High efficiency electron spin polarization analyzer based on exchange scattering at Fe/W(001)

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We report on a compact electron spin analyzer based on exchange scattering from a magnetic surface. The heart of the detector is an Fe(001) thin film grown on W(001) with chemisorbed oxygen in the $p(1\times1)$ structure. The device is mounted at the exit of an energy dispersive analyzer and works at a scattering energy of about 13.5 eV. Its figure of merit is 2×10^{-3}, combined with an excellent stability of more than 2 weeks in UHV. © *2008 American Institute of Physics.*
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I. INTRODUCTION

Electron spectroscopies aim at the reliable characterization of electrons in all their degrees of freedom. Apart from the energy and momentum, the spin is a fundamental property determining the behavior of electrons in solid state systems leading directly to such effects as magnetism and other electron correlation phenomena. This illustrates that it is of utmost importance to be able to efficiently detect and to analyze the spin in electron spectroscopic experiments.[1–3]

All spin detectors rely in some way or another on a differing scattering cross section for electrons having opposite projections ($+\hbar/2$ or $-\hbar/2$) of their spin on a quantization axis which is defined by the geometry of the scattering experiment. Systematic comparisons of the defining properties of various types of spin detectors can be found in Refs. 4 and 5 (in addition, a recent detailed characterization of the spin polarized low energy electron diffraction (SPLEED) detector can be found in Ref. 6). The prominent example for a mechanism that provides a spin sensitivity in scattering experiments is the spin-orbit interaction, on which a large group of spin polarimeters is based. However, the size of the spin-orbit interaction energy is usually small in comparison to the Coulomb interaction, which dominates the scattering cross section in most circumstances. Experimentally, this means that one has to select special scattering conditions where the absolute effect of the Coulomb scattering is small in order to increase the sensitivity to the spin-orbit interaction. This necessity introduces an overall reduction in count rate by two to three orders of magnitude.[1]

Another, different, type of spin-dependent interaction is supplied by the exchange mechanism in magnetic systems. The corresponding interaction energy is of the order of 2 eV in ferromagnetic iron. The size of this energy is significant in comparison to the energies involved in the scattering of very low energy electrons ($\lesssim$20 eV) at surfaces and thus it can be expected that the scattering cross section for these electrons can become noticeably influenced by the spin-dependent exchange energy in specific circumstances.

For instance, a magnetic surface can show spin-dependent band gaps caused by the exchange interaction. The presence of a band gap means that electrons of specific energies and momenta are reflected with high intensity from such a sample because in the solid there are no states which they can occupy. If at the same time this energy is low enough so that no diffracted beams are created by the periodic surface potential, practically all the reflected intensity is concentrated in the specular beam. A high spin sensitivity results if the band gap is spin dependent, so that the reflectivity is high for one spin direction, while it is low for the other. In this context, it has been predicted theoretically[7] and observed in various investigations that the scattering of very low energy electrons at ferromagnetic Fe surfaces shows a large spin asymmetry and at the same time a large scattering efficiency due to an exchange-split band structure.[8,9] This effect was suggested to be used in a spin detector and, subsequently, spin polarimeters have been introduced which were based on spin-dependent reflection of very low energy electrons from surfaces of Fe(001) films (thickness $>$3000 Å) grown on MgO(001) (Refs. 10 and 11) or ultrathin Fe(001) films grown on Ag(001).[12,13]

Because of the very high intrinsic efficiency of the discussed scattering effect on Fe surfaces, we also decided to design a spin detector based on this promising principle. We chose to base the detector on Fe films grown on W(001) substrates, because of the relatively simple and fast preparation of this substrate. We have tried to optimally address the practical requirements for an efficient spin detection in the design of our spin detector which is described in this article.

II. DETECTOR DESIGN

The detector was designed to fit onto a commercially available cylindrical sector analyzer with 90° deflection angle (*Focus CSA300*). With outside dimensions fitting a space of $20\times20\times60$ cm^3, the detector is very compact and easy to integrate in standard UHV systems. Except for the electron bombardment heating, the spin detector itself requires no high voltages during operation.

