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Laser-Electron-Gamma-Source*

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D. H. Dowell, B. Fineman, G. Giordano[†], O. C. Kistner, G. Matone,
A. M. Sandorfi, C. Schaerf[†], C. E. Thorn, and W. Ziegler

Physics Department
Brookhaven National Laboratory
Upton, New York 11973

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[†]Present address: INFN-Laboratori Nazionali di Frascati, Italy

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1. FACILITY

When completed, the Laser Electron Gamma Source (LEGS) will provide intense beams of monochromatic and polarized (circular or linear) gamma rays with energies up to 500 MeV. The layout of this facility with its experimental areas is shown in Fig. 1. The gamma-ray beams will be produced by Compton backscattering UV laser light from the electrons circulating in the

Figure 1: Layout of the LEGS facility now under construction.

2.5-3.0 GeV "X-RAY" storage ring of the National Synchrotron Light Source (NSLS) at BNL. The beams will be tagged by detecting the scattered electrons in a spectrometer incorporated into the storage ring. The gamma-ray beam production is described in detail in ref. 1 and 2.

2. PROGRESS WITH INSTALLATION

The first stages of the installation of LEGS began in December of 1985 with the modifications to the shielding walls of the x-ray ring, providing access to the dipole magnet immediately following the interaction straight section, and a separate enclosure for the focal plane of the tagging spectrometer. This was completed in June, 1986. There will be three colinear target areas for basic medium-energy nuclear physics research at LEGS, one in the existing NSLS building, and two in a new addition. The construction of this new building addition began in January of 1986, is presently on schedule, and should be completed by October, 1986. The new building includes a 32 ft. diameter goniometer area which will accommodate a planned magnetic spectrometer, a 12 ft. diameter target area, a remote shielded beam dump, computer and data acquisition rooms, overhead cranes, and the usual amenities. The third target area inside the original NSLS building accommodates equipment within a circle of approximately 10 ft. diameter.

The installation of the first laser (Ar-Ion) on the experimental floor of the NSLS has just begun. For high luminosity it will be necessary to ensure that the laser and electron beams are colinear. To achieve this, the laser system has been completely computer controlled and can now position its beam to an accuracy of 10 micrometers and 10 microradians. For comparison, the electron beam reaches a waist (2 sigma) of 800 x 52 micrometers in the center of the interaction straight section, with horizontal and vertical divergences

of 243 and 78 microradians, respectively.

The tagging spectrometer for LEGS is a 3DQD system, the first element of which is one of the ring dipoles. The crucial components of this system are shown in Fig. 2. The first magnetic element associated with the spectrometer will be installed at the end of August, 1986. This is a beam line sextupole that has been modified to provide a large gap between the poles and the return yoke (SD in Fig. 2). The tagging electrons will pass through this gap on their way to the focal plane. The installation of the main tagging-spectrometer components awaits a major shutdown of the ring in which the vacuum chambers can be changed. This had been scheduled for 1985, but was postponed by the NSLS because of problems encountered in commissioning the storage ring. The X-Ray ring is now operating in a user mode and no further

Figure 2:
FIRST 3 ELEMENTS OF TAGGING SPECTROMETER

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LEGS

delays are expected. The shutdown to install the LEGS vacuum chambers and tagging spectrometer components, along with equipment in four other straight sections of the ring, will begin in January, 1987. We will begin to look at the first gamma-ray beams from LEGS while the ring is being recommissioned the following summer. Regular operation is expected by the fall of 1987.

