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MASTER**MEASUREMENTS OF SPUTTERING YIELDS
FOR LOW-ENERGY PLASMA IONS**

BY

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MEASUREMENTS OF SPUTTERING YIELDS FOR LOW-ENERGY PLASMA IONS

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ABSTRACT

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Sputtering yields of various wall/limiter materials of fusion devices have been extensively measured in the relevant plasma environment for low-energy light ions ($E < 300\text{eV}$). As a plasma source we have used an energetic arc device (QED-1 machine) in which hydrogen, deuterium, helium and argon plasma can be generated with a density of up to 10^{14}cm^{-3} and electron temperature up to 10eV . Target materials used were C (graphite), Ti, Mo, Ta, W and Fe (stainless steel). In order to study the dependence of the sputtering yields on the incident energy of ions, the target samples were held at negative bias voltage up to 300V . The sputtering yields were determined by a weight-loss method and by spectral line intensity measurements. The data obtained in the present experiment agree well with those previously obtained at the higher energies ($E \geq 200\text{eV}$) by other authors using different schemas; the present data also extend to substantially lower energies ($E \geq 30\text{eV}$) than hitherto.

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I. INTRODUCTION

The control of impurities in plasma is well recognized to be one of the most essential requirements for attaining the breakeven conditions in magnetically confined fusion devices. Mechanisms responsible for generation of impurity atoms in such devices have been investigated for many years, and the phenomenon of sputtering has been found to play an important role in the interaction of plasmas with wall and limiters in present tokamaks [1-3].

Sputtering data have been accumulated for a long time [1], and such data help us to understand the mechanism of impurity flow into tokamak plasmas. Existing data for sputtering are mainly for high-Z ions or high-energy low-Z ions, where as, the edge ion temperature in present tokamaks, which is strongly correlated with the impurity level, is low (50-100eV,) and the bulk of plasma ions are H^+ or D^+ . Thus data relevant to present tokamak conditions are very scarce, making it difficult to elucidate the impurity problem in tokamaks conclusively.

Sputtering yields for low-energy ions have been investigated by several groups in past decades. Laegreid and Wehner [4] have measured sputtering rates of Ar^+ and Ne^+ ions in the energy range 50 to 600 eV using metal targets. Stuart and Wehner [5] have determined experimentally the threshold energies for sputtering rates of heavy ions such as Ar^+ , Ne^+ , Kr^+ , Xe^+ and Hg^+ on metals. Sputtering data of low-energy low-Z ions have recently been collected by Roth et.al. [6-8] and Sone

for Mo, stainless steel and graphite, and threshold energies for D^+ and H^+ ions have been obtained experimentally [8]. Rosenberg and Wehner have also investigated the sputtering phenomenon using He^+ ions with energies of 100eV to 600eV [10].

In this paper, we present extensive sputtering data for low-energy low-Z ions against materials used in tokamak walls, limiters and divertor collectors. In the present experiment we have used the energetic arc device at PPPL (QED-1) [11] to generate the source plasma with density up to 10^{14} cm^{-3} and with electron temperature of up to 10eV. Target materials used were C(graphite), Ti, Mo, Ta, W and Fe (Stainless steel). In order to study the dependence on the incident energy of ions, the samples were negatively biased up to 300 V. The sputtering yields were determined by a weight-loss method and by spectral line intensity measurements.

The experimental set up and the methods of measurement of the sputtering yield are described in Section II. In section III, we present the experimental results, together with an interpretation of these results and considerations on possible error sources. Finally, the relation of the edge ion temperature to the impurity influx in the PLT (Princeton Large Torus) device is discussed in terms of the sputtering yield obtained in the present experiment.

II. EXPERIMENTAL PROCEDURES

The main reason why data are so scarce for low-energy low-Z ions is that their sputtering yield is very low, and, therefore, is difficult to measure. In the present experiment, use of a dense plasma source has removed this difficulty.