The most important parts and their relative arrangement are shown in the drawing in Fig. 1. The electrostatic lenses L1, L2, and L3 transfer the electrons from the exit slit of the

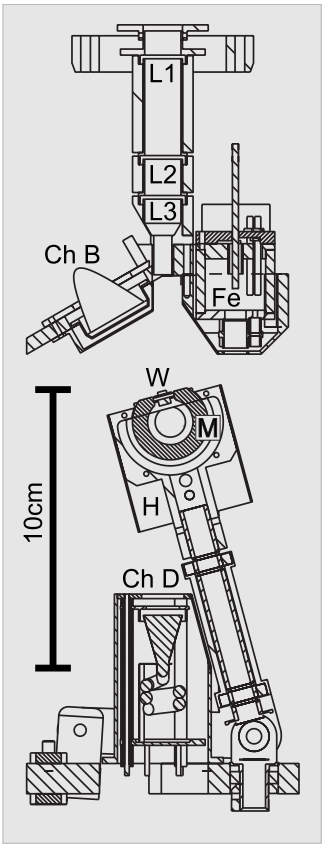

FIG. 1. Drawing of the main parts of the detector. (L1, L2, L3) electrostatic transfer and focusing lenses, (W) W(001) crystal, (M) electromagnet, (H) holder for W, M, and heating filament (can be tilted and rotated), (Ch B) the channeltron collecting the electrons reflected from W, and (Ch D) the channeltron which is used for spin-integrated measurements when H is moved into the position under the Fe evaporation source (Fe).

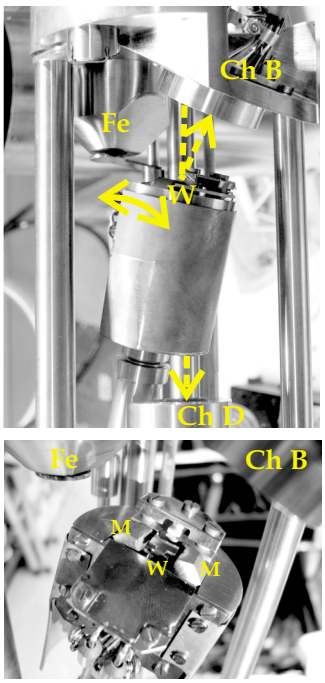

FIG. 2. (Color online) Photographs showing the crucial parts of the spin detector. The following parts are marked: (W) the W(001) crystal, (Ch B) the channeltron collecting the electrons reflected from W(001), and (Ch D) the channeltron which is used for spin-integrated measurements when W is moved into the position under the Fe evaporation source (Fe). In the lower photograph, (M) are the ends of the ferrite ring used to magnetize the ultrathin Fe film on the W(001) crystal.

analyzer to the scattering target W, the Fe film on the W(001) crystal. The crystal is surrounded by the electromagnet M which consists of a ferrite ring around which a coil has been wound. The crystal and ferrite ring are mounted on a holder H which can be flipped into the path of the electrons coming from the analyzer. The electrons leaving the sample are partially collected by the "back" channeltron Ch B. The incidence angle of the analyzed electrons is 15° degrees with respect to the surface normal of the W(001) crystal.

The channeltron B is preceded by a high pass energy filter consisting of two parallel grids. The first grid seen by the electrons is at the scattering potential (i.e., the potential of the target and all the surrounding electrodes) while the second grid is 3–4 V more positive than the scattering potential. This design is based on the observation[14] that electrons scattered inelastically due to the generation of Stoner excitations show a spin asymmetry of about 25% at ≈10 eV. The inclusion of these electrons in addition to the elastically scattered ones enhances the count rate without major sacrifice of spin sensitivity, while secondary electrons from the inner part of the detector region (presumably with no spin asymmetry) are suppressed. The very moderate energy filtering reduces the part of the apparatus asymmetry which is due to slight changes in the elastic scattering conditions. It was reported in Ref. 14 for Fe(110) and in Ref. 15 for Fe(001) that the variation of the spin sensitivity with respect to the angle of incidence is small from 0° of incidence up to about 15°. This also ensures that the spin sensitivity of the detector is practically independent of the azimuthal rotation of the detector crystal. This means that any orientation of the transversal spin polarization vector of the beam leaving the energy analyzer can be measured with the same spin sensitivity.

