SPECTROPHOTOPOLARIMETER: A SIMPLIFIED VERSION FOR REAL TIME MEASUREMENT AT SELECTED WAVELENGTHS

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Abstract. A device for real-time measurement of Stokes parameters is described. It comprises an original optical part, an electronic phototransducer unit with digitization and a personal computer. The optical adjustment is easy and calibration is achieved with a single measurement of a linearly polarized light beam with known intensity and wavelength. The instrument is used for real-time measurement of the photoinduced anisotropic changes in the optical constants of samples of rigid solution of fluorecein in orthoboric acid.

Резюме. Описаны параметры прибора для измерения параметров Стокса в реальном времени. Прибор состоит из оригинальной оптической части, цифрового электронного фотоприемника и персонального комлютра. Оптическая юстировка проста и калибровка осуществляется путем однократного измерения линейно поляризованным светом с заданной интенсивностью и длиной волны. Прибор использован для измерения фотоиндуцированных анизотропных изменений оптических констант твердых растворов флюоресцена в ортоборной кислоте в реальном времени.

1. Introduction

A method for real time simultaneous measurement of Stokes parameters of light by splitting the measured light beam to four beams was first proposed by Azzam Modifications of this method that made use of different types of beam splitters were described and experimentally realized [2-4]. Recently we have also proposed a scheme of Stokesmeter [5], in which the measured beam is split by only one beam splitter (a polarization holographic diffraction grating) to four beams — reflected, directly transmitted and two diffracted beams.

All these schemes cannot be used to measure the spectral distribution of the Stokes parameters of light $S_i(\lambda)$, (i = 0, 1,2,3). A theoretical consideration of an optical scheme for fast simultaneous measurement of $S_i(\lambda)$ is presented in [6]. This scheme includes two diffraction gratings, a polarization grating and a classical grating, and splits the measured light into four dispersed beams. Four CCD linear arrays measure these four spectra and from the obtained electrical signals $S_i(\lambda)$ are calculated. Here we describe the technical realization of a simplified version of this spectrophotopolarimeter. The four CCD linear arrays were replaced by four large-area photodetectors. In this case the device retains the basic characteristics of the spectrophotopolarimeter, but can be used to measure Si and their changes in the time of quasimonochromatic light.

2. Operation Principle and Technical Realization of the Device

The schematic diagram of the spectrophotopolarimeter is shown in Fig. 1. It consists of an optical splitter (PBS) providing four dispersed beams from the measured light Lo with intensities depending unambiguously on its polarization, four CCD linear arrays (PD) with control and amplification units, a unit for commutation (COM) of the four electric signals for subsequent analog-to-digital conversion (A/D) and a personal computer with dedicated software.
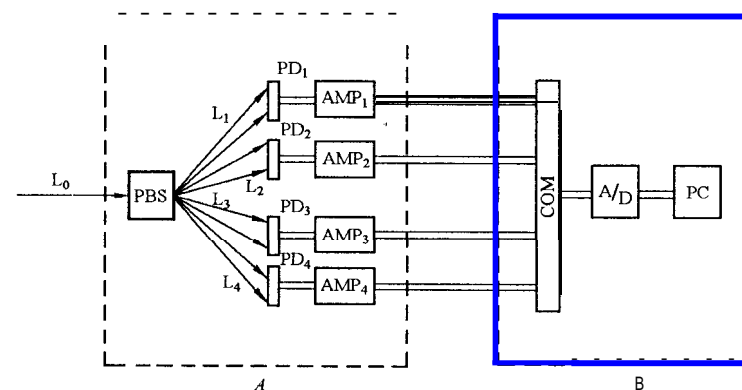

Fig. 1. Scheme of the spectrophotopolarimeter. Lo — the measured light beam; Li (i = 1,2,3,4) — four dispersed light beams; **PBS** -- polarization beam splitter; PDi -- phototransducers, **AMP** -- amplifiers, **COM** --- electronic commutator, A/D — analog-to-digital converter; **PC** — personal computer, A — optical head, B -- data acquisition system