The experimental setup is shown schematically in Fig. 1. A linear hollow-anode, arc-discharge was used as a plasma source. The Princeton's QED-1 (Quiet-Energetic Dense) device [1], can provide a hot ($T_e \approx 1\text{--}10\text{eV}$) isothermal, current-free plasma with an arcjet plasma gun. In this machine, 1-2 cm-diameter plasma streams along the magnetic field into a burial chamber where the plasma recombines on the neutralizer plate and the resulting neutral gas is pumped away. High speed differential pumping ensures low background pressure in the experimental region, and thus uniform plasma. A plasma density of $n_e = 10^{12}\text{--}10^{14}\text{ cm}^{-3}$ and temperature of $T_e = 1\text{--}10\text{eV}$ were obtained for various noble gas discharges, H_2 , D_2 , He, Ar. The anode of the arcjet gun is made of oxygen-free hard copper with a 1.6 mm thick wall between the vacuum and water cooling channel. The cathode is 3% thoriated tungsten, 9.5 mm diameter, the same dimension as the anode orifice.

In our experiment, the plasma column has a diameter of 1.5 cm. The base pressure in the vacuum vessel was kept below 2×10^{-6} torr before the operation. The pressure during plasma discharges was of the order of 10^{-4} torr. Concentration of impurity atoms and molecules in the plasma was monitored using a spectroscopic method. Without insertion of target samples, the impurity concentration of the flowing

plasma was negligibly small (less than 0.1%). The degree of ionization in the hydrogen plasma has also been checked by the means of probes and spectroscopy, and the plasma was found to be almost fully ionized in the target area.

Samples used were made of typical tokamak wall/limiter material such as C, Ti, Mo, Ta, W and Fe, (SS 304). The dimensions of the sample were 38 mm in diameter and 0.5 mm in thickness. No special treatment was made for conditioning the surface of the sample. In each run four target samples were mounted on a copper sample holder which was air-cooled during the plasma bombardment. Samples were mounted on the holder by two or four screws for each sample. The surface temperature of the sample was frequently monitored using a pyrometer, and it was found that its maximum temperature under normal operational conditions was about 800° C, while that of the holder itself was measured to be about 150° C by thermocouples.

Samples were negatively biased up to 300V in order to measure sputtering yields as a function of incident energy of ions. It is well known that when the collector plate is biased negatively with respect to the plasma potential, a sharp voltage drop occurs in a sheath region of the order of a Debye length ($\ll 1\text{mm}$) [12]. Even if the bias voltage is increased by an order of magnitude, the plasma temperature and the density remain the same except inside the thin sheath region in front of the target. In most of the operation conditions, no sign of arcing was observed between the plasma and target samples. The ion flux to the sample was obtained

by measurement of the current running through the sample holder. The ion current was controlled by changing the plasma density and the feeding rate of gas (T_e , n_e) and was kept below 1.5A. The heat load on the sample was less than 150 W.

In the weight-loss method for obtaining sputtering-yield data, the change in weight of the sample due to the plasma bombardment is measured directly. The sputtering yield, η , is given by

$$\eta = \frac{\Delta w}{M_o} \frac{N_o}{I_{io}} \frac{1}{\tau} \quad (1)$$

where Δw , M_o , N_o , I_i , and τ are the change in weight, the atomic mass number of the sample, the Avogadro number, the total flux of ions, and the duration time of the bombardment respectively. The values for Δw and τ were typically 0.1-5mg and $10^2 \sim 10^3$ sec. respectively. The ion (positive) current j measured in the present experimental set up is expressed as follows;

$$j = (1' + \gamma) e I_{oi} = (1 + \gamma) \bar{n}_e e V_d A \quad (2)$$

Here I_{oi} is the actual influx of ions from the plasma, γ the secondary electron emission rate which depends on the material as well as the kind of energy of the incident ion, $\bar{n}_e$ the average density of electrons, V_d the drift velocity of the plasma ($\leq \frac{1}{3} \sqrt{\frac{T_e + 3T_i}{M}}$), and A the cross section of the plasma column. In the case of a helium or argon plasma, Eq.(2) has

to be modified by taking into account the concentration of multiply-ionized ions. But in all of the present operating conditions, almost all the ions (>95%) are singly ionized. In the recent experimental conditions, the electron density of $\sim 10^{13} \text{ cm}^{-3}$ and the electron temperature of 2eV in the hydrogen plasma yield a total ion current of 1.5A. The correction factor, α , for secondary electrons is of the order of 0.1.

