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Response of boundary layer flow to vortices normal to the leading edge

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Abstract – The response of a boundary layer at a plate with a blunt nose to steady vortices normal to the leading edge was studied experimentally. The wake behind a wire stretched normally to the plate was used as a source of vortical disturbances. Three regimes of wake/boundary layer interaction, distinguished by the distribution of spanwise disturbances and their downstream development were observed. In particular, the non-symmetric response of the boundary layer to a high velocity deficit symmetric wake has been discovered. It was shown that wake vorticity field deformation by the flow around the leading edge plays a decisive role in streamwise vortex formation above the boundary layer and boundary layer distortion. © 2001 Éditions scientifiques et médicales Elsevier SAS

boundary layer / receptivity / vorticity / transition

Nomenclature

x, y, z	streamwise, spanwise and vertical coordinates, mm
ν	kinematic viscosity, m^2s^{-1}
u_∞	outer flow velocity, ms^{-1}
d	diameter of wire, mm
L	distance from wire to leading edge, mm
b	half-width of wake, mm
r	radius of leading edge, mm
δ	boundary layer thickness at the leading edge, mm
Δu_b	distortion of boundary layer (difference between the maximal and minimal velocity in the spanwise profile), ms^{-1}
R_d	Reynolds number based on diameter of wire (non-dimensional)
u_0	velocity deficit in wake (non-dimensional)
K	inviscid non-dimensional parameter, responsible for regime of interaction
K_ν	viscous non-dimensional parameter, responsible for regime of interaction

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1. Introduction

A longitudinal streaky structure usually appears in a boundary layer subjected to free-stream turbulence [1,2]. This structure is believed to give rise to the so-called by-pass transition (a term introduced by Morkovin [3]). Most authors [4–7] suppose that streaks are generated by streamwise vortical disturbances, producing the cross-flow velocity at the boundary layer. Modern theories of this type based on the PSE-method developed by Herbert and Lin [5] and Bertolotti [6] predict well the downstream growth of low-frequency pulsations in the boundary layer and their vertical profiles measured in experiments [1,2]. The response of the boundary layer to artificially generated single streamwise vortices was studied in experiments [7] and results were in good agreement with theory [6] also.

In the alternative theory of Goldstein et al. [8,9], the non-uniformity of free-stream velocity along the span or vorticity normal to the leading edge is considered as the reason for streak formation. Owing to vortex-lines stretched by the flow around the blunt leading edge, the normal to plate vorticity is transformed into streamwise vortices distorting the boundary layer. The receptivity of the boundary layer to normal-to-leading edge vorticity generated by a vibrating ribbon positioned upstream of the plate and oriented normal to it was studied in earlier experiments by Kachanovet al. [10]. The measurements were made in the vicinity of a sharp leading edge and only slight amplification of the streamwise velocity pulsations within the boundary layer was observed. The response of the boundary layer on the flat plate and blunt nose wing to vortical disturbances, introduced by impulsive air blowing from a tube located upstream of the leading edge, was studied in [11]. Effective streak formation in a boundary layer of a sharp nose plate caused by almost immeasurably small steady non-regular free-stream non-uniformities was observed in a recent experiment of Watmuff [12].

Our work is devoted to a quantitative study of the influence of well-controlled flow non-uniformity on the boundary layer at a blunt nose plate. The non-uniformity was produced by the wake behind a wire placed normal to the plate upstream of the leading edge.

2. Experimental setup

The experiment was performed in the low-turbulence direct-flow wind tunnel T-36 I of TsAGI. The test section is 2.6 m long, 0.5 m wide and 0.35 m high, and is preceded by a 12 : 1 contraction. The free-stream turbulence level in the test section is 0.06%, measured in the band 5–1500 Hz. The general outline of experimental setup is shown in *figure 1(a)*. The interaction of the wake from a vertically stretched wire with the boundary layer on a horizontally mounted 20-mm-thick plate with 4 : 1 elliptical leading edge was studied. Special efforts were made to achieve zero pressure gradient over the plate and symmetric flow around the leading edge.

