the selection process, only if the isotopes are fully stripped [5, 6]. If electrons occur around the free nucleus, the hyperfine interaction between the nuclear spin and the randomly oriented electron spin causes a loss of the reaction-induced orientation during the flight through vacuum. In some cases the alignment can be partially maintained if a noble gas charge state is selected [9]. To obtain fully-stripped isotopes from a projectile fragmentation reaction the primary beam needs to have a sufficiently high energy, which increases with the mass of the desired isotope. In order to avoid the pick-up of electrons in the particle identification detectors along the beam trajectory, the secondary beam energy needs to stay sufficiently high up to the point of implantation. For isotopes in the region of ^{132}Sn, the secondary beam energy should be at least 300 MeV/u along the whole trajectory. Thus the primary beam has to be relativistic, with an energy of more than 500 MeV/u. Such beams are provided at the GSI facility in Darmstadt, Germany.

We present here the goals and some preliminary results from a campaign to measure for the first time the g factors of isotopes with $A > 100$ using relativistic beams. The Cluster HPGe detectors from RISING [10] have been used for detecting the isomeric decay. Both fragmentation and fission reactions were investigated. For the latter, the present experiment serves as a proof that spin-aligned isomeric beams can be selected after a relativistic fission reaction. Results for isomers in the region of ^{132}Sn, produced by both reactions mechanisms, are presented. In the neutron-rich isotopes near ^{132}Sn, several isomers have been observed during the past decades. Different methods were used for producing the isomers: deep-inelastic reactions [11], spontaneous fission [12], thermal neutron-induced fission [13, 14], proton-induced fission followed by β-decay into the isomer [15,16], relativistic fission of a ^{238}U beam [17] and recently also fragmentation of a ^{136}Xe beam. To study the g factor of these neutron-rich isomers, spin-aligned relativistic beams as produced at the FRagment Separator FRS [18], may proof to be one of the few available methods.

2. Experimental method and set-up

2.1. Production and selection of the isomeric beams

A primary target of 1 g/cm^2 ^{9}Be (with a 221 mg/cm^2 Nb stripper foil), placed at the entrance of the FRS, is bombarded by a ^{238}U beam (750 MeV/u, average intensity 10^8 pps) to produce fission fragments or a 600 MeV/u ^{136}Xe beam (average intensity 2×10^8 pps) to produce projectile fragments, respectively. In both experiments, a cocktail of isotopes around ^{127}Sn is selected using the four dipole stages of the FRS and an Al degrader placed in its middle focus (schematic layout shown in Fig. 1) [18]. A thickness of 5 g/cm^2 Al was used to select fission fragments, while for the projectile fragments the wedge degrader was 2 g/cm^2 thick.

Ion identification is performed on an event-by-event basis using a system of tracking detectors: two multi-wire proportional counters (MW41 and MW42) for position determination, a MUltiple Sampling Ionizing Chamber (MUSIC) for Z determination and two fast scintillators (position sensitive Sc21 in the middle focus and Sc41 at the final focus) for time-of-flight (TOF) measurements [10].

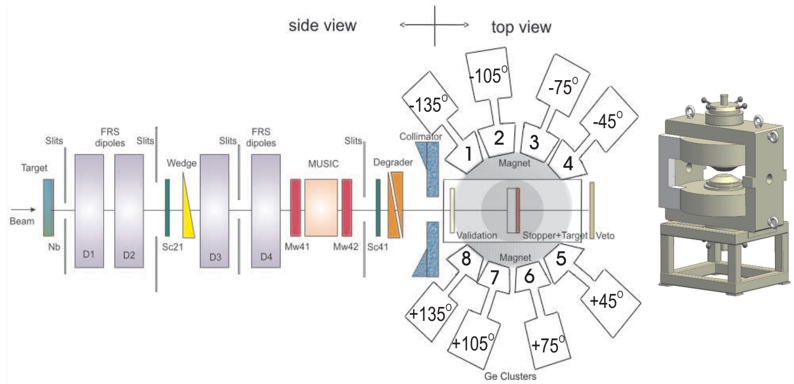

Fig. 1. Schematic layout of the FRS and g-RISING set-up (left) and drawing of the magnet (right).

