Basic Monochromator for Instructional Use

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INTRODUCTION

THE purpose of this article is to describe the design, construction, and performance of a simple, inexpensive Czerny–Turner monochromator which is used extensively in an elementary physics laboratory program. The instrument consists of a medium-precision plane-reflection grating which is mounted in an optical system employing two spherical mirrors. The monochromator possesses two principal advantages in that its resolving power is significantly higher than most spectrographic instruments available for undergraduate laboratory experiments and that its range extends from the ultraviolet to the near infrared region of the spectrum. The monochromator is sufficiently simple in design that it may be constructed without elaborate machine shop practice. The instrument is used to measure the Balmer series, to determine the ratio of Planck's constant to the electronic charge (h/e), and to resolve the hydrogen–deuterium spectral-line splitting. In addition, the instrument may be used in conjunction with a Lummer–Gehrcke plate to measure the Zeeman effect and to present a continuous display of line spectra on an oscilloscope.

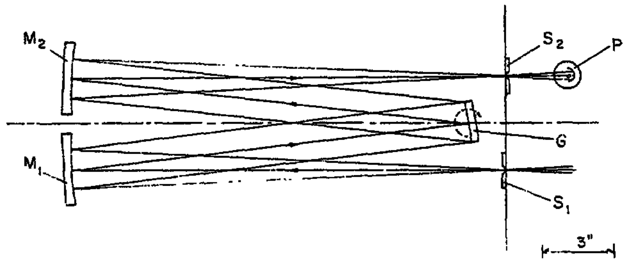

FIG. 1. Arrangement of optical components showing principal and extreme rays of system. S_1 and S_2 are the entrance and exit slits, respectively, M_1 and M_2 are spherical mirrors, G is a plané reflection grating, and P is the phototube detector.

I. DESCRIPTION OF OPTICAL SYSTEM

The principal ray diagram of the monochromator is shown in Fig. 1. The instrument consists of a plane-reflection grating G which is mounted such that it can rotate about a vertical axis passing through the plane of its ruled surface. The grating G is illuminated by light which enters the system at the entrance slit S_1 and is collimated by a spherical concave mirror M_1. The light diffracted from the grating G is, in turn, focused on the exit slit S_2 by a second spherical concave mirror M_2. The mirrors are located equidistant from the geometric axis of the instrument, and their respective focal planes are coincident with the planes of the entrance and exit slits. The slits are also located equidistant from the geometric axis of the instrument so that near-perfect symmetry is achieved on both sides of the axis. The slit separation is governed by elementary geometrical considerations which are dependent primarily upon three parameters; the focal length of the mirrors, the axial separation of the mirrors, and the distance separating the diffraction grating from the focal plane of the mirrors. Given the physical limitations imposed by the size of the grating and mirrors, the monochromator is designed to minimize the angles of incidence and reflection at each optical element. The height of the entrance and exit slits is established by the geometry of the system in order to insure that the entire aperture of the phototube is fully utilized. A baffle is inserted between the mirrors, extending to the point where the extreme rays cross the geometric axis, to prevent light reflected from the mirror M_1 from reaching the exit slit S_2. Finally, a phototube detector is mounted beyond the exit slit S_2 at a distance sufficient to insure that its photocathode is uniformly illuminated by light passing through the monochromator.

The operation of the instrument as a monochromator requires only that the diffraction grating rotate about its axis, allowing monochromatic light to reach the exit slit. Thus, the instrument functions as a selective filter which may be adjusted to transmit one particular wavelength of light while rejecting all others.

The plane reflection grating[1] incorporated in this design has 590 grooves/mm blazed at 4500 Å. The ruled area of the grating is 44 mm wide and 32 mm high on a blank thickness of 9.5 mm. The concave spherical mirrors[2] are 76 mm in diameter, 9.5 mm thick, and have a focal length of 463 mm. The mirrors are specified as ¼ wave, aluminized front surface, and silicon monoxide overcoated.