The weight-loss method was used primarily for calibration purposes; measurements were carried out for at least twice for each combination of the plasma ion, and target material and applied bias. Reproducibility in this measurement was found to be satisfactory (within 20-30% error).

The spectroscopic method was used for relative measurement of sputtering yields. Under condition of constant electron density and temperature, intensity of an spectral line from atoms of a particular kind in front of the target is directly proportional to the density of such atoms. The electron density was frequently monitored and the appropriate compensation was made when n_e changed with an increase of ion-acceleration voltage. The constant electron temperature along the column was ensured because electron's heat conduction was high. No significant differences among the data for different atomic lines was found, although the excitation and ionization energies for atoms and ions emitted these lines were different. This was additional proof n_e and T_e remained constant. (under changes of bias voltage).

The **monochromator** used was a 0.5m Farrell-Ash Ebert-Fastie type, with a resolution of about $1 \text{ \AA}$. In most cases the collimator was adjusted to look at the plasma about 5 mm from the surface of the sample. The collimator axis was set perpendicular to the plasma axis, and therefore, parallel to the sample.

As a check on the present spectroscopic method for determining the sputtering yields and to investigate the backflow of the sputtered material, we have performed a measurement of the neutral and ion line intensities of the sputtered material along the plasma column. Fig. 2 presents the line-intensity from the neutral and ionized molybdenum atoms [$\text{MoI}(4810\text{\AA})$, $\text{MoII}(2853\text{\AA})$] as a function of distance from the target surface along the plasma column. The solid curve was calculated on the assumption that all sputtered atoms were emitted isotropically from the 5 mm radius sample surface, in considerably good agreement with the experimental data. Furthermore the data shows that the back flow of sputtered-then-ionized target atoms was too small to affect the present data [See-MoII lines]. The self-sputtering effect can thus be neglected in most of the present conditions. The calculation of the mean free path for ionization of the sputtered atoms ($>50\text{cm}$) and the poor confinement of heavy ions ensure this conclusion.

The spectroscopic method was applied successfully to most plasma/target combinations; the exceptions were hydrogen or deuterium plasma with W or Ta, in which cases the sputtering rate was very low and there was an absence of very strong lines for the target material. In these cases the weight-loss method was only used.

III. RESULTS AND DISCUSSIONS

Results are shown in Fig. 4 to 9 for target materials C (graphite), Ti, Mo, Ta, W and Fe (SS 304). Results obtained by other authors are also shown in these figures for comparison and good agreement is found in the higher energy region. In most cases the spectroscopic measurements were fully utilized to obtain a parametric dependence of the sputtering yield on the incoming ion energy (bias voltage). The following lines were used; CI 2478Å, CII 2837 Å, FeI 3737Å, FeI 2736Å, MoI 3798Å, MoI 4760Å, MoII 2816Å, TaI 2844Å, TaI 2940Å, TiI 4679Å, TiI 5064Å, TiII 5189Å, WI 3294Å, WI 4234Å.

Sputtering data of Ar^+ and He^+ are in good agreement with those obtained by Wehner et al. [4,10]. Titanium shows a very small sputtering yield for low-energy protons. Data for stainless steel samples indicate that the sputtering yield is generally higher than that of Ti. Our results for H^+ plasma are larger by a factor of two than those obtained by Bohdansky et al. [7], while results for the other plasmas show very good agreement with previous data.

We estimate the threshold energy for sputtering by linear extrapolation with secondary-electrical-yield (γ) correction of the yield curves to zero sputtering yield, although the shape of the yield curve near the threshold is unknown. The results are summarized in Table I. The errors shown in the Table were deducted by taking into account all the possible curves that could be drawn for each linear fitting. Our data agree in general with those of other authors [5,8] and the

predicted value based on the maximum energy transfer from incident ion and the sublimation energy E_s of the materials [13], i.e.,

$$E_{th} = \frac{(M_1 + M_2)^2}{4M_1M_2} E_s \quad [3]$$

where M_1 , M_2 are the mass numbers of bombarding ions and target atoms. Our results for H^+ and D^+ on W and Ta are small compared with both the experimental values of Bay et. al., [8] and the estimated value by Eq. [3]. The present results for H_e^+ and Ar^+ show good agreement with those obtained by Stuart and Wehner [5].