The optical splitter comprises of a specific polarization diffraction grating PG, conventional diffraction grating DG, two linear polarizers P1 and P2 (Fig. 2). The transmission axes of linear polarizers, placed in the path of the beams L1 and L2, subtend an angle $0°$ and $45°$, respectivelly, with the diffraction plane. The polarization grating PG has only two orders of diffraction (± 1) and the light intensities I_{+1} and I_{-1} are proportional to the two orthogonal circular (left-hand and right-hand)
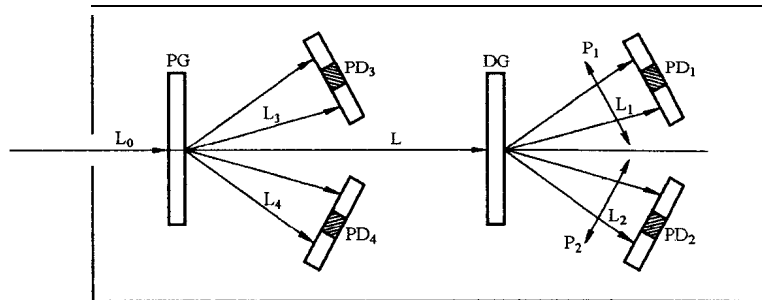
Fig. 2. Scheme of the optical beamsplitter. PG -- polarization diffraction grating; DG — conventional transmission diffraction grating; P_1 and P_2 — linear polarizers with axes, oriented at $0°$ and $45°$; PD1, PD2, PD3 and PD4 — phototransducers; Lo — measured light beam; I1, L2, L3 and L4 — dipersed light beams; L — light beam, transmitted undiffractidely after PG

components of the light wave incident on it [7]. This property of PG simplifies the measurement of the last Stokes parameter S_3 and makes it possible to calibrate the scheme with only one calibrating light beam with linear polarization.

The four light beams diffracted at the ± 1 orders of the two gratings are converted into electric signals by four CCD linear arrays. For each wavelength, the relationships between the four measured photo signals I_j^λ (j = **1,2,3,4**) and Stokes parameters S_i^λ are as follows [6]:

$$S_0^\lambda = k_3^\lambda I_3^\lambda - k_4^\lambda I_4^\lambda$$
$$S_1^\lambda = 2k_1^\lambda I_1^\lambda - k_3^\lambda I_3^\lambda - k_4^\lambda I_4^\lambda$$
$$S_2^\lambda = 2k_2^\lambda I_2^\lambda - k_3^\lambda I_3^\lambda - k_4^\lambda I_4^\lambda \qquad (1)$$
$$S_3^\lambda = k_3^\lambda I_3^\lambda - k_4^\lambda I_4^\lambda.$$

In order to calibrate the spectrophotopolarimeter, i.e. to determine coefficients k_j for each wavelength, only one preliminary measurement of photocurrents I_j, induced by a light beam with a known intensity I_0 at this wavelength and linear ppolarization is necessary; k_j are determined by

$$k = I_0/I_1, \ k_2 = I_0/2I_2, \ k_3 = I_0/2I_3, \ k_4 = I_0/2I_4. \qquad (2)$$

The polarization diffraction grating PG was produced holographically by recording the light field resulting from the superposition of two light beams with orthogonal circular polarizations on AgCl emulsions with photoanisotrcpic response [8]. The grating has a spatial frequency of 1 000 mm^{-1} and diffraction efficiency ≥ 1 % in the spectral region of 550-800 nm. The grating DG is also recorded holographically in dichromated gelatin and its diffraction efficiency is about 30 % in the ± 1 orders [9].

In the simplified version of the device described here beams L_1, L_2, l3 and L_4 are measured with four PIN photodiodes, with an active area of 8 x 8 mm^2. The

four amplification channels, together with the whole optical part, are housed in an optical head (block A, Fig. 1) sized 70 x 70 x 200 mm^3. The commutation of the four photosignals I_j from photodiodes PD$_1$, PD2, PD3, PD4 and their digitization is carried out with the data acquisition system, comprising an electronic commutator, ADC and personal computer (block B, Fig. 1).

The analog-to-digital converter is 12bit (4096 levels). The dark current in each of the four photodetector channels (including photodiode, amplifier, ADC) does not exceed the ± 1 level.

The device is experimented for two wavelengths (633 and 780 nm). At various wavelengths the four diffracted light beams propagate in different directions, but the active areas of the photodiodes (8 $\times$ 8 mm^2) are sufficient for their measurement. The noise in the photosignals is ± 3 levels. The nonlinearity of the photodetector channels is 0.5 %.