The inherent advantages of the arrangement of optical components shown in Fig. 1 were recognized and verified by Czerny and Turner[3] in 1930, although systems of this type were in use prior to that time. A single-mirror system, using the same principal ray diagram, was published by Ebert[4] as early as 1889. However, Ebert did not use his system as a monochromator and apparently failed to recognize the advantages of doing so. More recently, Fastie[5] published the design of a single mirror monochromator developed independently of Ebert's work. Fastie's design, with his innovation of curved slits, produced a monochromator of exceptional performance, and his publications provided substantial insight into the design of this instrument.

The cardinal point that Czerny and Turner established is that a system possessing the symmetry shown in Fig. 1 is essentially self-correcting in that the coma aberration introduced by the first off-axis reflection, at mirror M_1, is entirely compensated by the second off-axis reflection at mirror M_2. The net result of the symmetry is that it ensures that all rays traveling from the entrance slit to the exit slit are of equal length, an important consideration in the image forming properties of any optical system. Necessarily, a system of this type will still exhibit astigmatism, particularly if the slits are unnecessarily long; however, the virtual elimination of coma alone substantially enhances the performance of this type of system.

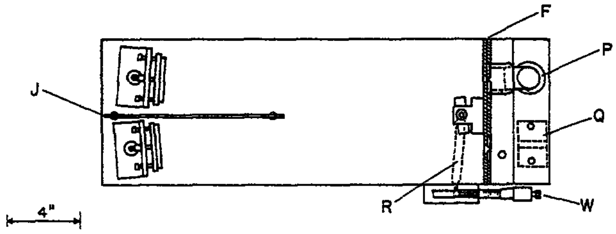

FIG. 2. Mechanical assembly of the monochromator including faceplate *F*, phototube housing *P*, fore-optics support *Q*, drive arm *R*, micrometer head *W*, and baffle *J*.

II. MECHANICAL ARRANGEMENT

The mechanical assembly of the monochromator is shown in Fig. 2. The design of the instrument is predicated upon simplicity, utilizing components which can be easily obtained[6] or constructed.[7] The resultant instrument is reasonably rugged, stable, and easily portable.

The base of the instrument is fabricated from a 25-in. length of 8-in. aluminum channel. The 0.205-in. web thickness of the channel is sufficient to allow the tapped holes required to mount all of the major components. Two areas of the channel face must be milled flat to ensure stable alignment of the mirror mounts and faceplate. In addition, a single milled slot is required on one side to allow motion of the drive arm. The position of the holes required for the phototube housing and the mounting screws are located by manual layout, as high precision is not necessary.

The mirror mounts and faceplate are fabricated from 4-in. aluminum channel which is modified by removing one flange, thus yielding a substantial right angle support, 0.320 in. thick. The complete mirror mounts are assembled as

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[1] Jarrell–Ash Co., Waltham, Mass. (Cat. No. 37-00-99-49).

[2] Edmund Scientific Co., Barrington, N. J. (Cat. No. 30 219).

[3] M. Czerny and A. F. Turner, Z. Physik **61**, 792 (1930).

[4] H. Ebert, Wied. Ann. **38**, 489 (1889).

[5] W. G. Fastie, J. Opt. Soc. Am. **42**, 641 (1952).

[6] The total cost of purchased components and materials did not exceed $100.00.

[7] Machine shop sketches of the principal components are available from the University of Pennsylvania, Physics Department, Philadelphia, Pa. 19104.

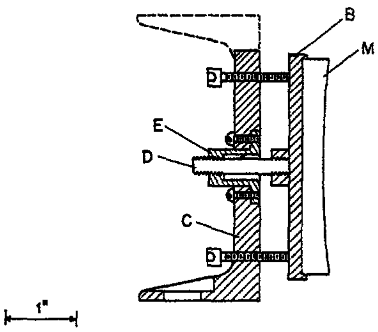

FIG. 3. Adjustable mirror mount.

shown in Fig. 3. A single Allen bolt in an oversize hole positions the mirrors with respect to the other optical components providing for focus and coarse angular adjustment. The spherical mirror *M* is attached to a brass disk *B* which locates the axis of the mirror with respect to the mount and also protects the spherical figure of the mirror from mechanical distortion. A minimal amount of epoxy resin applied to the center of the glass serves as a bond between the mirror and its support. The use of an excess amount of resin will endanger the spherical figure of the mirror as mechanical stresses generated in alignment will be transferred to the surface of the glass. A short length of 0.250-in. threaded nylon rod stock *D* fixes the position of the mirror in the instrument and acts as a nearly rigid member which can be strained by the use of the four bolts acting against the mirror back. An extended brass sleeve *E* connects one end of the nylon rod to the aluminum support *C*. This mirror-mount design permits accurate positioning of the mirror with two nearly independent degrees of rotational freedom.