In the case of deuterium plasma bombarding a graphite (C) plate, one expects dominant effects of chemical sputtering. [Fig. 9] The intensity of a carbon line (CI 2478 Å) was very large when the applied bias was more than 60 V, while below this voltage it decreased by a factor of 5. In this measurement, with large ion current into the sample, the heat flux was unusually high. The surface temperature of the sample was estimated to be about 800°C for 60 V bias, and so the enhanced carbon yield may have been caused by chemical sputtering [9]. Since it was difficult to keep the sample near room temperature in our experimental setup, reliable measurement of physical sputtering yields for deuterium and hydrogen plasma could not be carried out.

There are several factors to be considered which might introduce errors into the results; (1) impurity ions in the plasma, (2) self-sputtering, (3) effect of multi-charged ions,

(4) effect of di-atomic ions, (5) evaporation, (6) energy distribution of the ions in the plasma, (7) reproducibility in the weight-loss measurement, (8) effect of secondary electron emission in the measurement of the plasma current, and other effects like arcing.

We have investigated all these factors experimentally. Below we discuss them although some of them were already discussed in Section II.

Impurity ions with heavier mass than the main component ions might increase the sputtering rate. They could especially have large effects on the data from light-ion plasmas, i.e., hydrogen and deuterium plasma. As mentioned earlier, spectroscopic measurement showed that the impurity concentration was less than 0.1%. The contribution of impurity ions to the sputtering yield is estimated to be not more than order of 10^{-5} in absolute scale.

The phenomenon of self-sputtering might also introduce systematic error into the results. The mechanism of self-sputtering is, as follows; sputtered atoms are ionized in the plasma, flow back to the sample, and hit it after acceleration in the sheath. Therefore, it is necessary to check how large a fraction of sputtered atoms flow back to the sample. The concentration of sputtered atoms in the plasma was measured as a function of the distance from the sample by the use of the spectroscopic method, and it was concluded that the back-flow was not large enough to affect the sputtering yield measurements. (Fig. 2).

The effect of multi-charged ions could be a problem in He or Ar discharges. In a helium plasma, however, discharge voltage was typically 42 V well below the second ionization potential of He (54.4 V) and the electron temperature was too low to provide doubly ionized ions. In the Ar plasma all of the strong lines observed have been identified as Ar I and Ar II lines. Therefore, the effect of multi-charged ions in the Ar discharge should be considered small.

The presence of di-atomic ions such as H_2^+ or D_2^+ might lead one to underestimate the sputtering yield because the effective energy of such ions is half that of the normal H^+ or D^+ ions. A measurement of the relative intensities of molecular ions (H_2^+) and atomic (H^+) spectral lines shows that di-atomic ions play a negligible role in this experiment.

Fig. 7 shows that the sputtering yields for deuterium on a tungsten target are smaller than those for hydrogen. This observation is inconsistent with data for other materials as well as with data for higher ion energies by other authors [2]. The reproducibility of this data has been carefully checked with satisfactory results. This result is yet to be explained.

Evaporation becomes important when the sample temperature goes up to near the melting point of the material. But, if the sample temperature is below $2/3$ of the melting point temperature, evaporation contributes less than 10^{-5} of the measured sputtering yield in our experimental conditions. During the experiment the surface temperature of the sample was monitored from time to time and found to be around 800°C .

at most. This temperature is well below the critical value mentioned above for stainless steel whose melting point is the lowest in the materials used in this experiment.

If the distribution of bombarding ion flux were broad in energy space, it would be more difficult to deduce the sputtering yield with respect the bombarding energy. In the present experimental condition of $V_{\text{sheath}} \gg \frac{T_i}{e}$ ($T_i \approx 3\text{eV}$), the ion energy distribution can be safely assumed to be monoenergetic due to the fact that a sheath acceleration reduces the ion temperature by a factor $T_o/2eV_{\text{sheath}}$. [14].