The spin asymmetry is measured under reversal of the Fe film magnetization by application of current pulses through the electromagnet M. The projection of the spin quantization axis onto the magnetization direction can be selected by rotating the holder H about the surface normal of the crystal W. This is accomplished by a rotation feedthrough. An additional linear feedthrough connected to a lever at the bottom of the holder H allows to flip the holder into the preparation position with the crystal W exactly below the electron beam evaporator Fe used to grow the iron film. This position also allows spin-integrated measurements because the electrons coming from the analyzer are going to the "direct" channeltron Ch D, as illustrated in the drawing of Fig. 1 and in the photographs of Fig. 2. We show the assembled device in Fig. 3.

For preparation of the W(001) crystal, electron beam heating is used. This is realized by a heated filament below the W crystal and by putting the W crystal on a positive voltage of about 1 kV with respect to the filament. In this way, crystal temperatures of 2500 K can be reached. This can be checked by observing the W(001) crystal with a pyrometer through a small viewport. Oxygen can be dosed by a leak valve. The whole spin detector is pumped by a separate ion getter pump and a titanium sublimation pump nearby.

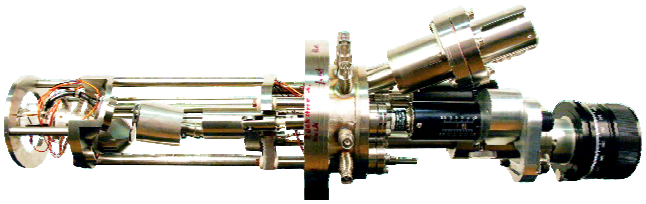

FIG. 3. (Color online) Photograph of the assembled device with the inner shielding taken off. The mounting flange (seen near the center) is a 100 mm inner diameter conflat flange.

To prepare the spin detector for operation, the W(001) crystal is treated in a similar way as in the SPLEED detector where the same type of crystal is used. One removes carbon contaminants, tungsten oxides, and carbon monoxide by treatments of the sample with oxygen and by flashing the crystal to different temperatures.[6] In our case, the oxygen cleaning treatments are necessary only after bakeout. During regular operation, removing a used iron film and preparing a surface for growth of a new film is accomplished by flashing the crystal to 2000 K. After this, the Fe film is grown using the electron beam evaporator. The pressure in the device during growth is in the lower 10^{-10} mbar range. Immediately after the growth of the Fe film, it is dosed with 3 to 5 L O_2, in our case this is done for 60–100 s at 3×10^{-8} mbar. At this oxygen coverage, the Fe(001)–$p(1\times1)$O surface structure is expected to form.[16] Finally, the sample is heated to about 600 K to anneal the film and desorb excess oxygen. A complete preparation cycle takes less than 15 min.

III. CHARACTERIZATION

In the spin detector, we measure the normalized intensity asymmetry A by counting the electrons that reach the back channeltron when the Fe film magnetized either parallel ($\rightrightarrows$) or antiparallel ($\rightleftarrows$) along the spin quantization axis.

$$A = \frac{I_{\rightrightarrows} - I_{\rightleftarrows}}{I_{\rightrightarrows} + I_{\rightleftarrows}}. \tag{1}$$

These two measurements necessarily have to be carried out at successive times and the time difference has to be kept short enough as to minimize the influence of intensity variations. From the measured asymmetry A, one determines the spin polarization component P along the magnetization axis as

$$P = A/S, \tag{2}$$

where S is the spin sensitivity (also called Sherman function with Mott detectors), which describes which asymmetry A the spin detector would measure for a completely polarized beam with $P=1.0$.

If one assumes that the intensity variations of the electron beam to be analyzed are approximately linear in time, this can be taken into account by adopting a special measurement sequence. The counts in the back channeltron are measured for a magnetization pulse sequence of

$$I_{\rightrightarrows}(t_1), I_{\rightleftarrows}(t_2), I_{\rightleftarrows}(t_3), I_{\rightrightarrows}(t_4), \ldots, I_{\rightrightarrows}(t_{2m-3}),$$
$$I_{\rightleftarrows}(t_{2m-2}), I_{\rightleftarrows}(t_{2m-1}), I_{\rightrightarrows}(t_{2m}) \tag{3}$$

and then forming the sums for calculation of the asymmetry:

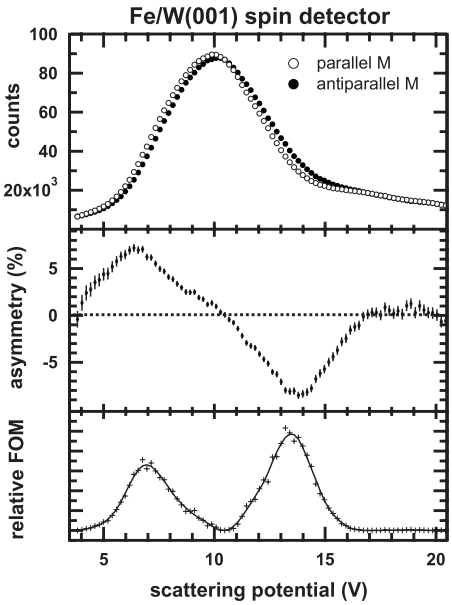

FIG. 4. Measured intensity (top) and asymmetry (middle) as a function of scattering potential (this is the potential difference between the stainless steel inner cylinder of the CSA and the Fe–$p(1\times1)$O target. Up to a small work function difference between stainless steel and the target of a few tenths of an eV this corresponds to the kinetic energy of the electrons in eV). In the bottom part, the corresponding relative figure of merit (FOM) is shown, indicating optimum operation at 13.5 eV scattering energy.

$$I_{\rightrightarrows} = \sum_t I_{\rightrightarrows}(t), \tag{4}$$

$$I_{\rightleftarrows} = \sum_t I_{\rightleftarrows}(t). \tag{5}$$

Because the spin detection principle in our device does not involve different geometrical pathways to measure the two conjugated scattering intensities (e.g., a "left" and a "right" counter as in Mott or SPLEED detectors), the corresponding instrumental asymmetry due to unsymmetrical alignments is largely suppressed. In addition, the asymmetry due to a magnetic field is suppressed as much as possible by carefully designing the electromagnet and its surroundings to show a negligible remanent magnetic field. The use of a thin magnetic Fe film instead of a bulk Fe sample reduces the magnetic stray fields. In sum, this leads to a spurious instrumental asymmetry of about $\pm0.3\%$, as is measured for unpolarized electrons.

To determine the optimum scattering energy in the detector, we measured the reflected number of electrons N and the corresponding asymmetry A under reversal of the magnetization of the Fe film in the detector. The maximum of the *relative* figure of merit defined by $F_R=A^2\times N$ as a function of the potential of the scattering film then indicates the optimum working condition for the detector. This is shown in Fig. 4. The spin polarization of the measured electrons was about 30%.

To calculate the polarization from a measured asymmetry like in Fig. 4, we need to determine the Sherman function. For this purpose, we measured the low energy secondary electrons (kinetic energy of 2 eV) from a Co film grown on Cu(001) using a primary electron beam of 2 keV energy

from an electron gun. The secondary electrons are estimated to have a spin polarization P of $0.35(\pm 0.03)$. This value was determined in Ref. 17 for secondary electrons excited from Co(0001) by photons of 58 eV energy. From the measured asymmetry A of $0.085(\pm 0.005)$ with our detector, we can calculate the Sherman function $S=A/P$ to be $0.24(\pm 0.03)$ at the optimum scattering energy of 13.5 eV. A comparison with an in-plane magnetized 12 ML thick Fe film on Cu(001) resulted in an asymmetry of 0.075 for the low energy secondary electrons measured at 120 K. With our calibration of the spin sensitivity ($S=0.24$) we arrive at 31% for the spin polarization of the Fe film, in good agreement with the values of 25%–35% reported in the literature for this system.[18,19]

We additionally cross-checked our spin sensitivity with two-photon photoemission measurements from Co films on Cu(001), which are expected to show a spin polarization of about 45%–60% when excited with p-polarized optical pulses of 3 eV photon energy.[20,21] Using our spin detector, we observe an asymmetry of 0.15 at a binding energy −0.5 eV below the Fermi level, which would translate into a Sherman function between 0.23 and 0.30 for the mentioned values of the spin polarization, which is in good agreement with the value obtained from the secondary electron spin polarization measurements.

We have found that our detector shows a reproducible asymmetry over at least 2 weeks without any repreparation. This is due to the chemical inertness of the Fe surface with chemisorbed oxygen and has been also observed in other applications of this system.[11] This is a major advantage for long-term experiments with intrinsically low count rates.