The diffraction grating is mounted in a brass yoke as shown in Fig. 4. Four small brass blocks *V* exert sufficient force upon the edge of the ruled surface to align the plane of the grating normal to the axis of the instrument. The back surface of the grating bears against four miniature O-rings which are partly recessed in the face of the yoke directly beneath the location of the blocks *V*. Four set screws *S* are provided, which bear against the upper and lower sides of the grating blank in order to align the direction of the grooves parallel to the axis of the entrance and exit slits. A thin 0.010-in. strip of polyethylene (not shown in drawing) inserted above and below the grating blank protects the sides and face of the grating from excess forces applied by the set screws *S* or blocks *V*. A length of 0.250-in. ground steel shaft *H* extends above and below the grating yoke. This shaft supports two (0.750-in. o.d.) medium-precision ball bearings *T*, which allow accurate rotation of the grating around its axis.

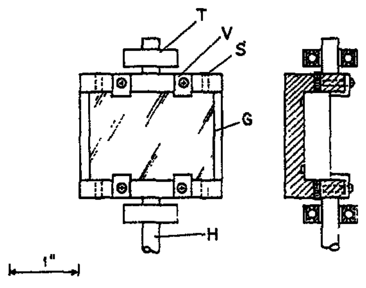

FIG. 4. Detail of diffraction-grating yoke.

The grating yoke assembly, supported between the ball bearings, is mounted against the faceplate of the instrument with the use of two support blocks bored to accept the outer race of the bearings. These blocks, with the inserted ball bearings, serve to define the axis of rotation of the grating with respect to the instrument.

The faceplate *F* of the instrument is assembled as indicated in Fig. 5. A carefully milled groove extending across the front surface of the faceplate serves to define accurately the position of the entrance- and exit-slit jaws. The corners of this groove are relieved to ensure that the slit jaws lie flat against the bottom surface. Two elongated holes milled in the faceplate behind the location of the slits permit the passage of light into and out of the instrument. The holes required for mounting the grating support blocks and the slit jaws are indicated from the geometric axis of the instrument to ensure that the symmetry conditions of the principal ray diagram are met. The bottom surface of the faceplate must be machined flat, perpendicular to the surface which mounts the grating support blocks, so that the grating will rotate about an axis perpendicular to the base of the instrument.

The slit jaws are machined from tool steel which is hardened prior to grinding. Considerable care must be exercised with these components as the performance of the monochromator is strongly dependent upon the quality of the slit edge. In general, the surfaces of the slits should be ground, and if ultimate performance

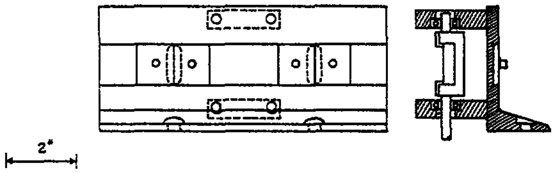

FIG. 5. Monochromator faceplate assembly *F* showing position of slit jaws and grating support.

is required, each surface must be lapped. Creditable results may be obtained, however, with slit jaws which are carefully machined and finished with fine crocus cloth. The hole in each jaw is oversize to permit adjustment of the slitwidth over a wide range of values.

The shaft on the lower side of the grating assembly extends beyond the ball bearing, through the web of the base, to a point where it connects to the drive arm. This arm extends at right angles to the axis of rotation, through the side of the base, where it is spring loaded against the face of a micrometer head.[8] A polished steel sphere soft soldered to the end of the arm approximately 4½ in. from the grating axis serves as the point of contact between the arm and the flat face of the micrometer head. Adjustment of the micrometer head accurately rotates the grating about its axis providing the required wavelength adjustment for the instrument. The arrangement of the drive mechanism yields a nearly linear relationship between the micrometer setting and the wavelength transmitted by the monochromator.

