The process \(e^+e^- \rightarrow J/\psi X(3940)\) at \(\sqrt{s} = 10.6\) GeV in the framework of light cone formalism.

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This paper is devoted to the study of the process \(e^+e^- \rightarrow J/\psi X(3940)\) in the framework of light cone formalism. In our calculation two hypotheses about the structure of \(X(3940)\) meson are considered: \(X(3940)\) is \(3^1S_0\) state and \(X(3940)\) is one of \(2^3P\) states. The former hypothesis leads to a good agreement with the cross section measured at the experiment. As to the latter one, it is proposed a mechanism that allows one to understand the suppression of \(2P\) mesons production in hard processes.

PACS numbers: 12.38.-t, 12.38.Bx, 13.66.Bc, 13.25.Gv

I. INTRODUCTION

There are a number of charmonium-like mesons discovered recently in different experiments (see review [1]). Our paper is devoted to a charmonium-like meson \(X(3940)\) discovered in inclusive process \(e^+e^- \rightarrow J/\psi +\text{anything}\) at Belle [2]. The distribution of masses recoiling against the reconstructed \(J/\psi\) in \(e^+e^- \rightarrow J/\psi +\text{anything}\) events measured at this experiment is shown in Fig. 1.

\[\begin{align*}
|\eta_c\rangle & \rightarrow |\eta_c\rangle \\
|\chi_{c0}\rangle & \rightarrow |\chi_{c0}\rangle \\
|\chi_c(2S)\rangle & \rightarrow |\chi_c(2S)\rangle \\
|X(3940)\rangle & \rightarrow |X(3940)\rangle
\end{align*}\]

Fig. 1: The distribution of masses recoiling against the reconstructed \(J/\psi\) in \(e^+e^- \rightarrow J/\psi +\text{anything}\) events.

Evidently the theory that pretends to the understanding of the mechanism of \(X(3940)\) meson production in \(e^+e^-\) annihilation must also describe well the processes \(e^+e^- \rightarrow J/\psi \eta_c, J/\psi \eta'_c, J/\psi \chi_{c0}\) measured at Belle. Considering charmonium mesons as a nonrelativistic bound states of \(c\bar{c}\) pair one tried to apply NRQCD to these processes [3], but the results of these calculation proved to be in contradiction with Belle and BaBar measurements [4, 5].

Another approach to the prediction of the cross sections of these processes is light cone formalism. The authors of paper [6] calculated the process \(e^+e^- \rightarrow J/\psi \eta_c\) in the framework of this approach. Despite of the uncertainties the agreement with the experiments was rather good. Further progress in understanding of exclusive double charmonium production in \(e^+e^-\) annihilation was connected with papers [7] and [8]. In the former paper the process \(e^+e^- \rightarrow J/\psi \eta'_c\) was calculated. The latter one predicts the cross section of the process \(e^+e^- \rightarrow J/\psi \chi_{c0}\). The values of the cross sections obtained in these papers are in good agreement with experimental results. In addition to good agreement with the experiments the application of light cone formalism allows one to understand that the wave functions of charmonium mesons are too wide to describe double charmonium production in the framework of NRQCD.
In our paper we will consider \( X(3940) \) meson in the framework of conventional quark model and suppose that this meson is an excitation of charmonium meson already seen at Belle experiment. There are tree mesons \( \eta_c(1S_0), \eta_c'(2S_0), \chi_c(1S_0) \) in Fig. 1. Actually the peak labeled by \( \chi_c(1S_0) \) can arise from \( \chi_c(1S_0), \chi_c(1P_1), \chi_c(1P_2) \) mesons, although \( \chi_c(1S_0) \) gives dominant contribution. So two scenarios must be considered: \( X(3940) \) is \( \eta_c'(3S_0) \) state and \( X(3940) \) is one of \( \chi_c(2S_0), \chi_c'(2S_0), \chi_c'(2P_2) \) states.

This paper is organized as follows. In section 2 the model for the light cone wave functions used in our calculation is considered. Section 3 is devoted to the calculation of the cross section of \( X(3940) \) meson production. In last section we discuss results obtained in our paper.