The device is calibrated for the two wavelengths. The coefficients k_i^λ are determined experimentally by a single measurement at each wavelength, using relationships (2). Since this calibration measurement is performed with a single linearly polarized light beam that can be set up with high accuracy, the accuracy of the four coefficients k_j is much higher than that in the methods described in [3-5]. Since the values of k_j are measured practically simultaneously, the error depends only on the noise in the photodetector channels and is below'0.2 %. The systematic error depends on the instrument for independent measurement of the calibrating light beam intensity.

The error of the instrument in measuring the values of S_i of light beams with different polarizations is determined by two types of experiments:

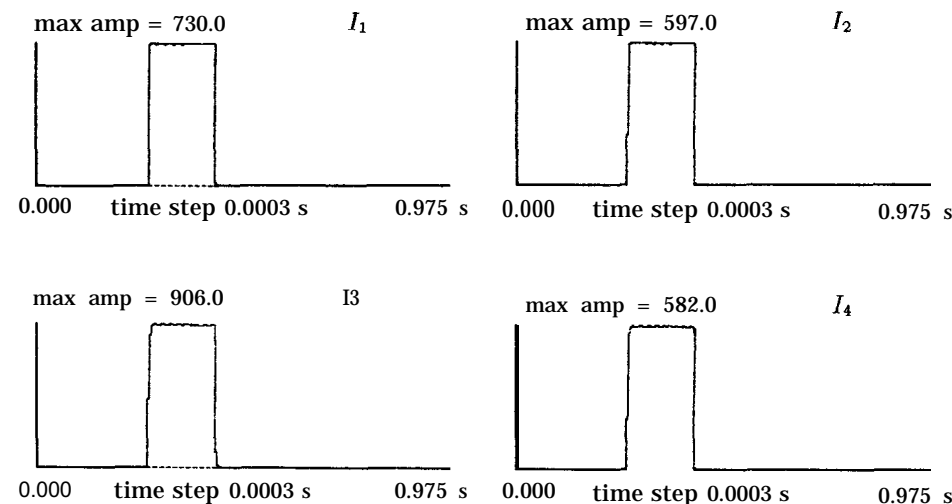‾ measurement of Si of linearly polarized light beams with different, indepen-

Fig. 3. The shape of the four photosignals obtained as a response of a rectangular light pulse. The time interval between two digitizations is 3 ms
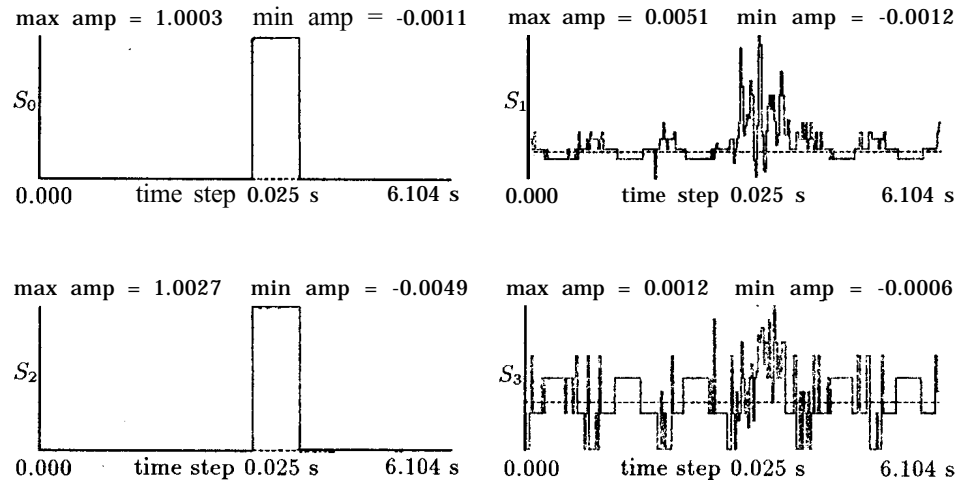
max amp = 1.0003   min amp = -0.0011

max amp = 0.0051   min amp = -0.0012

max amp = 1.0027   min amp = -0.0049

max amp = 0.0012   min amp = -0.0006

Fig. 4. The values of the normalized Stokes parameters obtained at the measurement of a rectangular light pulse linearly polarized at 45°

dently measured polarization azimuths;

  - measurement of S_i of light beams with different ellipticities.