Scintillator Sc41 is used also as a particle trigger for ions entering the g-RISING set-up and to give the start for the subsequent γ-decay measurement. A scintillator (validation) inside the magnet is used to validate the γ-event, and another scintillator (veto) at the end of the set-up is used to exclude events that come with an ion observed in this detector (and thus did not stop in the stopper). Figure 2 shows the selected isotopes in both experiments.

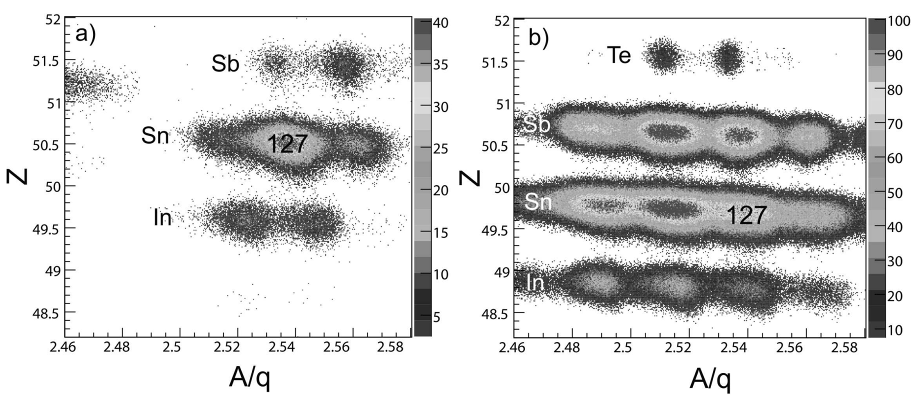

Fig. 2. Isotopes selected in case of a Xe-fragmentation reaction (a) and a U-fission reaction (b).

The particle cocktail arrives at the final FRS focus with an energy of almost 500–600 MeV/u, where all the detectors are placed with air gaps between them. Thus the probability for picking up electrons needs to be estimated according to the energy loss after each detector. Such calculations were performed using the simulation codes GLOBAL [19] and LISE++ [20]. For the fission fragments around ^{127}Sn almost 90% of the isotopes are fully stripped after Sc41. Their energy of about 500 MeV/u is further reduced by a variable thickness Al degrader placed in front of the g-RISING set-up, in order to adjust their implantation point in the stopper. To avoid the pick-up of electrons in the air and in the validation detector behind this degrader, the energy of the fragments needs to stay above 300 MeV/u. The Al-degrader thickness was therefore limited to less then 3 g/cm^2. To protect the set-up from upstream radiation, a lead wall with a collimator of 70 mm diameter is used in front of the magnet yoke, which has a hole with diameter 75 mm through which the beam has to pass (Fig. 1).