The base of the instrument extends beyond the faceplate to allow rigid mounting of the fore-optics support *Q* and a phototube housing *P*. The fore-optics support consists of an adjustable steel bar which positions a front-surface concave mirror required to image a given light source upon the entrance slit. In many cases, the bar also supports the source itself, contributing to the over-all mechanical stability of the system. The phototube housing, consisting of a 1½-in. copper plumbing tee, is rigidly attached to the base approximately 2¾-in. beyond the exit slit. This distance is sufficient to allow the exit beam to diverge and to illuminate fully the cathode aperture of a variety of phototubes and photomultipliers. A sleeve of foam-rubber tubing[9] serves as a light-tight coupling between the phototube housing and the faceplate of the monochromator.

The instrument can be easily converted to a recording monochromator by the addition of a spline which connects the micrometer head to a synchronous clock motor. Several motors may be employed to provide scanning speeds ranging from 0.08 to 0.4 Å/sec.

III. ALIGNMENT OF THE OPTICAL SYSTEM

The alignment of the monochromator proceeds directly from the principal ray diagram. The location of the grating axis with respect to the focal plane of the mirrors is fixed by mechanical considerations at 37.5 mm. The diameter of the two mirrors imposes a lower limit to their axial separation which is fixed at 90 mm. The slit separation which results from these dimensions in addition to the focal length of the mirrors is calculated, for the single mirror case, to be 97.8 mm. In practice, the slit jaws are positioned symmetrically on either side of the geometric axis, using a slit width of approximately 100 μ. In turn, each mirror is positioned 45 mm from the geometric axis such that its focal distance coincides with the plane of the slit associated with it. The focal lengths of the purchased mirrors are subject to some variation, consequently it is advantageous to measure this parameter for each mirror prior to installation.

The performance of the monochromator is strongly dependent upon the care with which the instrument is aligned. The most general requirements which must be met are: (1) the slitwidths should be equal and the jaws parallel; (2) the mirrors must be carefully positioned; (3) the grating must be properly aligned. Requirements (1) and (2) are established by focusing an intense mercury arc on the entrance slit and examining the monochromatic field with a card placed behind the exit slit. This field should appear and disappear as uniformly as possible, given sufficient rotation of the grating to scan over an intense spectral line. In general, motion of the field in the horizontal direction

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[8] L. S. Starrett Co., Athol, Mass. (Cat. No. 263-MRL).

[9] Armstrong Cork Company, Lancaster, Pa. (Armaflex Pipe Covering).

indicates that the mirrors are not focused correctly, whereas motion in the vertical direction, along the slit axis, indicates that the slits are not parallel. The third requirement (3) is established by observing the position of successive orders of a given monochromatic line on either side of the grating normal. Ideally, these orders will not deviate from the horizontal plane as the grating is rotated about its axis.

Each mirror mount incorporates four adjusting screws which allow two degrees of rotational freedom. These adjustments are used to (1) position the mirror axis in the vertical direction such that the principal rays incident to and diffracted from the grating lie in the same plane and (2) adjust the angles prescribed by the principal ray diagram so that the aperture of the grating is fully utilized.

IV. DESCRIPTION OF DETECTION SYSTEM

The phototube housing will accommodate a large variety of vacuum phototubes and side-window photomultipliers. The necessary electrical connections may be made either from the top or bottom of the housing. Frequently the connections are arranged to include a standard BNC female connector mounted on the side of the channel and a UHF female connector mounted on the top of the phototube housing. This arrangement facilitates the use of vacuum phototubes constructed with anode connections sealed through the glass envelope. Separate provision is made for mounting the high-voltage dividing network required in photomultiplier tube applications.

The measurement of the Balmer series or the determination of the ratio of Planck's constant to the electronic charge is accomplished with the use of a vacuum photodiode.[10] The potentials required for these experiments are small and may be easily provided by the use of a battery operated potentiometer. In more sophisticated experiments requiring the use of photomultiplier tubes,[11] well-regulated high-voltage power supplies are employed. In either case, the resultant photocurrents are measured directly by a direct current micro-micro ammeter[12] providing twenty ranges between 1×10^{-3} and 3×10^{-13} A full scale. Instruments[13] are available for electronically recording the output of the micro-micro ammeter, if the monochromator is arranged to operate as a recording instrument.