In the PLT Tokamak a strong correlation has been found between high-Z impurity concentrations and the ion edge temperature. Tungsten line radiation (the limiter material being tungsten) becomes observable when the edge ion temperature is above 40eV, and it increases quite rapidly with increasing temperature [15,16]. (Similar correlation was observed in the case of an iron limiter). Simultaneous measurements of electron and ion temperature at the plasma edge indicate good quantitative correlation. This evidence supports a notion that the incident energy of ions onto the limiter is about three times as high as the edge ion temperature due to a sheath acceleration. In Fig. 10, are presented (from Ref. 15) intensities of tungsten radiation from a PLT deuterium plasma, measured in the VUV region as a function of ion energy E , assuming $E \approx 3T_i$ ($T_e \approx T_i$ at edge). The curve for the PLT data was normalized to our sputtering yield curve at $E \approx 150\text{eV}$. One can see very good functional agreement between the PLT data curves and our sputtering data.

The density of W ions was typically 10^{10} cm^{-3} in PLT discharges with a tungsten limiter. This value can be roughly explained by our results, assuming that (i) the sputtering occurs primarily due to bombardment by hydrogen or deuterium atoms and (ii) the particle confinement time of tungsten ions in the plasma is 50-100msec, although there still remains an uncertainty of a factor of two in the quantitative comparison.

In conclusion, sputtering yields of various wall/limiter materials of fusion devices have been intensively measured in the relevant plasma environment for low-energy light ions ($30\text{eV} < E < 300\text{eV}$) for the first time. The result agree well with those previously obtained at the higher energies ($E > 200\text{eV}$) by other authors using different schemes. Furthermore the relation of the edge plasma temperature to the impurity influx in the PLT device has been explained in terms of the sputtering yield obtained in the present experiment.

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REFERENCES

- ¹Behrisch, R., Proc. of the Summer School 1976 of Tokamak Reactors (Erice, Italy, 1976) and references therein.
- ²Scherzer, B.M.U., Behrisch, R., and Roth, J.
Proc. Int. Symp. on Plasma-Wall-Interaction. (Julich, Oct. 1976). EUR 5782 e (Pergamon Press, New York, 1977)
- ³Kaminsky, M., Proc. 7th Int. Conf. on Atomic Collisions in Solids (Moscow); September 1977)
- ⁴Laegreid, N., and Wehner, G.K., J. Appl. Phys. 32 (1961) 365.
- ⁵Stuart, R.V., and Wehner, G.K., J. Appl. Phys. 33 (1962) 2345.
- ⁶Roth, J., Bohdansky, J., and Hofer, W.O., Plasma Wall Interaction (Proc. of the Int. Symp. on Plasma-Wall-Interaction, Julich, 1976) (Pergamon Press, New York, 1977).
- ⁷Bohdansky, J., Boy, H.L., and Roth, J., Proc. of the 7th Int. Vacuum Congress and the 3rd Int. Conf. on Solid Surfaces. (Vienna, Sept. 1977).
- ⁸Bay, H.L., Roth, J., and Bohdensky, J., J. Appl. Phys. 48 (1977) 4722.
- ⁹Sone, K., Ohtsuka, H., Abe, T., Yamada, R., Obara, K., Tsukakishi, O., Narusawa, T., Satake, T., Mizuno, M., and Konuya, S., Plasma Wall Interaction (Proc. Int. Symp. on Plasma-Wall-Interaction, Julich, 1976) EUR 5782e (Pergamon Press, New York, 1977)
- ¹⁰Rosenberg, D., and Wehner, G.K., J. Appl. Phys. 33 (1962) 1842.

- ¹¹Owens, D.K., and Yamada, M., to be published, PPPL 1520
- ¹²Bohm, D., in "The Characteristics of Electrical Discharges in Magnetic Fields, edited by Guthrie, A., and Wakerling, R.K., (McGraw-Hill, Inc., New York 1949) Chap. 9
- ¹³Hotston E., Nucl. Fusion 15, 544, (1975)
- ¹⁴Sato, N., Sugai, H., and Hatakeyama, K., Phys. Rev. Lett 34, 931 (1975).
- ¹⁵Suckewer, S., Hawryluk, R., Phys. Rev., Lett. 40, 1979 (1978)
- ¹⁶Hinnov, E., Bol, K., Hawryluk, R., Meservey, E., Suckewer, S., Review Meeting, Princeton, May 1978, to be Published.