3. TESTS OF TAGGING SPECTROMETER COMPONENTS

Cancellation of the tagging spectrometer's leakage fields at the position of the electron beam is critical for operation of the storage ring. To maintain this cancellation at high fields, the two dipoles D2 and D3 in Fig. 2 are septum magnets made of HyperCO-50/Vanadium Permendue, a 49% Iron - 49% Cobalt - 2% Vanadium alloy that maintains very high permeability at high fields. The design of the septa are quite unconventional, in that they have been taken outside the magnet gap and increased in height to about six times the gap. The height of the septum has been chosen to cancel the quadrupole component of the residual leakage field at the position of the stored beam. The first septum magnet (D2 in Fig. 2) has a gradient of 300 gauss per centimeter while the second (D3) has flat poles. D2 was tested this March, and achieved 22 kilogauss peak field in the gap with a leakage field that is never more than 7 gauss anywhere outside the magnet and falls to only 2 gauss at 3 cm from the front face--the expected position of the stored electron beam. This sets a new record for DC septum magnets. A set of trim coils has been constructed to further improve residual field cancellation, but may prove unnecessary. The second septum magnet, D3, is being assembled and should be tested by the end of the summer. A second set of pole tips for D3 will also be constructed and will provide a 200 gauss per centimeter gradient. This will allow the tagging spectrometer to be operated in an energy-loss mode with

a future tune of the ring.² A large bore, low gradient magnet quadrupole, and a modest field conventional dipole (neither are shown in Fig. 2) complete the tagging system.

The position of the tagging electron on the spectrometer focal plane determines the corresponding gamma-ray energy, provided that the energy of the primary stored beam is known to sufficient accuracy. However, this is rarely the case with synchrotron light sources. LEGS will use a second laser back-scattering process, a CO₂ laser mounted near the center of the straight section, to calibrate the ring energy. The CO₂ light colliding with the stored beam at 145° will produce 1 MeV gamma rays at 0° which are simple to detect with high resolution. This laser has been purchased and tested, and its associated optics and computer controls are being fabricated.

4. A SECOND LASER FOR HIGHER ENERGY OPERATION

The laser now being installed at LEGS has an Argon-Ion cavity tuned to the 351.1 nm wavelength line. This will produce a maximum γ -ray energy of 300 MeV with the X-Ray storage ring running at 2.5 GeV and 420 MeV when the X-Ray ring reaches 3.0 GeV. A planned second phase of LEGS originally called for the construction of a higher-powered Ar-Ion laser to increase the γ -ray flux, while relying for high energies on a Free-Electron Laser (FEL) which was being constructed on the VUV ring. Since the FEL project has come to a standstill, the goal of this second phase has been diverted to achieving higher γ -ray energies. Since the X-Ray ring energy cannot be substantially increased, higher γ -ray energies must come from shorter laser wavelengths. However, at present there are no commercially available sources of UV laser light capable of providing the required intensity of a few watts. Second harmonic generation (SHG) in non-linear crystals has traditionally been recognized as a

technique that can reach very short wavelengths, but the very poor conversion efficiency of the available crystals has made this method impractical. However, during the past few years there has been a substantial improvement in growing good quality and larger size crystals, and this method has now become much more attractive.

For the particular application of achieving higher photon energies at LEGS, we are studying a scheme that will quadruple the infrared line of a Nd-YAG laser ($\lambda = 1.06 \mu\text{m}$) to the UV-line of $\lambda = 266 \text{ nm}$ by using two different crystals: one for the transition IR $\rightarrow$ green and another for the transition Green $\rightarrow$ UV.³ This would increase the energy of gamma-ray beams to 380 MeV at 2.5 GeV and 530 MeV at 3.0 GeV ring energy.

A joint research project with a major manufacturer of Nd-YAG lasers began in March of 1986 to test the efficiency and stability of new frequency doubling crystals. Barring as yet unforeseen complications, this new laser could be constructed, tested, and installed on LEGS by 1988.

5. EXPECTED BEAM PARAMETERS

The X-ray ring is presently operating at 2.5 GeV with injected currents of about 150 mA and lifetimes of about 3 hours. Higher energies at lower currents, and higher currents at lower energies, are both attainable, but achieving high current operation at higher energies requires changing the power supplies for the sextupoles in the ring. This will be completed during the 1987 shutdown, after which the ring should be able to reach 2.8 GeV with an injected current of about 250 mA. The timescales for reaching either 3.0 GeV or the design current of 500 mA are still uncertain.