All three components of velocity were measured with a DISA 55M01 hot-wire anemometer. A hot-wire probe with horizontal wire of diameter 5 μm and a sensitive length of 0.5 mm was used for streamwise velocity measurements. Spanwise and vertical components of velocity were measured by a specially designed X-wire probe of similar dimensions. The probe was traversed in the streamwise and vertical directions. Instead of spanwise movement of the probe the wire was traversed in this direction. The streamwise coordinate x is the distance from the leading edge in streamwise direction, y is the distance from wire along the span, z is the vertical distance from plate surface. This coordinate system together with general designations used are shown in *figure 1(b)* and *1(c)*.

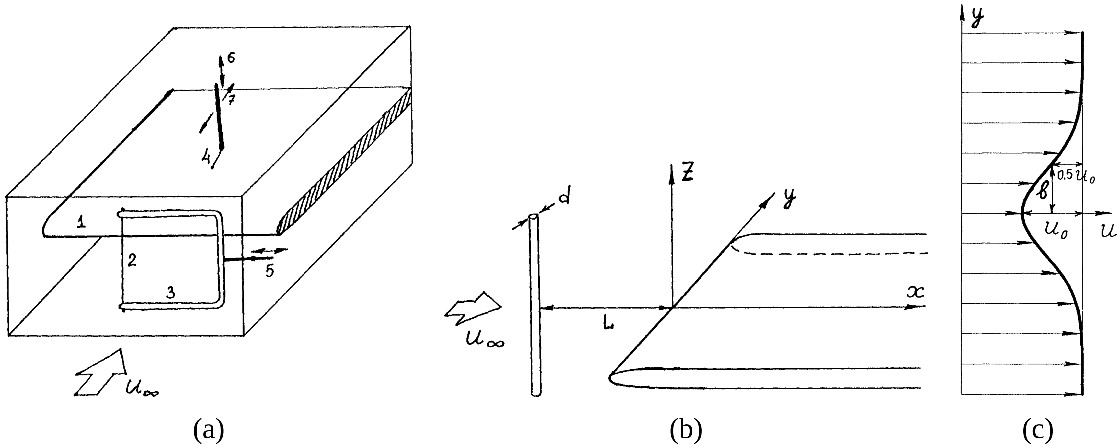

Figure 1. (a) Experimental setup: 1 – plate, 2 – wire, 3 – wire holder, 4 – probe, 5 – wire movement, 6, 7 – probe movements; (b) coordinate system and general designations; (c) parameters of oncoming wake: u_0 – velocity deficit, b – half-width.

3. Results

The wake behind the wire of diameter $d = 0.09$ mm in a flow with speed $u_\infty = 17$ ms^{-1} was used as a source of oncoming flow disturbances. The Reynolds number based on diameter of the wire was approximately $R_d = 105$, so that a Karman vortex street occurs in the flow behind it [13]. This street decays gradually downstream and, for a distance greater than 100 d, the associated peak in the velocity pulsation spectrum disappears. Pulsations in such decayed Karman vortex streets were about 0.2% of the free-stream velocity. Interaction of this wake with the boundary layer was studied for different distances L from wire to leading edge. The profile of the mean velocity u in the wake at the leading edge was found to be well correlated with the formula

$$\frac{u}{u_\infty} = 1 - u_0 \exp\left[-\left(\frac{y}{b}\right)^2 \ln 2\right]; \quad u_0 = \frac{A}{\sqrt{L}}; \; b = B\sqrt{L},$$

where u_0 is velocity deficit, b is half-width of the wake, A and B are constants. Oncoming wake parameters for all distances L tested are listed in *table I*.

There were found three distinct regimes of wake/boundary layer interaction: linear regime, symmetric nonlinear regime and antisymmetric nonlinear regime. Spanwise distributions of a streamwise velocity in boundary layer measured in these regimes are shown in *figure 2*. The boundary layer flow distortions Δu_b as functions of distance from the leading edge x for the same regimes are plotted in *figure 3*. This distortion Δu_b is determined as a difference between the maximal and minimal streamwise velocities in the spanwise profile measured for z corresponding to $u = 0.5u_\infty$.

The linear regime occurs when the distance from wire to leading edge is large enough ($L \geqslant 500$ mm) so the velocity deficit of the oncoming wake is small and its width is large. In this case the shape of the spanwise distribution of velocity in the boundary layer approximately repeats the velocity profile in the wake. The amplitude of boundary layer distortion in accordance with predictions of all theories [5,6,8,9] grows with distance from leading edge.