FIGURE CAPTIONS

Fig. 1. Schematic drawings of the QED-1 device (1a) and the target arrangement (1b). Plasma Parameters
 $(n_e \leq 5 \times 10^{13} \sim 2 \times 10^{12} \text{ T}_e \leq 6\text{eV} \text{ . diameter} = 1.5 \text{ cm.}$
 Energy input to the samples $1\text{W} \sim 100\text{W}/\text{cm}^2$

Fig. 2. Line-intensity from MoI, MoII versus distance from the sample (Mo) surface. The solid curve was based on a model of isotropic (uniform) emission of MoI atoms from 5mm radius sample.

Fig. 3. Sputtering yields for graphite of Ar^+ (●), and He^+ (◆) ions. Open circles were obtained by Rosenberg and Wehner (10).

Fig. 4. Sputtering yields for Ti of Ar^+ (●), He^+ (◆), D^+ (■), and H^+ (▲) ions. Open circles were data obtained by Laegreid and Wehner (Ar^+) [4], and Rosenberg and Whhner (He^+) (10).

Fig. 5. Sputtering yields for Mo of Ar^+ (●), He^+ (◆), D^+ (■), and H^+ (▲) ions. Open circles were data obtained by Laegreid and Wehner (Ar^+) (4), Rosenberg and Whhner (He^+) (10), Ray et al. (D^+) (8), and Sone et al. (H^+) (9).

Fig. 6. Sputtering yields for Ta of Ar^+ (●), He^+ (◆), D^+ (■), and H^+ (▲) ions. Open circles were data obtained by Laegreid and Wehner (Ar^+) (4), and Rosenberg and Wehner (He^+) (10).

Fig. 7. Sputtering yields for W of Ar^+ (●), He^+ (◆),

FIGURE CAPTIONS

D^+ (■) and H^+ (◆) ions. Open circles were data obtained by Laegreid and Wehner (Ar^+) (4), and Rosenberg and Wehner (He^+) (10).

Fig. 8. Sputtering yields for SS 304 of Ar^+ (●), He^+ (◆), D^+ (■) and H^+ (▲) ions. Open circles were data obtained by Laegreid and Wehner (Ar^+) (4), Rosenberg and Wehner (He^+) (10), and Bohdanský et al. (D^+, H^+) (7).

Fig. 9. Relative sputtering yield of Carbon Atoms by D^+ bombardment with respect to the bias field. Also shown are values for heat loads (●) on the sample.

Fig 10. Comparison of PLT data with the present sputtering data. (closed circles) plotted vs: bombarding ion energy E_i (eV). PLT data curve is normalized at $E_i = 150$ eV with an assumption of $E_i \approx 3T_e$ ($\approx 3T_i$) .(Ref.[15]).

Table 1. Measured threshold energy for sputtering.

*In the cases of H^+ , D^+ and C, data for physical sputtering are not available because of dominant chemical sputtering.

Table 1. Measured Threshold Energy for Sputtering

Target Material Bombarding Ion	Ti	Fe(SS)	Mo	Ta	W	C
H^+	$80 \pm 10 \text{ eV}$	$80 \pm 10 \text{ eV}$	$100 \pm 25 \text{ eV}$	$90 \pm 10 \text{ eV}$	$100 \pm 30 \text{ eV}$	*
D^+	50 ± 10	51 ± 10	55 ± 15	60 ± 15	110 ± 25	*
H_e^+	32 ± 5	38 ± 10	50 ± 10	52 ± 10	50 ± 10	$44 \pm 10 \text{ eV}$
Ar^+	19 ± 3	24 ± 5	35 ± 5	32 ± 5	28 ± 5	34 ± 5

QED-1 CONFIGURATION

Fig. 1a. 786156

Fig. 1b. 786155

Fig. 2. 793175

Fig. 3. 786162

FIG. 4. 786158

Fig. 5. 786160

Fig. 6. 786159

Fig. 7. 786157

Fig. 8. 786161

Fig. 9. 786154

Fig. 10. 793194

ALL CATEGORIES

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EXPERIMENTAL
THEORETICAL

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