II. THE LIGHT CONE WAVE FUNCTIONS OF \( ^1S_0, ^3S_1 \) AND \( ^3P_0 \) THE MESONS.

In this section the light cone wave functions of \( ^1S_0, ^3S_1 \) and \( ^3P_0 \) mesons will be considered. The functions used in our calculation are defined as follows (for details see [3, 5, 6]):

\( ^3S_1 \) meson

\[
\langle \lambda \mu | \bar{Q}_\gamma (z) Q_\alpha (z) | 0 \rangle = \frac{f_{\bar{Q}Q} M_{\bar{Q}Q}}{4} \int_0^1 dx_1 e^{i p_2 (x_1 - x_2)} \left\{ \bar{p} (z) V_L(x) + \left( \bar{e}_\lambda - \bar{p} (z) \right) V_\perp(x) + \frac{2M_{\bar{Q}Q}}{M_{\bar{Q}Q}^2} Z_t (\sigma_{\mu \nu} e_\lambda \mu p^\nu) V_T(x) + \frac{Z_t}{V_{\gamma \mu} M_{\bar{Q}Q}^2} \left( \lambda = \bar{e}_\lambda (z) \right) V_A(x) \right\} ,
\]

\( ^1S_0 \) meson

\[
\langle \gamma \mu | \bar{Q}_\gamma (z) Q_\alpha (z) | 0 \rangle = \frac{i f_{\bar{Q}Q} M_{\bar{Q}Q}}{4} \int_0^1 dx_1 e^{i p_2 (x_1 - x_2)} \left\{ \bar{p} \gamma_\gamma \mu P_A(x) - \frac{M_p}{2M_{QQ}} Z_p \gamma_\gamma P_{\gamma \mu} \right\} ,
\]

\( ^3P_0 \) meson

\[
\langle \gamma \mu | \bar{Q}_\gamma (z) Q_\alpha (z) | 0 \rangle = \frac{f_{\bar{Q}Q} M_{\bar{Q}Q}}{4} \int_0^1 dy e^{i p_2 (x_1 - x_2)} \left\{ \bar{p} \gamma_\gamma \mu S_V(x) - \frac{M_p}{2M_{QQ}} Z_p S_S(x) \right\} .
\]

Here the following designations were used: \( M_{QQ} = M_{QQ} (\mu = M_{QQ} M_{QQ}), x = x_1, x_2 = 1 - x \) are the fractions of meson momentum carried by \( c \) quark and \( \bar{c} \) antiquark correspondingly, the factors \( Z_p, Z_t, Z_m, Z_v \) are defined as

\[
Z_p = \left[ \frac{\alpha_s (\mu^2)}{\alpha_s (M_{QQ}^2)} \right]^{-3C_F/8b_o}, \quad Z_t = \left[ \frac{\alpha_s (\mu^2)}{\alpha_s (M_{QQ}^2)} \right]^{C_F/8b_o}, \quad Z_m = \left[ \frac{\alpha_s (\mu^2)}{\alpha_s (M_{QQ}^2)} \right]^{-3C_F/8b_o}, \quad Z_v = \left[ \frac{\alpha_s (\mu^2)}{\alpha_s (M_{QQ}^2)} \right]^{8C_F/8b_o},
\]

where \( C_F = 4/3, b_o = 25/3 \). The wave functions \( \phi_3 = V_L, V_\perp, V_T, V_A, P_A, P_P, S_S \) are normalized as follows: \( \int_0^1 dx_1 \phi_i = 1 \). The wave function \( S_V \) is normalized as \( \int_0^1 dx_1 (x_1 - x_2) S_V(x) = 1 \). The dependence of the light cone wave functions on the scale \( \mu \) is very slow and it will not be considered in the full form in all functions used in our calculation. Only renormalization factors of the corresponding local currents \( Z_p, Z_t, Z_v \) will be regarded.