  The light intensity for all measurements was 0.1 mW.

  The maximum difference between the normalized values of Si, measured with the new device and using standard techniques, for the first type of experiments is less than 0.01. For the second series of experiments ΔS_i reaches 0.02 at greater light ellipticities. In our view, this is related to the accuracy of the independent measurement of S_i with an analyzer and compensator.

  In order to investigate the time characteristics of the photopolarimeter, rectangular light pulses are used and the photosignal I_j is viewed. The electrical waveforms are shown in Fig. 3. The time interval between two measurements (digitizations) is 0.003 s. As can be judged by the figure, there is a slight difference between the time constants of the four channels, but they are all less than 10 ms.

  Fig. 4 shows the values of S_i, obtained on measuring the light pulses with linear polarization asimuth of 45°. The maximum deviation of the values of S_i is 0.005. The scale of Fig.46 and c permits an estimation of the temporal stability of the measured values.

3. One Application of the Device

One of the possible applications of the instrument described is the polarimetric measurement of the photoinduced optical anisotropy in various materials and its change with time. We used samples of rigid solutions of fluorescein in orthoboric acid [l0].

  The photochromic properties of fluorescein are well known. They are related to metastable triplet level population. A wide triplet absorption band is induced in
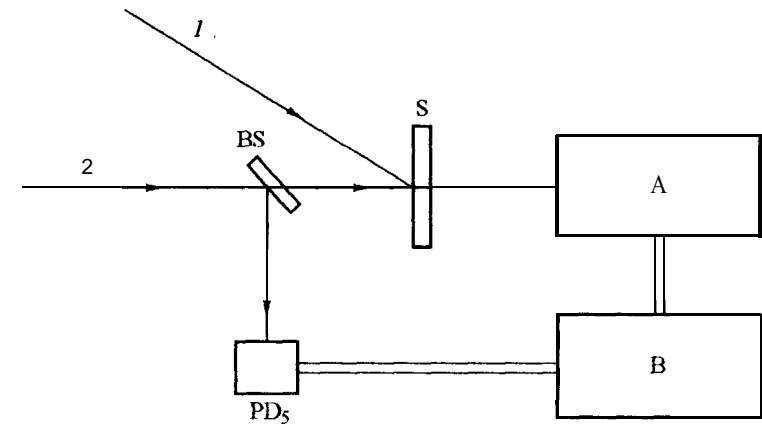
Fig. 5. Experimental setup for measurement of photoinduced anisotropy: 1 — exciting laser beam, 2 — measuring light beam, BS — beamsplitter, S — sample, PD5 — phototransducer, A -- optical head of the photopolarimeter, B — data acquisition system

the longer wavelength range of the visible spectrum at the expense of decay of the basic singlet band ($\lambda_{max} \approx 460$ nm). As shown in [10,l l], this photoprocess is accompanied with induction of optical anisotropy. We use the new photopolarimeter for measuring the appearence and decay of this photoanisotropy at λ = 632.8 nm and λ = 780 nm. The optical arrangement of Fig. 5 is used. The photoprocess in the sample is induced by an Ar laser beam 1 (λ = 488 nm), polarized in the plane of incidence. The measuring beam 2 from a He-Ne or a semiconductor laser with a polarization of 45° passes through the sample and the Stokes parameters of the output beam S_i^{out} are measured by the photopolarimeter. At the same time, an auxiliary photodiode PD5 measures continuously the intensity I of beam 2. The values of S_j^{out} are measured at time intervals At = 25 ms longer than the time resolution of the device.

  The experimental results are illustrated in Fig. 6. The intensity of the exciting laser beam is 30 mW. The photoinduced change in S_i^{out} is reached for less than 1 s after the onset of the photoprocess. The time constant of the reverse process (after exciting light switch-off) is somewhat longer, as is known from previous results [10].