When the wire was placed closer then 300 mm from the leading edge, the boundary layer response to the wake became noticeably non-linear. Non-linearity manifests itself as a deformation of the spanwise profile of velocity in the boundary layer (see *figure 2(b)* and *2(c)*). For a moderate distance from leading edge

Table I. Parameters of the configurations tested.

L (mm)	u_0	b (mm)	regime$^{(*)}$	K	K_ν
40	0.0553	0.46	a.s.	0.3	5.6×10^{-3}
150	0.0393	0.7	tr.	0.14	2.5×10^{-3}
250	0.0317	0.88	s.	0.09	1.7×10^{-3}
500	0.0236	1.13	l.	0.046	8.5×10^{-4}
720	0.0142	1.31	l.	0.030	5.65×10^{-4}

$^{(*)}$ regimes of interaction: l. – linear, s. – symmetric nonlinear, a.s. – antisymmetric nonlinear, tr. – transient regime between s. and a.s.

150 mm$< L <$ 300 mm, the profile remains symmetric with respect to the wake centre, so this regime of interaction is called the nonlinear symmetric one. If the wire is placed nearer to leading edge ($L \leqslant 100$ mm), the boundary layer response to the symmetric wake becomes antisymmetric as shown in *figure 2*. This type of wake/boundary layer interaction will be called the nonlinear antisymmetric regime. There are two possible antisymmetric regimes: the 'right' regime (shown in *figure 2(c)*) with maximum of streamwise velocity at the right side and the 'left' one with maximum at the left side. Both of these regimes were observed and they exchanged randomly when the wind tunnel was stopped and started again. Unlike the linear regime, the flow distortion in both nonlinear regimes reaches a maximum at about 100 mm from the leading edge and then decays downstream (see *figure 3*). At large distances from the leading edge, the distortion from a weak wake, initiating the linear regime, becomes greater than distortion from high-deficit wake initiating the non-linear regime.

Velocity vectors in the (y, z) plane for non-linear symmetric and antisymmetric regimes are shown in *figure 4*. Dashed lines at $z = 2$ mm show the outer edge of the boundary layer where $u = 0.99u_\infty$. *Figure 4(a)* shows that the nonlinear symmetric regime is associated with two counter-rotating vortices located above the boundary layer at $z \cong 4$ mm. Similar but weaker vortices above the boundary layer were observed in the linear regime. For nonlinear antisymmetric regime only one streamwise vortex at $z \cong 4$ mm was observed as shown in *figure 4(b)*. This means that one of two vortices disappears or became much weaker than the other one. The mechanism of this phenomenon is not clear and it will be discussed in section 4. It is apparent that remaining single vortex produces an antisymmetric streamwise velocity distribution in the boundary layer, which is similar to that initiated by an axial vortex in [7]. The vertical and spanwise velocity components generated by streamwise vortices at the upper edge of the boundary layer are of the same order of magnitude as the velocity deficit in the oncoming wake. So, as was pointed out in [9], the origination of streamwise vortices above the boundary layer is a significant feature of the spanwise inhomogeneous flow interacting with the leading edge.

Vertical distributions of boundary layer distortion Δu_b measured in all three regimes are shown in *figure 5*. This shows good coincidence of all flow distortion profiles with profile of pulsations in boundary layer under an enhanced outer flow turbulence level measured by Kendall [1]. So, one may suppose that vortex/boundary layer interaction in symmetric as well as in antisymmetric regimes is a source of low-frequency pulsations in a boundary layer in high-turbulence level outer flow.

4. Discussion

In this section the results obtained are compared with predictions from theory. In accordance with Goldstein's theory [8,9], the wake/boundary layer interaction occurs in two steps. The first step is the transformation of oncoming flow non-uniformity into streamwise vortices by means of vortex-line deformation around the leading edge, the second one is boundary layer distortion by the resulting streamwise vorticity. In [8,9] a linear rapid-