To compare our spin detector quantitatively to other devices, we estimate the figure of merit F which determines the counting time needed to reach a given statistical error in the spin polarization.[1] The statistical figure of merit is determined by the Sherman function S and the relative intensity response I/I_0 (which describes how many incident electrons are needed for one detection event):

$$F = S^2 I/I_0. \tag{6}$$

From this formula it can be seen that a spin detector is desired to show a large Sherman function as well as a high intensity response, while a relative improvement of the Sherman function is potentially more efficient in decreasing the required counting time.

An upper bound for the intensity response I/I_0 can be gained from the relative counting rates in the direct channeltron ($\approx I_0$) without the scattering crystal, and the counts in the back channeltron (I) with the scattering crystal in the path. We observe that I_0 is a factor of 13 higher than I at maximum, corresponding to $I/I_0 \approx 0.076$ at the scattering potential of 13.5 V. Since we do not measure the incident current at the position of the detector crystal but several centimeters downstream, there might be fewer electrons arriving at channeltron D than at the crystal.

In the literature, a value of $I/I_0 \gtrapprox 0.10$ is reported for clean Fe(001)/Ag(001) (Ref. 13) and a value of 0.06 for Fe(001)$-p(1\times1)$O.[10] Assuming $S=0.24$ and $I/I_0=0.076$ and taking into account that it is necessary to perform two sequential measurements with reversed Fe film magnetization, we arrive at $F \approx 2.2\times10^{-3}$ for the figure of merit of our detector. This value is consistent with Hillebrecht *et al.*,[13] where a lower limit of about 1×10^{-3} has been estimated (with a maximum of up to 10×10^{-3}) and with Bertacco *et al.*[11] who report 0.7×10^{-3} for their combination of energy analyzer and detector. These lower limit values show that the detection principle based on exchange scattering at an Fe surface is about one order of magnitude more efficient than the Mott and the SPLEED detectors.[5,6] It has to be kept in mind, however, that the high efficiency in spin analyzers of the presented design is available only in a limited energy range. This means that this type of spin analyzer is best suited for electron spectroscopic experiments which anyway detect a limited bandwidth of electron energies, e.g., using electrostatic energy analyzers. In cases where a broader range of electron energies is to be analyzed by the spin detector (e.g., secondary electrons without energy analysis), other types of detectors might be more favorable.

IV. DISCUSSION

Among the class of spin polarization detectors with energy analysis and single-electron detection, two devices have been described based on exchange scattering: one by Bertacco *et al.*[11] and the other by Hillebrecht *et al.*[13] Among these, the detector of Bertacco is closest to ours and we therefore discuss similarities and dissimilarities compared to our detector. Both use Fe(001)$-p(1\times1)$O which shows extraordinary time stability, as is confirmed by our results. Bertacco *et al.* use thick epitaxial Fe films on MgO, with the property that the detector can be "rejuvenated" many times by simple heating in oxygen atmosphere. A new crystal, however, is prepared in a separate vacuum system, requiring a new MgO crystal preparation. In our case, rejuvenation is not possible. We deposit Fe on W(001) at a thickness beyond the spin reorientation transition (≈40 ML). This is a metastable system with respect to high temperatures because the Fe film disintegrates into μm-sized crystallites with a 1 ML Fe carpet underneath (Stranski–Krastanov growth). Therefore, a used film must be replaced by a new one (after about 2 weeks). This is done *in situ*, within less than 15 min.

The electron reflectivity shows consistently a broad peak around 10 eV kinetic energy, with sizable polarization effects on the lower as well as the higher kinetic energy sides (Fig. 4). We work on the high energy side, while Bertacco *et al.* prefer the low energy side. In their test measurements with an elastic reflection of a well defined beam[9] they found a high exchange asymmetry of up to 44%, which decreased by more than a factor of 2 in their actual device.[11] We do not find this large asymmetry either in our device. This feature seems to be extremely sensitive to unknown factors. However, the performance of our instrument in terms of figure of merit is clearly better than their instrument.[11]

Another important design consideration concerns the geometrical constraints: our combined device uses an electron spectrometer with a deflection angle of 90°. If we define the deflection plane of the analyzer by the incoming beam axis and the outgoing beam axis, an ingoing longitudinally