The maximum LEGS gamma-ray energies are shown in Table 1 for the present, expected, and ultimate energies of the X-Ray ring. Although the gamma-ray

Table 1: Maximum LEGS gamma-ray energies

LASER	λ	$E_e = 2.5$ GeV	$E_e = 2.8$ GeV	$E_e = 3.0$ GeV
	(Å)	(present)	(Oct/87)	(?)
Ar-Ion	5145	210 MeV	260 MeV	300 MeV
Ar-Ion	3511	300 MeV	370 MeV	420 MeV
Nd-YAG	2660	380 MeV	465 MeV	530 MeV

spectrum extends down to zero energy, there is a lower limit of about 175 MeV on the energy that can be tagged, this limit being imposed by restrictions on the proximity of the first septum magnet (D2 in Fig. 2) to the stored beam. The spectrometer will tag all photons in the range from this limit to the maximum gamma-ray energy with no more than 3 different magnetic field settings, depending upon the dynamic range required.

Since the gamma-ray flux can often be limited, not by laser power, but by the perturbation made to the ring lifetime, the maximum tagged flux-per-MeV can be obtained by not letting the gamma-ray energy exceed the dynamic range that is required. This would be accomplished by using a laser line which will produce a maximum backscattered energy as near as possible to the energy of interest in a given experiment. For this purpose, the laser control system is being designed to allow switching between the various laser lines of Table 1 in a straightforward and routine fashion. At 2.8 GeV with 250 mA in the ring, the full tagged backscattered flux will be between $1-5 \times 10^7$ photons/sec, depending upon the laser used and upon the tune of the storage ring.

The energy resolution in the tagged gamma-ray beam is entirely limited by the energy spread of the electrons in the storage ring. With the standard tune of ring that is now in use at 2.5 GeV, this will result in a resolution of 5.1 MeV that is essentially independent of gamma-ray energy. This energy

spread will increase, with the square of the stored electron momentum, to 6.4 MeV when the ring operates at 2.8 GeV. These will be the limiting resolutions for at least the first year of operation at LEGS. However, the tagging spectrometer has been designed to accommodate operation in an energy loss mode. Depending upon the momentum dispersion that can be achieved in the interaction straight section of the ring, the gamma-ray resolution could be reduced to about 2 MeV. This will require a detailed study of various possible storage ring tunes, which we hope to begin after the LEGS installation has been completed.

Since the spin-flip amplitude in backward Compton scattering is so small at these energies, the gamma-ray beam can be highly polarized.² Circular or linear polarizations as high as 90% will be possible and changing directions of polarizations will involve only simple adjustments of the laser.

The size of the gamma-ray beam will be determined by the divergence of the electron beam in the straight section. With the present tune of the ring, the photon beam would be a flat ribbon about 10 mm high and 30 mm wide at the second target area of Fig. 1. We expect this beam to be essentially background free.

6. EXPERIMENTAL EQUIPMENT FOR PLANNED RESEARCH

a. Photodisintegration of deuterium

1. Review of existing data with polarized beams

The first experiment planned for LEGS will measure the photodisintegration of deuterium. In preparation for this we have reviewed all existing data. The asymmetry in this reaction, which is just the ratio between the linear polarization-sensitive and -insensitive parts of the cross

Figure 3: Published measurements of the photon asymmetry in $d(\gamma, p)$.

section, is shown in Fig. 3 for a proton detected at 90° . Many of the published measurements have been done only at this angle, and this plot includes all available data below 1 GeV.⁴

The short-dashed, long-dashed and dot-dashed curves are calculations by Laget⁵ in which the reaction amplitude is expanded into leading elementary diagrams, each of which is explicitly calculated. The solid curve is a coupled-channel calculation by Leidemann and Arenhovel⁶ using a perturbative expansion including one-pion exchange, and two-body meson exchange currents

and delta isobar currents. Within the accuracy of the available data, both this calculation and Laget's long-dashed curve are adequate here below 350 MeV. The agreement appears not to be as good at other angles, but it is difficult to tell because the data are very sparse. Measurements with much higher statistics, better energy resolution, and many more angles are needed before the details of these calculations can be compared in a critical way.

The regime above 350 MeV, where all of the calculations are vastly different from the data, is the region in which a number of possible dibaryon resonances have been reported. Among the best candidates are features with $T(J^\pi) = 1(3^- \text{ or } 2^-)$ at 423 MeV and $T(J^\pi) = 0(3^+ \text{ or } 1^+)$ at 572 MeV extracted by the Tokyo group from proton polarization data.⁷ Their description in terms of dibaryons has since been shown to be at least incomplete by some rather difficult photodisintegration measurements extending to very forward angles.⁸ On the other hand, one could have come to this same conclusion by simply comparing the predictions from the Tokyo model with the photon asymmetry. This is shown as the dotted curve in Fig. 3 and clearly bears no resemblance to the data. This exercise illustrates the sensitivity of polarization data to the presence of high-spin dibaryons.