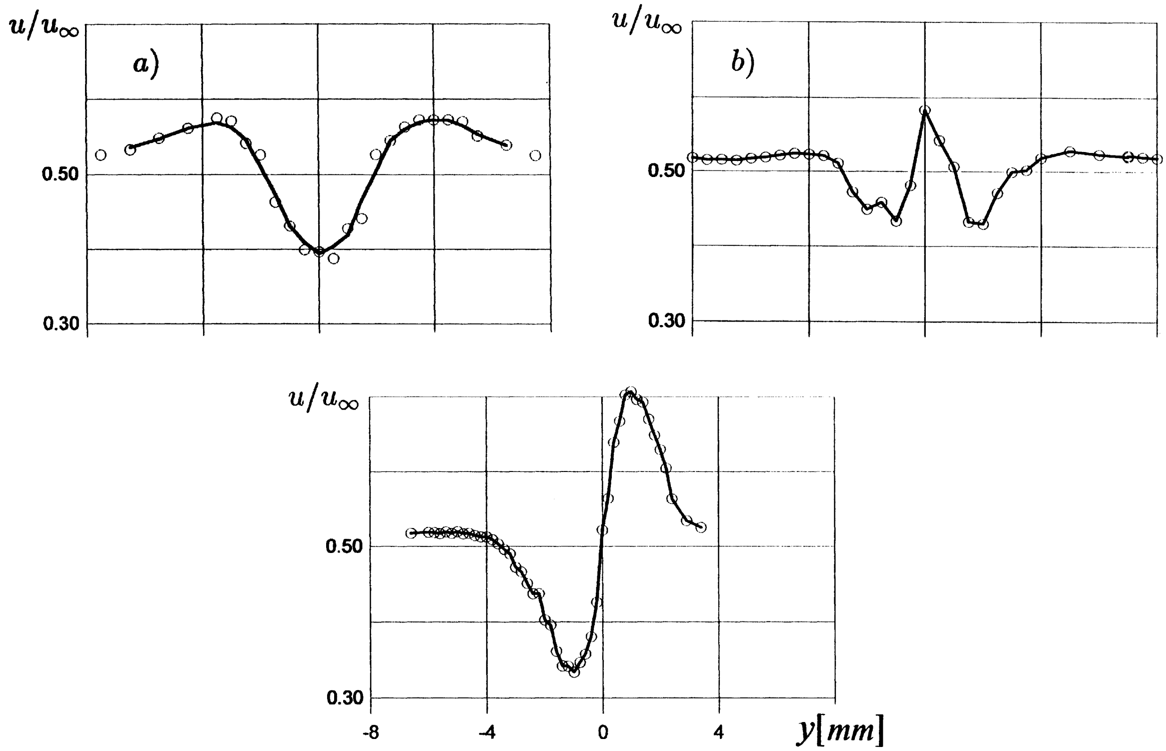

Figure 2. Spanwise profiles of velocity in the boundary layer measured for z corresponding to $u = 0.5u_\infty$. (a) – linear regime ($L = 720$ mm, $x = 250$ mm); (b) – nonlinear symmetric regime ($L = 250$ mm, $x = 150$ mm); (c) – nonlinear antisymmetric regime ($L = 40$ mm, $x = 150$ mm).

distortion method is used for the description of the first step and non-linear analysis is applied to the second step. To imagine the deformation of the vorticity field, let us consider the wake as a pair of counter-rotating vortices. Stretching of these vortices around the nose should produce a pair of counter-rotating streamwise vortices. It is such vortices which were observed above the boundary layer in the linear and nonlinear symmetric regimes of interaction (see *figure 4(a)*). Theory [8,9] predicts the decrease of the boundary layer velocity in the minimum of the oncoming velocity profile, since fluid lifted between the vortices causes a diminution of boundary layer velocity. However, only the distortion in the linear regime of interaction coincides with theoretical predictions. In the nonlinear symmetric regime a local maximum of velocity appeared in the middle of the wake, associated with unexpected downwards movement of fluid in the boundary layer (see *figure 4(a)*). Since the non-linear symmetric regime occurred when the wake became strong and narrow, it may be caused by some non-linear effects not accounted for in Goldstein's scheme. Among other possible mechanisms for such non-linearity, we may consider the formation of a separation bubble near the stagnation point as shown in figure 3 of Morkovin's review [14], or the local flow separation near the ellipse-plate junction. The appearance of the antisymmetric regime may be caused by instability of any type of separation-bubble flow associated with the nonlinear symmetric regime or by a Crow-type instability of a pair of streamwise vortices [15] above the boundary layer.