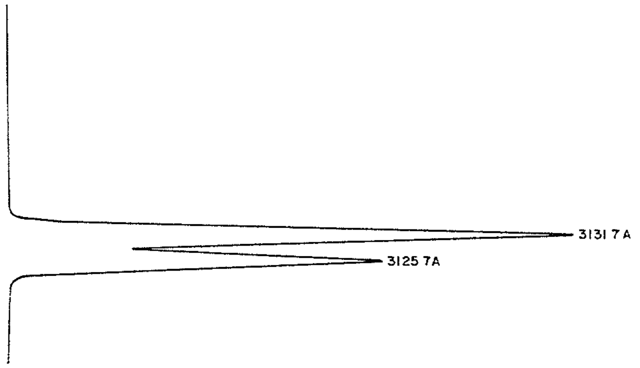

FIG. 6. First-order scan of 3125.7- and 3131.7-A mercury lines using 100-μ slits.

V. PERFORMANCE OF THE MONOCHROMATOR

The linear dispersion of the monochromator in first order is approximately 37 Å/mm over the range of 2400 to 6800 Å. The optical speed of the system is f/11. A recorded scan of the first-order 3125- and 3131-Å ultraviolet mercury lines is shown in Fig. 6. This scan indicates the performance of the monochromator using 100-μ slits with a passband of 3.7Å. The resolving power obtained from the half-width of the lines is 900. The dispersion and resolving power displayed by this scan is sufficient for most experiments used in undergraduate laboratory programs. Figure 7(a) illustrates the resolution of a critically aligned monochromator scanning the hydrogen–deuterium red lines at 6562.8 and 6561.0 Å, respectively. Figure 7(b) shows the same spectral lines with higher resolution obtained by limiting the slit height to 5 mm. This trace illustrates the effect of image curvature on the resolving power of the monochromator and indicates an upper limit of performance under nearly

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[10] Radio Corporation of America, Lancaster, Pa. (Types 925, 929, 935).

[11] Radio Corporation of America, Lancaster, Pa. (Types 1P21, 1P28).

[12] Keithley Instruments, Cleveland, Ohio (Type 410).

[13] Leeds and Northrup Company, Philadelphia, Pa.

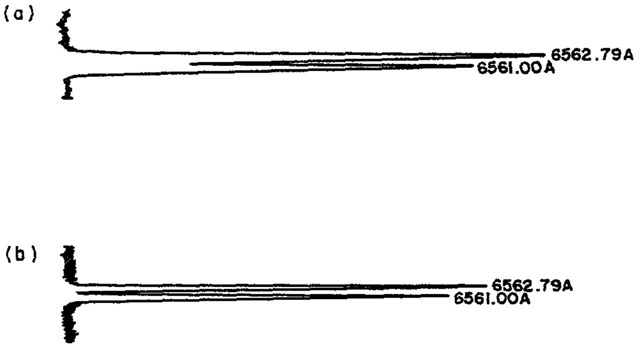

FIG. 7. First-order scan of the hydrogen–deuterium red lines. (a) 28-mm slit height, (b) 5-mm slit height.

ideal conditions. The trace shown in Fig. 7(b) indicates that the monochromator design is capable of achieving a resolving power approaching 9000 with a slitwidth of 15 μ. It should be emphasized that this performance is attainable only after careful alignment and is not to be regarded as typical or necessary for most applications. Our experience indicates that the quality of the slits and the accuracy of their alignment impose the upper limits of resolution obtainable with this instrument.

The wavelength drive of the instrument can be calibrated to an accuracy of ± 2 Å. A nearly linear dispersion curve may be obtained by identifying a number of spectral lines over the range of the instrument and plotting the known wavelengths against micrometer reading. A graph of the departures from a linear fit to this dispersion curve represents the corrections which are applied when highest wavelength accuracy is desirable. Figure 8 illustrates the correction curve obtained from a 42-point linear least squares fit between the known wavelengths of mercury and neon and the corresponding micrometer readings. This curve indicates that the wavelength drive is linear to ± 10 Å without correction and accurate to ± 2 Å with correction over the range of 2500–6800 Å. The least count of the micrometer head is equivalent to 2.9 Å.