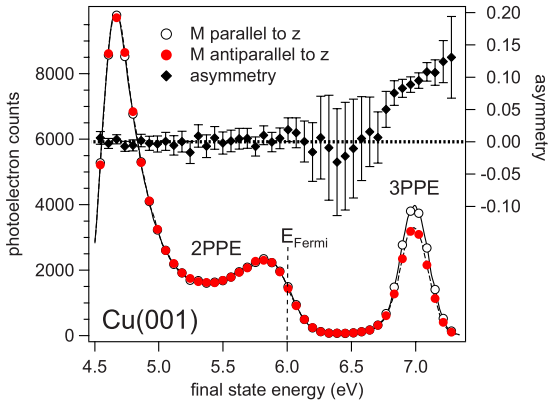

FIG. 5. (Color online) Photoelectron spectra and measured spin asymmetry for excitation of Cu(001) with circularly polarized laser pulses of $h\nu$=3.0 eV. The spin quantization axis is oriented along the surface normal z of Cu(001). Two-photon excitation is possible up to 6.0 eV final state energy, above that we see a three-photon photoemission peak at 7 eV. Electrons in this peak are spin polarized by as much as about 45%, as calculated from the measured asymmetry.

polarized beam is transformed into a transversely polarized beam while the transverse component perpendicular to the deflection plane of the analyzer stays perpendicular. By virtue of our rotatable detector crystal, both these components can be measured. A transverse component in the deflection plane cannot be measured. However, if the whole device (energy analyzer plus detector) is rotated by 90° about the axis of the incoming beam, the remaining component can be measured. The longitudinal component is then measured redundantly. The device is sufficiently lightweight and compact to be mounted on a differentially pumped rotary platform (100 mm inner diameter). In this way, the full polarization vector of the beam (arbitrarily oriented in space) can be measured. This is not possible with a 180° degree deflector, such as used in Refs. 11 and 13 because the longitudinal component stays orthogonal to the in-plane magnetization of the detector crystal, but, alternatively, the other detectors could, in principle, be also be used with a 90° degree deflecting analyzer.

As an application of our spin detector, we show in Fig. 5 a photoelectron spectrum from a Cu(001) surface which was excited by ultrashort circularly polarized laser pulses with a photon energy of 3 eV. The energy resolution of the energy-analyzer/spin-detector combination was set to 150 meV. Because the work function of Cu(001) is about 4.6 eV, these electrons must have absorbed the energy of at least two photons to leave the sample. With two photons, electrons initially at the Cu(001) Fermi level can be excited up to 6 eV above the Fermi level, which is where the Fermi edge is visible in the final state energy scale of Fig. 5. Beyond the two-photon Fermi edge, we see a peak at 7 eV which is due to a resonant three-photon transition of electrons from the Cu d bands via unoccupied sp bands and the n=1 image-potential state.[22] Using our spin detector, we have been able to show that the d band electrons excited by three circularly polarized photons are spin polarized.[23] This can be seen in Fig. 5 where the measured asymmetry for the spin quantization axis along the surface normal z of the Cu(001) sample is shown as black diamonds. The origin of the effect is the spin-orbit interaction in the Cu d bands which in connection with the optical selection rules for circularly polarized light leads to the excitation of spin-polarized electrons even from nonmagnetic materials such as Cu.[24] In contrast, the photoelectrons excited from clean Cu(001) by only two photons (energies up to 6 eV in Fig. 5) originate from initial states in the sp band near the Fermi level. These initial states are not influenced by the spin-orbit interaction and thus the measured two-photon part of the spectrum in Fig. 5 does not show a spin polarization.

By our observation we have demonstrated a way to excite spin polarized electrons into unoccupied image-potential states of a nonmagnetic surface. Moreover, the excitation of spin-polarized electrons by circularly polarized ultrashort laser pulses at an extremely well-defined system such as clean Cu(001) might provide a reliable standard for calibration purposes.

Summarizing, we have designed and characterized a compact and reliable spin detector with excellent long-term stability based on the scattering of very low energy electrons on ultrathin Fe films on W(001). This instrument has been built in 1999 and has operated satisfactorily ever since.

ACKNOWLEDGMENTS

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