Unfortunately today there is no information about the light cone wave function obtained directly from QCD Lagrangian. So to proceed with numerical analysis we are forced to use some model for these wave functions. To find the leading twist wave functions \( V_L(x), V_T(x), P_A(x), S_V(x) \) we will apply Brodsky-Huang-Lepage(BHL) procedure which allows one to connect the light cone wave functions of leading twist with the equal time wave function in the rest frame. The equal time wave functions of charmonium mesons will be taken from the solution of Schrodinger equation with Buchmuller-Tye potential [10]. Having these wave functions in momentum space \( \psi(k^2) \) one can get the light cone wave functions of leading twist using the following rule [11]:

\[
\phi_i \sim \int k_1^2 < k^2 > d^2k_1 \psi_i (x, k_1),
\]

where \( \psi_i (x, k_1) \) can be obtained from \( \psi(k^2) \) after the substitution [9]

\[
k_1 \to k_\perp, \quad k_z \to (x_1 - x_2) M_0, \quad M_0^2 = \frac{m_c^2 + k_\perp^2}{x_1 x_2}.
\]

Here \( m_c \) is the quark mass in the potential model.
It is worth noting that in paper [12] the relations between the light cone wave functions and equal time wave functions of charmonium mesons in the rest frame were derived. The procedure proposed in paper [12] is similar to BHL with the difference: in formula (5) one must make the substitution $d^2k_\perp \to d^2k_\perp \sqrt{k^2 + m_c^2}/(4m_c x_1 x_2)$. But this substitution was derived at leading order approximation in relative velocity of quark-antiquark motion inside the charmonium. At this approximation $k^2 \sim O(v^2)$, $4x_1 x_2 \sim 1 + O(v^2)$ and the substitution amounts to $d^2k_\perp \to d^2k_\perp (1 + O(v^2))$. Thus at leading order approximation applied in [12] these two approaches coincide.

Using equation (5) the expression for the leading twist wave functions can be easily written in the following form

$$\phi_i(x) = c_i \phi^{as}_i(x) \tilde{\Phi}_i(x),$$

where the constants $c_i$ are fixed from the normalization condition, $\phi^{as}_i(x)$ are the asymptotic forms of wave functions of leading twist\(^1\), the functions $\Phi_i(x)$ are given by the formulas

$$\Phi(x) = \int_0^{x_1^2/x_2} d\xi \psi(\xi + (x_1 - x_2)^2 4x_1 x_2 - m_c^2),$$

for S-wave mesons,

$$\Phi(x) = \int_0^{x_1^2/x_2} d\xi \psi(\xi + (x_1 - x_2)^2 4x_1 x_2 - m_c^2),$$

for P-wave mesons.

For the light cone wave functions of nonleading twist there is no relation similar to equation (5) and to calculate these functions the following model will be applied. It is known that nonleading twist wave functions can be written as a product

$$\phi_i(x) \sim \phi^{as}_i(x) \tilde{\Phi}_i(x),$$

with unknown functions $\tilde{\Phi}_i(x)$. In our calculation we will suppose that the functions $\tilde{\Phi}_i(x)$ equal to the corresponding functions $\Phi_i(x)$ of leading twist. Thus the model for the light cone wave functions of leading and nonleading twist is given by equations (7)-(8).

III. THE STUDY OF THE PROCESS $e^+e^- \to J/ΨX(3940)$.

First let us consider the hypothesis: **X(3940) is one of $\chi'_{c0}(2^3P_0), \chi'_{c1}(2^3P_1), \chi'_{c2}(2^3P_2)$ mesons.** At Belle $X(3940)$ is seen to decay to $D\overline{D}$ [2] and not to $D\overline{D}$. If this $D\overline{D}$ is dominant decay mode then $X(3940)$ is $\chi'_{c1}(2^3P_1)$. Unfortunately the process $e^+e^- \to J/ψ\chi'_{c1}(2^3P_1)$ has not been considered in the framework of light cone formalism yet but this formalism tells us that the cross section of the process $e^+e^- \to J/ψ\chi'_{c1}(2^3P_1)$ is suppressed by the factor $1/s$ in comparison with the cross section of the process $e^+e^- \to J/ψ\chi'_{c1}(2^3P_0)$ [3]. So one can expect that the cross section of $\chi'_{c0}$ production is greater than the cross section of $\chi'_{c1}$ production and if $\chi'_{c1}$ is seen at the experiment $\chi'_{c0}$ meson must be seen also. But the decay mode of $\chi'_{c0}$ meson is $D\overline{D}$ and since this decay mode is not seen at the experiment we reject this hypothesis.