Our experience with 20 instruments,[14] introduced into the instructional laboratories two years ago, indicates that the monochromator will function reliably with minimal adjustment and maintenance.

VI. APPLICATIONS OF THE MONOCHROMATOR

The monochromator is used primarily in the elementary physics laboratory to measure the Balmer series and to determine the ratio of Planck's constant to the electronic charge.[15] However, the instrument is sufficiently versatile to perform many other experiments and demonstrations without alteration. In addition, the monochromator can be modified to perform advanced experiments and demonstrations. One application of substantial interest in undergraduate laboratory programs is the measurement of the Zeeman effect.[16] This experiment requires the

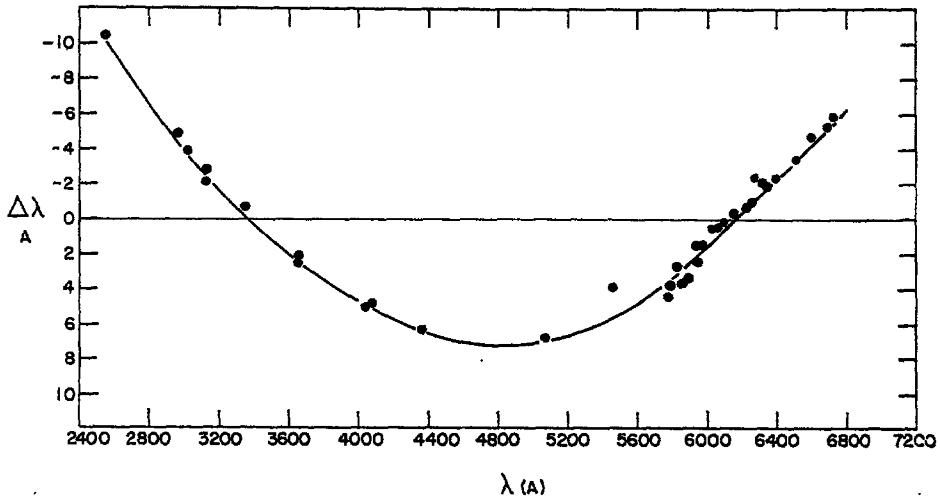

FIG. 8. Error curve for typical monochromator showing departures from linearity over range of instrument.

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[14] These instruments were constructed with the financial assistance of the National Science Foundation, NSF-GE-1997.

[15] A. M. Portis, *Berkeley Physics Laboratory, Part C-5* (McGraw–Hill Book Co., New York, 1964).

[16] A. Melissinos, *Experiments in Modern Physics* (Academic Press, Inc., New York, 1966).

use of a high-resolution optical element, such as a Lummer–Gehrcke plate or a Fabry–Perot étalon, crossed with a spectrograph or monochromator of sufficient dispersion to separate the spectral lines required for study. In order to perform an experiment measuring the Zeeman effect with this monochromator, a special unit was constructed which mounts all of the required optical components including the monochromator on a single length of channel. This arrangement simplifies the alignment procedure and contributes substantially to the mechanical stability of the apparatus.

A second modification which is of importance in lecture demonstrations consists of sinusoidally driving the wavelength arm with a ball bearing eccentric mounted on a synchronous motor. This arrangement causes the monochromator to sweep through its entire wavelength range in approximately one second. The output of the photomultiplier tube is connected to the vertical input of an oscilloscope which displays the intensity of the respective spectral lines. An electrical signal derived from the mechanical system triggers the horizontal sweep of the oscilloscope at a predetermined point in the spectrum so that the display is repetitious starting with a given spectral line. The net result is a stable oscilloscope presentation of the intensities and relative wavelength separations of a fixed region of the spectrum. Necessarily, the wavelength drive is not linear; however, limited regions of the visible and ultraviolet spectrum can be displayed with remarkable wavelength accuracy.

VII. SUMMARY

This basic monochromator design will fulfill the requirements of a number of undergraduate laboratory experiments. The cost of the instrument is moderate, the mechanical construction is straightforward and the principles involved in its design and construction are readily understood by undergraduate students. The range and resolution of the monochromator is substantially greater than many spectrographic instruments used in undergraduate laboratory programs.

ACKNOWLEDGMENT

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