To characterize the relative strength of non-uniformity, the velocity gradient (or vorticity) in it, u_0/b, should be compared with some characteristic velocity gradient in flow around the leading edge. Two characteristic gradients u_∞/r and u_∞/δ (where r is the radius of the nose and $\delta = (\frac{r\nu}{u_\infty})^{1/2}$ is the boundary layer thickness) may be proposed and two non-dimensional parameters $K = \frac{u_0}{b}\frac{r}{u_\infty}$ and $K_\nu = \frac{u_0}{b}\frac{\delta}{u_\infty}$ can be calculated. Both

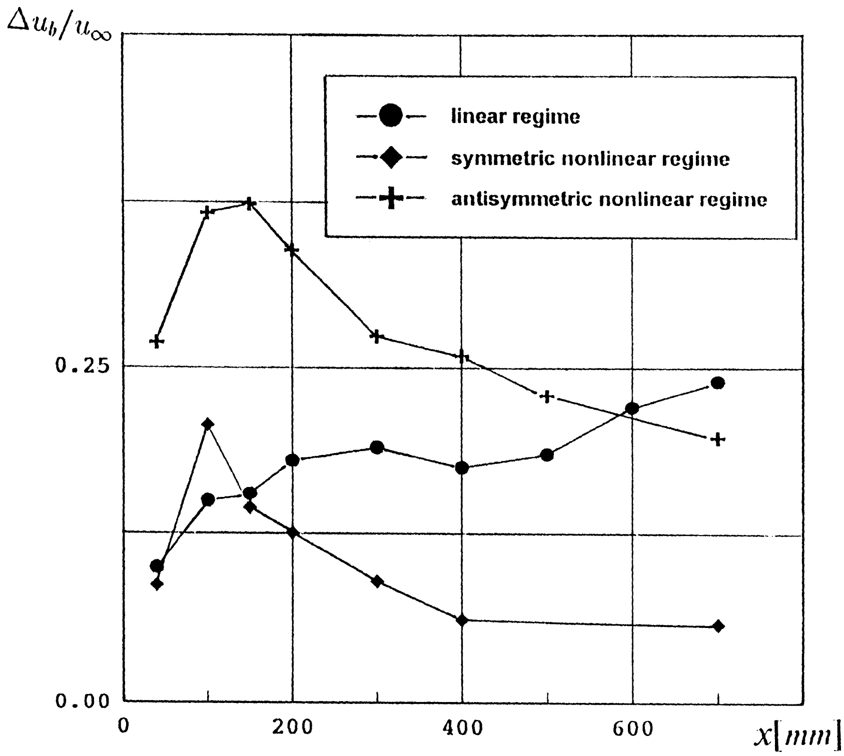

Figure 3. Boundary layer distortion Δu_b as a function of distance from the leading edge.