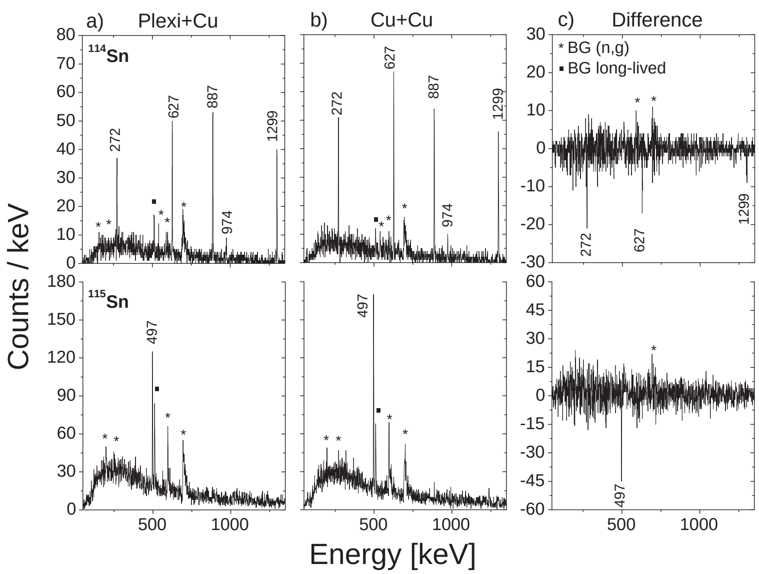

Fig. 3. γ-spectra from ^{114}Sn (upper panel) and ^{115}Sn (lower panel) isomeric decays. The isomeric transitions are shown with their energies. They are more intense for a Cu+Cu (b) than for a plexi+Cu (a) degrader/stopper combination. In (c) the difference spectra illustrate that the low-energy background radiation is similar in both spectra.

A high-purity (4N) Cu foil with a size of 80×80 mm^2 and 2 mm thickness, annealed under Ar atmosphere up to 750°C during several hours, was used as a perturbation free environment for the isomers. To stop a 300 MeV/u beam in Cu, a total thickness of 4 mm is required, which is obtained by gluing another 2 mm Cu to the stopper plate (to avoid an air gap). In [10] it was calculated that the cross section for atomic processes leading to low-energy background radiation in the γ-spectra increases with increasing Z of the target material. Therefore, we compared isomeric γ-spectra measured with a low-Z (20 mm plexiglass) and with a high-Z (2 mm Cu) degrader fixed to the Cu stopper (Fig. 3(a) and 3(b)). For ^{114}Sn ($I^\pi = 7^-$, $t_{1/2} = 733$ ns) the γ-spectrum is recorded in a [160 ns — 3 μs] time window after the ion arrival (top row Fig. 3) and for ^{115}Sn (I^π=11/2$^-$, $t_{1/2} = 159\,\mu$s) the time window is [160 ns — 15.5 μs] (bottom row Fig. 3). The isomeric transitions are on average 27% and 36% more intense for the Cu/Cu combination. This is in agreement with calculations from the LISE++ code, which predicts 24% loss of isomers caused by the higher amount of nuclear reactions in the plexi-glass degrader. Subtracting both spectra, in Fig. 3c, shows that the low-energy background radiation in the Cu/Cu case is not significantly larger than in the plexi/Cu case. Thus using a high-Z degrader is more advantageous than using a low-Z one, contrary to what was believed before. However, in the experiments we used the plexi/Cu combination.

2.2. g-Factor measurement using RISING detectors

To study the g factor of microsecond isomers, a spin-aligned ensemble of isomers is implanted in the annealed Cu host that maintains the spin-orientation during the nuclear lifetime. By applying a static magnetic field, the isomeric spins are decoupled from possible remaining perturbing electric field gradients [21]. The spin-oriented ensemble performs a Larmor precession around this vertically oriented static field. From the measured precession frequency $\omega_{\rm L} = \frac{g\mu_N B}{\hbar}$, the nuclear g factor is deduced if the applied magnetic field is known. The γ-decay is measured as a function of time in order to observe the Larmor precession, using eight former EUROBALL cluster detectors [22] placed in the horizontal plane around the magnet at a distance of about 43 cm from the center (Fig. 1). Each cluster consists of seven encapsulated HPGe crystals. For each of the fifty-six crystals, the γ-ray energy and decay time with respect to the ion arrival time in Sc41 is recorded in a time window of almost 20 μs. The trigger was given by a delayed γ detected within 600 ns to 20 μs after the ion arrival. The particle rate in Sc41 was used as a trigger as well, but reduced by a factor 2^8. Thus the event rate in the data acquisition system was typically 5000/s, with the delayed events favored and the dead time below 40%.