There are other dibaryon candidates that have been observed in γ +d reactions, such as a 40 MeV wide peak reported by the Saclay group in the $d(\gamma, p)X$ cross section at 2.23 GeV ($E_\gamma = 390$ MeV),⁹ and the recent observation from Bonn of a very narrow (<5 MeV) peak in the pp invariant mass distribution from $d(\gamma, pp)\pi^-$ at 2.01 GeV.¹⁰ (If the latter were formed as an intermediate state in photodisintegration, it would appear at a photon energy of 143 MeV.) However, the available asymmetry data (Fig. 3) are far too sparse and of too poor resolution to see effects due to either of these narrow features.

All of these considerations have assumed linearly-polarized photons. However, for high-spin dibaryons, probably the most striking reaction will be forward angle deuteron disintegration with circularly-polarized gamma rays. The specific helicity of the incoming photon highly polarizes the dibaryon intermediate state, so that for positive helicity only $M = 0$ or 1 substates contribute in the forward direction. As J increases, the relative polarization of a dibaryon becomes quite large, making the behavior of cross sections drastically different from that of background processes.

11. Progress on equipment for $d(\vec{\gamma}, p)$ at LEGS

The experiment at LEGS will measure the $d(\gamma, p)$ reaction with polarized photons ranging in energy from 50 MeV up to 465 MeV (and 530 MeV when available), with an accuracy sufficient to provide stringent tests for models including meson-exchange effects, and to search, with both linearly and circularly-polarized beams, for the effects of dibaryons. The $d(\gamma, p)$ reaction has a simple two body final state so that a measurement of either the γ -ray energy and proton angle, or the proton energy and proton angle determines the kinematics completely. This experiment will utilize two different detection systems, both of which are designed to overdetermine the kinematics as much as possible.

The first detector system is comprised of an array of 24 plastic scintillator modules each subtending 4° in θ and 12° in ϕ . Each module is a PHOSWITCH, consisting of a 2 mm layer of CaF followed by about 30 cm of plastic. (The lengths vary with angle to match the proton kinematics.) The CaF is completely insensitive to neutrons, and the comparison between its ΔE signal and the E signal in the plastic rejects other backgrounds as well as events in which a proton suffered a nuclear reaction in the detector. The latter effect becomes appreciable at high energies. The proton energy

resolution of each module will be between 2% and 3% at energies above 150 MeV, but increases appreciably for lower proton energies (to about 7% at 50 MeV). The fabrication of most of these modules has been completed.

The second detection system is optimized for proton energies below 150 MeV, and consists of four silicon micro-strip detectors to accurately measure the proton angle, a 2.5 cm thick plastic ΔE detector and an 18 cm thick NaI E detector. The energy resolution of this system will be about 3% for 50 MeV protons. Because of the low-energy threshold in the electron-tagging spectrometer of 175 MeV, the second detection system will be particularly important in extending the forward-angle measurements to lower energies. The micro-strip array has been designed to keep the error on the angle measurement significantly below the contribution to the error from the proton energy measurement. The pitch of the silicon strips is designed to provide 2° accuracy in θ_p and 8° in ϕ_p . At present, the strips have been delivered and are being tested.

The target for this experiment will be a liquid cell, cooled by a recirculating He refrigerator. The target cell is constructed out of 0.008 cm mylar and contains 3.8 cm of liquid, which represents 0.5% of a radiation length to the beam. The cell is wrapped with a total of 0.013 cm of aluminized-mylar superinsulation. The target cell and cryostat have been designed to reduce bubbles in the liquid deuterium so that the effective thickness in the target can be maintained to at least 2%, and possibly better. The construction of the liquid target and its safety control system is almost complete.

b. Progress on a high-energy gamma-ray spectrometer

Several experiments are planned for LEGS that will require the

detection of high-energy photons with good resolution and efficiency. These include measurements of the elastic scattering form factors from a range of nuclei, beginning with deuterium, and determination of the electric and magnetic polarizabilities of the proton when free, and when bound in deuterium. For experiments such as these a new NaI(Tl) detector is being constructed with performance goals of 2% resolution and 50% efficiency at 400 MeV. (This detector will also be used as one arm of a planned π^0 spectrometer.)