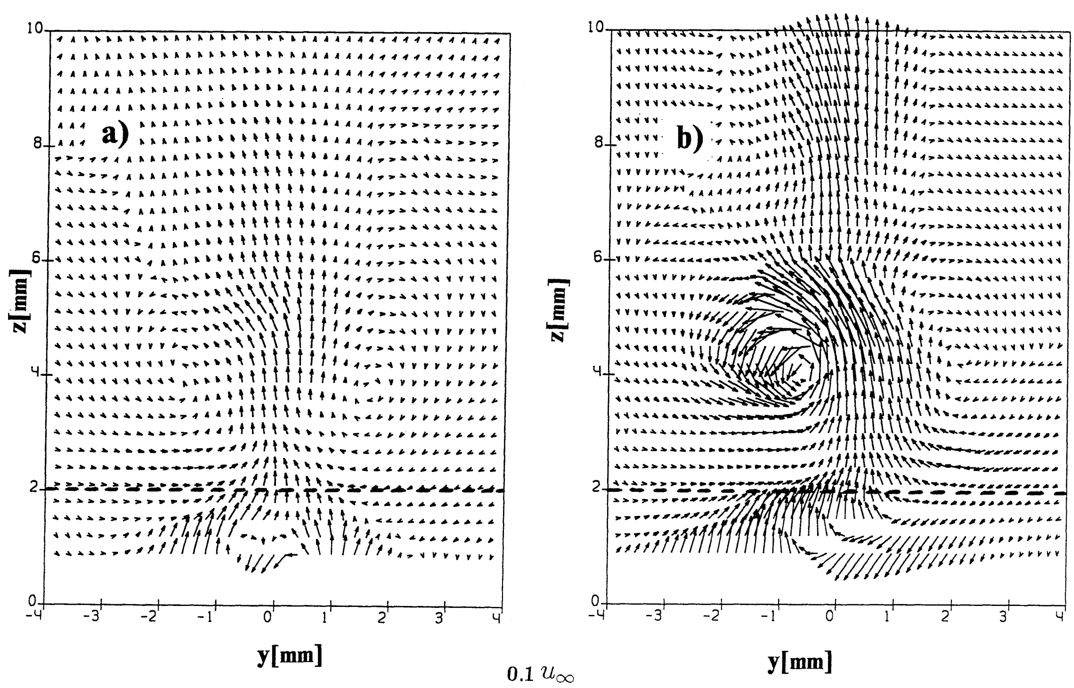

Figure 4. Velocity vectors in the y–z plane for: (a) nonlinear symmetric regime ($L = 250$ mm, $x = 150$ mm); (b) – nonlinear antisymmetric regime ($L = 40$ mm, $x = 150$ mm).

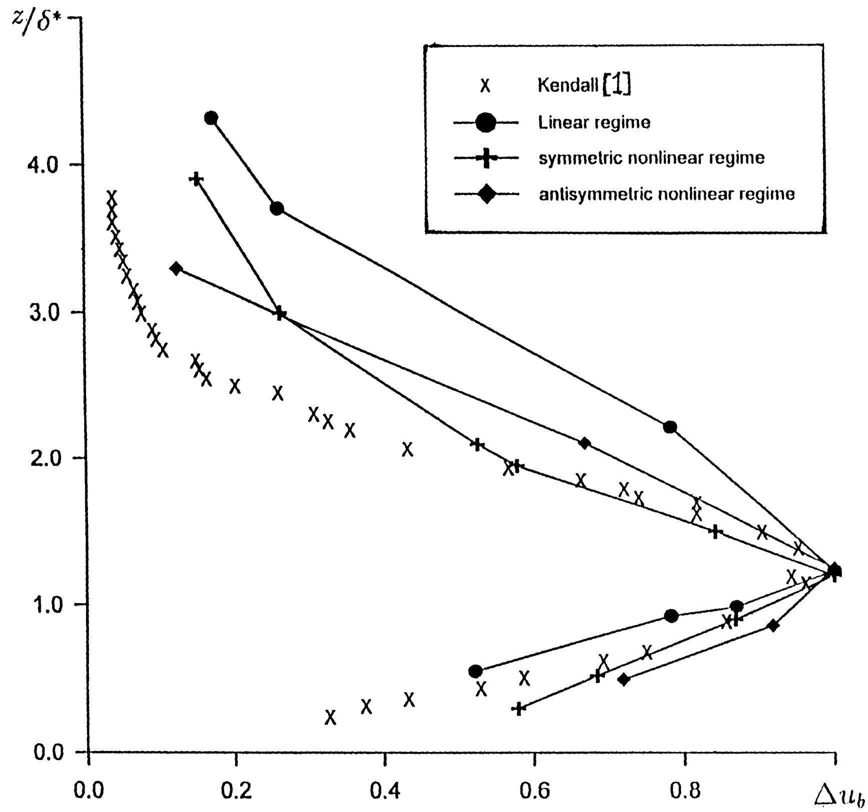

Figure 5. Vertical profiles of flow distortion in the boundary layer for different regimes of wake/boundary layer interaction. × – low-frequency pulsations in experiment [1].

parameters, for all configurations tested, are given in *table I*. It may be seen that when any one of the parameters increases, the boundary layer distortion changes from linear through symmetric nonlinear to antisymmetric regime. Preliminary studies of wake/boundary layer interaction for different velocities and shapes of leading edge showed a satisfactory correlation of the change of distortion regime with both parameters.

The aim of this short paper is to attract attention to new phenomena observed in the course of a study of the wake/boundary layer interaction. A detailed investigation of the velocity fields associated with non-linear regimes of interaction and a theoretical explanation of them require further research which is now in progress.

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