  From the measured values of S_j^{out}, the changes in the optical properties of the sample — induced optical density, dichroism and birefringence, can be determined, using the formulae [12]:

$$D_{\parallel} = I_g \{I/ (S_0^{out} + S_1^{out})\}$$

(optical density for light polarized along the induced optical axis)

$$D_{\perp} = I_g \{I/ (S_0^{out} - S_1^{out})\}$$

(optical density for perpendicularly polarized light)

$$AD = D_{\parallel} - D_{\perp} = I_g \{ (S_0^{out} + S_1^{out}) / (S_0^{out} - S_1^{out})\}$$

(dichroism)

$$An = \lambda\delta/2\pi d; \quad \delta = \arctan (S_3^{out}/S_2^{out})$$

(birefringence).

Here d is the film thickness (100 μm), λ is the wavelength, and I is the intensity of the incident beam.

Figs 7 and 8 illustrate the changes in $D_\parallel$, $D_\perp$, AD and δ of the sample at $\lambda = 633$ nm and $\lambda = 780$ nm under the action of an Ar laser beam with intensity

max amp = 1.0001   min amp = 0.6118

S_0

0.000   time step 0.021 s   6.168 s

max amp = 0.0075   min amp = -0.0411

S_1

0.000   time step 0.021 s   6.168 s

max amp = 1.0083   min amp = 0.5860

S_2

0.000   time step 0.021 s   6.168 s

max amp = 0.0151   min amp = -0.0023

S_3

0.000   time step 0.021 s   6.168 s

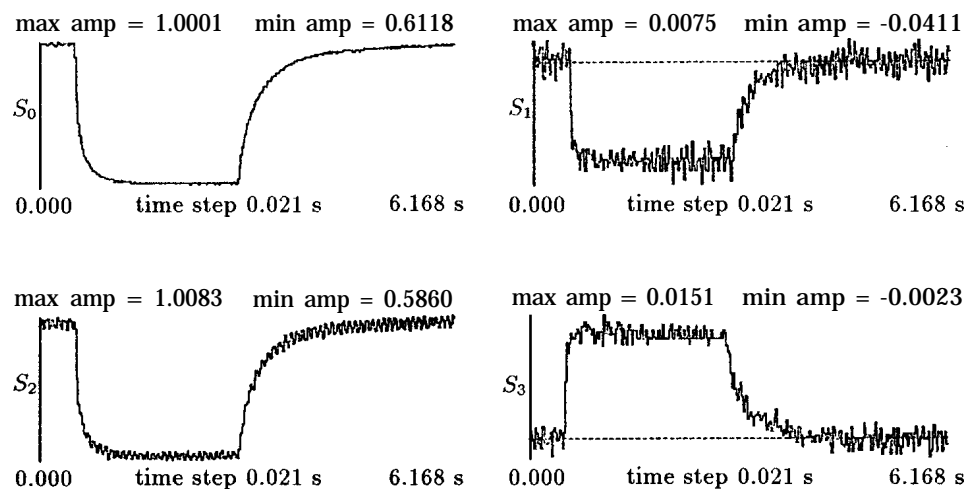Fig. 6. Normalized Stokes parameters of light beam with $\lambda = 632.8$ nm linearly polarized at $45°$ and passing through the sample of fluorescein. The changes in S_i are due to the changes of the optical constants of the sample induced by the Ar-beam, polarized in the plane of incidence
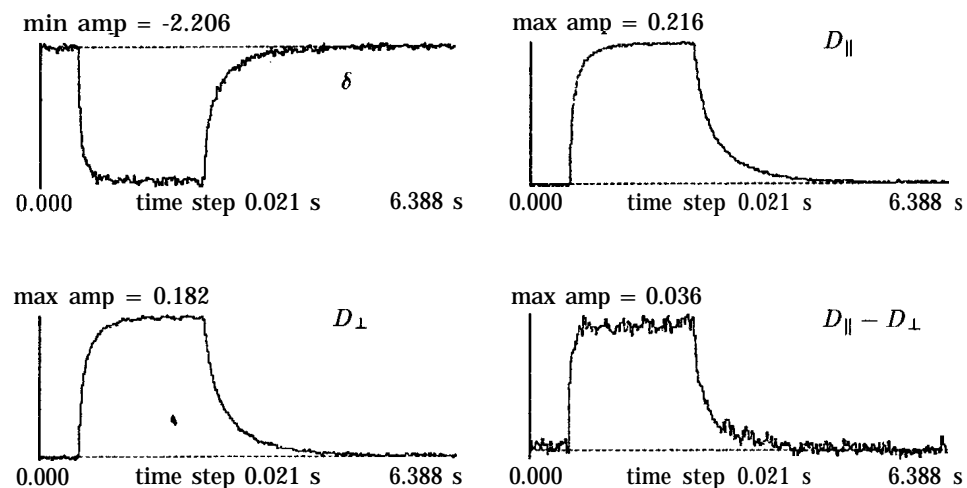
min amp = -2.206