The goals for this detector represent a considerable improvement over any existing spectrometer. At LEGS energies two factors will strongly effect the performance of this detector: the confinement of the shower produced by the γ ray, and nonuniformities in the response of the NaI crystal. The shower produced by a 400 MeV photon fills so large a volume that it is prohibitively expensive to make the NaI crystal big enough to completely contain it. With a reasonable size crystal, the resolution is then affected by statistical fluctuations in the amount of energy that escapes. If the NaI crystal is surrounded by a plastic scintillator, events where energy leaves the NaI can be rejected. This is the approach that we have taken. The Electromagnetic Generating Shower (EGS) code has been used to study the optimal configuration. The design calls for a 19-inch long x 19-inch O.D. single crystal of NaI surrounded by a 4-inch thick annulus of plastic scintillator.

To study the effects of NaI nonuniformities at high energies, and to test if the goal of 2% resolution was really feasible, measurements were made at the University of Mainz.¹¹ Photons from tagged bremsstrahlung ranging up to 300 MeV in energy entered a 10 inch x 14 inch NaI detector having 4 inches of plastic scintillator surrounding and behind it. The resolution of the bare detector at 300 MeV was measured to be 6%, and this is in excellent agreement with our EGS calculations for this crystal. These calculations neglect

Figure 4: Response of a 10" x 14" NaI detector with (dashed) and without (solid) rejection of escape radiation.

nonuniformity but, for this small detector, such effects should be entirely swamped by the statistical fluctuations in the escaping radiation. With the plastic shield rejecting events in which energy left the NaI, the resolution at 300 MeV was reduced to 2.7%, an impressive improvement. This is shown in Fig. 4. Of course, the efficiency was then only 17% since very few 300 MeV γ -ray showers can be contained by such a small crystal. With such a large fraction of the events being rejected, the ultimate resolution of this system

now depends critically on the efficiency of the plastic veto shield, which was not optimized for this type of use. Given these conditions, the 2.7% resolution achieved with the 10 inch x 14 inch detector system at 300 MeV strongly suggests that the goal of 2% resolution with a 19 inch x 19 inch detector system at 400 MeV is indeed reasonable, provided that the new large NaI crystal can be made as uniform as the smaller 10 inch x 14 inch detector.

There are two main sources of nonuniformity in the NaI(Tl) crystal response--the reflective properties of the crystal surface, and volume irregularities coming from impurities, crystal dislocations, and nonuniform thallium doping.

The best crystal preparation technique, in use for the last five years, involved scanning the surfaces with a collimated 6 MeV gamma-ray source and treating the surface to smooth out irregularities.¹² However, this is quite inadequate for a 19-inch diameter crystal since a 6 MeV photon will only produce light to a depth of 3 to 5 inches.

We have developed a new technique that uses cosmic-ray muons to scan the interior of the NaI. The muon is an ideal probe, being a high-energy charged particle, considerably heavier than an electron so as to penetrate deep into the crystal but lose energy only by ionization without electromagnetic shower production, and weakly interacting so as to avoid nuclear reactions which would smear out its energy loss. Most of the cosmic-ray muons are minimum ionizing and deposit 4.8 MeV per cm of NaI. Except for the very lowest energies, the muons will pass completely through a 19-inch diameter crystal leaving a narrow well-defined column of light. The amount of energy deposited depends very weakly upon the incident muon energy and, to first order, is a function only of the thickness of NaI through which the muon passed. Since the entire crystal is bathed in this muon flux, a triple coincidence with a

pair of small detectors located above and below the large NaI is necessary to define a trajectory. Such a coincidence then determines the NaI path length, and hence the energy deposited. If this pair of small detectors is moved about in the horizontal plane, all possible trajectories through the large crystal can be covered. Once the trajectories have been corrected for differences in NaI path length, the remaining differences in signal amplitudes reflect the nonuniformities within the NaI crystal. Because of the low cosmic-ray flux, such measurements are not practical with only one pair of small detectors. In fact, large position-sensitive arrays are required so that many trajectories can be measured simultaneously. When the crystal surface is made uniformly reflective, this amounts to taking a "CAT-scan" of the NaI volume, and techniques similar to those used in medical imaging can be used to locate regions within the crystal volume where the light output is above or below average. Provided such nonuniformities are not in the center of the NaI, the surface reflection can then be treated to compensate for these and optimize the uniformity of the crystal response.