In earlier projectile fragmentation reactions at intermediate [5, 6] and relativistic [23] beam energies, positive spin-alignment was observed for isomers selected in the center of their longitudinal momentum distribution and negative alignment in the wing of the distribution. In the present Xe-fragmentation experiment, the longitudinal momentum selection is not made by using the slits after the target or the wedge. Instead, the slits are fully open and the momentum selection is made off-line, using the position-sensitivity of the middle focal plane detector Sc21.

In the relativistic fission of a ^{238}U beam, spin-alignment has never been demonstrated. However, it is well-known that in spontaneous fission a strong correlation exists between the emission direction of the γ-ray and that of the fission fragment [7, 24]. We therefore expect to observe also spin-alignment in a selected ensemble of relativistic fission fragments. In a first step, no off-line momentum cut is performed, because the acceptance of the FRS ($\sim$ 2%) [18] is much smaller than the total width of the fission fragment longitudinal momentum distribution ($\approx$ 10%).

3. Results for ^{127}Sn

Prior to our study, two microsecond isomers were reported (lower part of Fig. 4). The ^{127}Sn fragments produced by thermal neutron induced fission were selected with the in-flight Lohengrin spectrometer at ILL Grenoble, where Pinston *et al.* [13] observed five γ lines with a $t_{1/2}$=4.5(3) μs. They assigned a spin/parity $19/2^+$ to this isomeric level, based on similarities with the decay schemes of the less exotic odd Sn isotopes. In the β-decay of ^{127}In to ^{127}Sn, Gausemel *et al.* [25] observed another microsecond isomer to which they assigned spin/parity $23/2^+$, with a half life of 1.26(15) μs, feeding the lower-lying $19/2^+$ state.

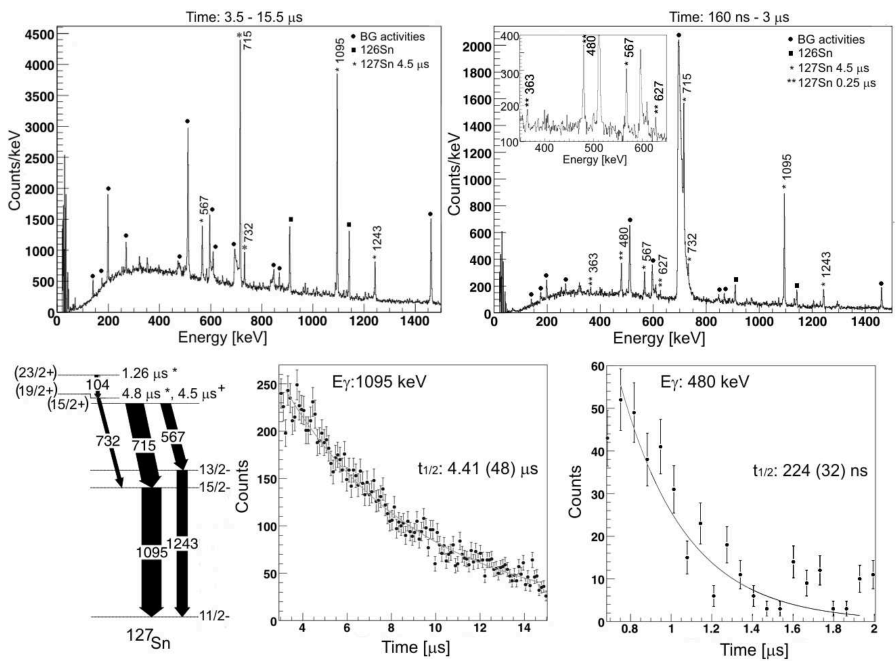

Fig. 4. Top: γ-spectra from the ^{127}Sn decay. Bottom: known isomeric levels and decay scheme (see text) and decay curves for the known and newly observed isomers.