δ

0.000   time step 0.021 s   6.388 s

max amp = 0.216

$D_\parallel$

0.000   time step 0.021 s   6.388 s

max amp = 0.182

$D_\perp$

0.000   time step 0.021 s   6.388 s

max amp = 0.036

$D_\parallel - D_\perp$

0.000   time step 0.021 s   6.388 s

Fig. 7. The changes in the optical constants $D_\parallel$, $D_\perp$, AD and σ of a sample of rigid solution of fluorescein in orthoboric acid induced by an Ar laser beam (488 nm) and measured at $\lambda = 633$ nm

50 mW. The induction of the photochromic process and its decay on exciting light switch-off can be observed. A new absorption band in the red region is created. It is dichroic for both wavelengths used at the measurements. The appearence and decay of birefringence in the sample can be measured at the same time. It is obvious that it is related to the absorption changes (in accordance with the dispersion relations). Since the sign of the birefringence is opposite to that of dichroism, it may be concluded that An is due to the decay of the basic singlet band of the dye during the optical excitation.
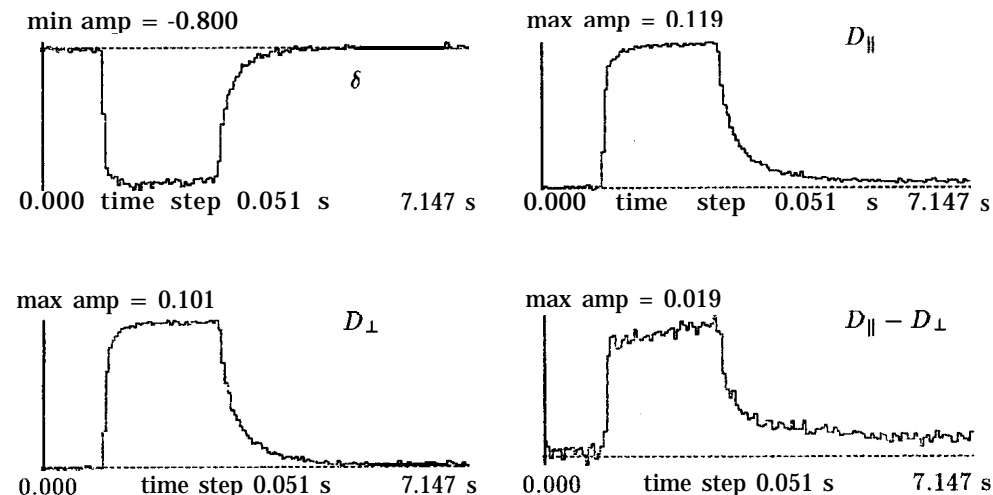
min amp = -0.800

δ

0.000 time step 0.051 s   7.147 s

max amp = 0.119

$D_\parallel$

0.000   time   step   0.051   s   7.147 s

max amp = 0.101

$D_\perp$

0.000   time step 0.051 s   7.147 s

max amp = 0.019

$D_\parallel - D_\perp$

0.000   time step 0.051 s   7.147 s

Fig. 8. The same as Fig. 6 but for measuring beam with $\lambda = 780$ nm

4. Conclusion

In our opinion, the results from the investigations of the simplified version of the spectrophotopolarimeter prove the potentialities of the proposed optical scheme. The good precision of the measurement and the easy handling of the device are related to the extreme simplicity of the calibration method.

It should be pointed out that such simultaneous measurement of the dichroism and birefringence change in time is impossipble to carry out using standard techniques (using rotating polarization optical elements). The high sensitivity of the measurement is also worth mentioning. The results prove that this device can measure accurately phase changes of 0.1' and AD = 0.01 under dynamic conditions that is not considered easy in the experimental practice.

We think that the general scheme of the spectrophotopolarimeter is also worth realizing. Such a device could do real time measurements of dichroic and birefringence spectra and would help very much investigations on photochemical reactions and their products.

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