A 'muon-CAT-scan' of a 10"x14" NaI crystal is shown in Fig. 5. Darker areas correspond to regions of lower light output. The crystal studied here detects 50 MeV photons with 2% resolution and has a uniformity of $\pm 0.4\%$ when scanned with a 6 MeV source.¹² This is to be compared with an 8% variation measured in this muon scan.

This new technique is an order-of-magnitude more sensitive, and will be used first to select a high-quality ingot and then to treat its surface to further improve its performance. The 19"x19" detector will be the largest single crystal of NaI. A furnace at Bicron Corp. has just been modified to accommodate it, and the first ingot is now being grown.

map04
10cm<y<11cm

z (cm)

y (cm)

y (cm)

map04
4cm<z<5cm

Energy
Shift

2.0 MeV
1.0 MeV
0.0 MeV
-1.0 MeV
-2.0 MeV
-3.0 MeV
-4.0 MeV
-5.0 MeV
-6.0 MeV
-7.0 MeV
-8.0 MeV

Elements Displayed Intersect
With 2 or More Trajectories

map04
0cm<x<1cm

Figure 5: Three intersecting planes from a "muon-CAT-scan" of a NaI crystal.

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References

1. A. M. Sandorfi, M. J. LeVine, C. E. Thorn, G. Giordano, G. Matone, and C. Schaerf, IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, 3083 (1983).
2. D. H. Dowell, G. Giordano, M. J. LeVine, G. Matone, A. M. Sandorfi, C. Schaerf, C. E. Thorn, and W. Ziegler, LEGS Progress Report, BNL 34938 (1984).
3. D. H. Dowell, G. Giordano, O. Kistner, G. Matone, A. M. Sandorfi, C. Schaerf, and C. E. Thorn, LEGS Report, BNL 37623 (1985).
4. D. H. Dowell, G. Giordano, O. Kistner, G. Matone, A. M. Sandorfi, C. Schaerf, and C. E. Thorn, LEGS Report, BNL 37622 (1985), and references contained therein.
5. J. M. Laget, Nucl. Phys. A312, 265 (1978); Can. J. Phys. 62, 1046 (1984).
6. W. Leidemann and H. Arenhovel, Phys. Lett. 139B, 22 (1984).
7. H. Ikeda, I. Arai, H. Fujii, T. Fujii, H. Iwasaki, N. Kajima, T. Kamae, K. Nakama, T. Sumiyoshi, and H. Takeda, Nucl. Phys. B172, 509 (1980).
8. K. Baba, I. Endo, H. Fukuma, K. Inoue, T. Kawamoto, T. Ohsugi, Y. Sumi, T. Takeshita, S. Uehara, Y. Yano, and T. Maki, Phys. Rev. C28, 286 (1983).
9. P. E. Argan, G. Audit, N. deBotton, J. L. Faure, J. Martin, C. Schuhl, G. Tamas, and E. Vincent, Phys. Rev. Lett. 46, 96 (1981).
10. B. Bock, W. Ruhm, O. Kaul, Th. Micayaika, W. J. Schwillie, K. H. Althoff, G. Anton, W. Ferber, H. W. Gelhausen, Th. Tahven, D. Menye, E. Schenuit, Proc. Conf. on Nucl. Phys. with electromagnetic Probes, Paris (1985), cont. paper A9, p. 64.
11. D. H. Dowell, W. P. Ziegler, A. M. Sandorfi, B. Ziegler, B. Schock, Nucl. Inst. and Meth.
12. A. M. Sandorfi and M. T. Collins, NIM 222, 479 (1984).

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