The γ-spectrum correlated to relativistic ^{127}Sn fission fragments is shown in Fig. 4 for different time windows. In the larger time window the five isomeric transitions from the $19/2^+$ decay are marked with their energy. The low energy of the γ transition connecting the $(23/2^+)$ and the $(19/2^+)$ isomers is not in the sensitivity range of our Ge detectors, because of the shielding we added to avoid the atomic background radiation, as suggested in [10]. Therefore, the population and decay of this isomer can only be observed indirectly through the γ-branch depopulating the $(19/2^+)$ isomer. The background subtracted decay curve for the $E = 1095$ keV transition can be fitted assuming one microsecond isomer (Fig. 4), with a lifetime in agreement with previous values. We see no significant contribution from an isomer above the $(19/2^+)$. A few short-lived transitions appear if only γ's in the first 3 μs are visualized, as shown in the right panel of Fig. 4. The newly observed short-lived isomer, for which the decay curve is shown, has a half life of about $t_{1/2} \approx 0.22$ μs. This isomer is most likely the seniority three $\nu(h^{-3}_{11/2})27/2^-$ isomer, which was observed previously also in the less exotic Sn isotopes [11]. Further analysis to build a level scheme and to give more arguments for the suggested spin/parity assignment, is in progress [26].

A detailed investigation of the γ spectra correlated to each isotope produced and selected by the relativistic fission of ^{238}U (Fig. 2b), has revealed more than thirty isomers, of which six new ones. This analysis is still in progress [26].

The goal of these experiments was of course to demonstrate that spin-alignment is present in the relativistic fission of ^{238}U and to compare it to that obtained via projectile fragmentation. The spin-alignment gives rise to a non-zero amplitude of the $R(t)$ function, constructed by combining the decay curves measured for individual detectors with opposite directions of the vertically applied magnetic field. They are labeled U (up) and D (down), respectively (see [27] for more details). The decay curves from detectors positioned at 90° and 180° with respect to each other (1,5 and 4,8 in Fig. 1), can be combined such that the $R(t)$ function reduces to a simple sine function:

$$R(t) \;=\; \frac{I_{\rm U}(t) - \epsilon I_{\rm D}(t)}{I_{\rm U}(t) + \epsilon I_{\rm D}(t)} = \frac{3A_2B_2}{4 + A_2B_2}\sin(2\omega_{\rm L}t) \qquad (1)$$

with $I_{\rm U}(t) = (I_1+I_5)\uparrow + (I_4+I_8)\downarrow$ and $I_{\rm D}(t) = (I_1+I_5)\downarrow + (I_4+I_8)\uparrow$. The summed U and D spectra were normalized by a scaling factor ϵ to correct for the different total statistics in each. To include also the statistics from the inner detectors (2,3,6,7), their time-spectra have to be shifted with respect to (1,4,5,8).

The time shift depends on the unknown g factor:

$$\Delta t = \frac{\Delta \Phi}{\omega_{\rm L}} = \frac{\pm 30^\circ \hbar}{g\mu_N B} \tag{2}$$

and therefore an iterative procedure has to be applied.

Here we present the results from the $R(t)$ functions constructed with part of the statistics using the four detectors placed at $\pm 45^\circ$ and $\pm 135^\circ$ (following expression (1)). In the fragmentation experiment we collected $\approx 10^4$ events in the decay curve of the 715 keV transition (for four detectors and both field directions, and making a momentum cut in the wing of the momentum distribution). The applied magnetic field was chosen such that it would lead to an $R(t)$ oscillation with a period of the order of the nuclear lifetime, $B \approx 0.12$ T. The obtained result is shown in Fig. 5. In the U-fission experiment the applied magnetic field was much higher, $B \approx 0.70$ T, which leads to a very fast oscillation with respect to the isomeric decay time. Therefore, we applied an autocorrelation analysis to fold back the statistics from the total 15.5 μs observation time window into the first 3 μs. In its discrete and normalized form, the autocorrelation function $AC(n)$ is given by:

$$AC(n) = \sum_{k=k_1}^{k_2-n} \frac{R(k)R(k+n)}{k_2-k_1-n} / \sum_{k=k_1}^{k_2} \frac{R^2(k)}{k_2-k_1}, \tag{3}$$

where $R(k)$ presents the data as a function of the channel number k, $(k_2 - k_1)$ is the detection window and n runs up to a maximum N, the folding window, with $N << k_2 - k_1$. If the data $R(k)$ would describe a pure sine function without noise components or relaxation, then also $AC(n)$ will be a pure sine function with the same period and with an amplitude 1. Thus any information related to the amount of alignment is lost in such analysis. To quantify it, the analysis will have to be done on the data including statistics from all detectors and in the full observation window of 15.5 μs. Events from the 715 keV and 1095 keV transitions were added to construct the $R(k)$ function. By taking the full momentum acceptance window, a total of 2.10^4 events (sum of both field directions) is collected.

The result from the autocorrelation analysis of the fission data is compared to the $R(t)$ result from the Xe-fragmentation data in Fig. 5. The periods deduced from both experiments agree with each other, considering that the applied magnetic field was about 5.5 times larger in the fission experiment. Thus the deduced g factors are in agreement with each other (a preliminary value $|g| \approx 0.16$ is found) and also in agreement with the empirical value for a $19/2^+$ isomer dominated by a $\nu(h_{11/2}^{-1} \otimes 5^-)$ configuration [27]. However, the fact that the analysed γ-transitions are fed also via the higher-lying isomers, will have to be considered in the analysis. Thus firm conclusions related to the nuclear structure cannot be made at this stage of analysis. A detailed analysis on the amount of spin-alignment and a comparison for both reactions is in progress.

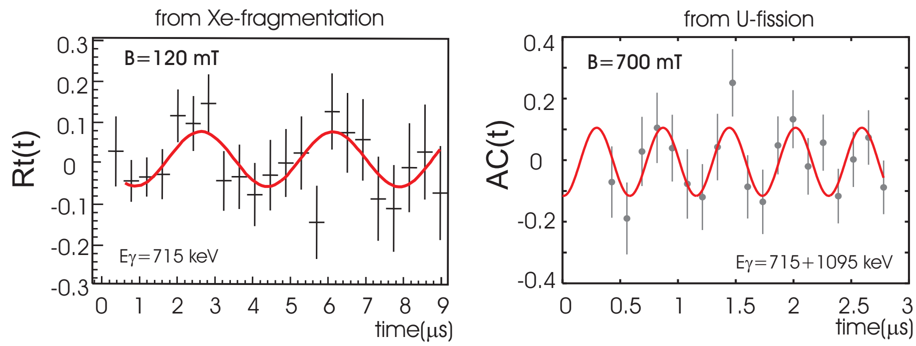

Fig. 5. Preliminary results from the $R(t)$ analysis for the $(19/2^+)$ isomer in ^{127}Sn.

4. Conclusions

The first results from two of the g-factor experiments performed within the g-RISING campaign at GSI have been presented. Isomers in ^{127}Sn have been produced by means of fission of a relativistic ^{238}U beam on one hand, and by the fragmentation of a ^{136}Xe beam on the other hand. A preliminary value for the g factor has been deduced from both data sets, leading to a preliminary consistent value $|g| \approx 0.16$. The fact that very different external field strengths were applied, gives confidence that the observed oscillations are indeed induced by the Larmor precession of a spin-aligned ensemble of isomers. A significant amount of spin-alignment has been observed for the first time in the relativistic fission of a ^{238}U beam, as well as in the fragmentation of a relativistic ^{136}Xe beam. Further analysis, including the observation of several new isomers, as well as the investigation of g factors of some other isomers, is in progress.

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