\(^1\) for the wave functions $V_L, V_\perp, V_T, V_A, P_A, P_P, S_S$ $\phi^{as} \sim x_1 x_2$; for the wave function $S_U$ $\phi^{as} \sim x_1 x_2(x_1 - x_2)$. The asymptotic forms of the other functions used in the calculation can be found in papers [4, 5, 8].
Contrary to the NRQCD predictions the values of the cross sections of exited charmonium mesons production measured at Belle and BaBar experiments are rather large. For instance due to this the process \( e^+e^- \rightarrow J/\Psi \eta_c \) with excited \( \eta_c \) meson production is seen at the experiments. In connection with this fact the question arises: if the process \( e^+e^- \rightarrow J/\Psi \chi_c \) is seen at the experiment and \( X(3940) \) is not \( \chi_c \) meson why one does not see the production of excited charmonium state \( \chi_c \). One of the possible answers to this question is presented in Fig. 2 where the functions \( \Phi(x) \) for 1P and 2P states are shown. From this plot one can see that contrary to 1P state the function of 2P state \( \Phi(x) \) is oscillating function. In light cone formalism this wave function must be integrated with the hard part of the amplitude of the process, consequently one can expect considerable cancellation in the amplitude. We will not consider the hypothesis: \( X(3940) \) is excited \( 0^{++} \) meson. Two diagrams that give contribution to the \( e^+e^- \rightarrow J/\psi P \) for final mesons with equal masses was first found in paper [6]. In our calculation the result of paper [7] will be used where the case of different masses was considered. The cross section of the process involved can be expressed through the formfactor \( F_{\psi p} \) defined as follows

\[
\langle V(p_1, \lambda), P(p_2)|J_\mu|0\rangle = \epsilon_{\mu\nu\rho\sigma}p_1^\nu p_2^\rho F_{\psi p},
\]

The formfactor \( F_{\psi p} \) equals

\[
|F_{\psi p}(s)| = \frac{32\pi}{9} \left| \frac{f_V f_P M_P M_V}{q_0^2} \right| I_0,
\]

\[
I_0 = \int_0^1 dx_1 \int_0^1 dy_1 \alpha_s(\mu^2) \left\{ \frac{M_P Z_2 Z_3 V_T(x) P_P(y)}{M_V^2} \frac{d(x, y) s(x)}{d(x, y) s(x)} - \frac{1}{M_P M_V^2} \frac{Z_m(\mu^2) Z_1 V_T(x) P_A(y)}{d(x, y) s(x)} + \frac{1}{2M_P} \frac{V_L(x) P_A(y)}{d(x, y)} + \frac{1}{2M_P} \frac{1}{dy} \frac{1}{d(x, y)} \frac{(1 - 2y) V_L(x) P_A(y)}{d(x, y)} + \frac{1}{8} \left( 1 - Z_1 Z_m \frac{4M_Q^2}{M_V^2} \right) \frac{1}{M_P} \frac{(1 + y)V_A(x) P_A(y)}{d^2(x, y)} \right\},
\]

where \( q_0^2 \simeq (s - M_T^2 - M_P^2) \), \( P_A, P_P, V_T, V_L, V_A \) are the light cone wave functions defined above, \( M_V, M_P \) are the mass of the vector and pseudoscalar mesons correspondingly, \( d(x, y), s(x), s(y) \) are defined as follows:

\[
d(x, y) = \frac{k^2}{q_0^2} = \left( x_1 + \frac{\delta}{y_1} \right) \left( y_1 + \frac{\delta}{x_1} \right), \quad \delta = \frac{(Z_m M_Q)^2}{q_0},
\]

\[
s(x) = \left( x_1 + \frac{(Z_m M_Q)^2}{y_1 y_2 q_0^2} \right), \quad s(y) = \left( y_1 + \frac{(Z_m M_Q)^2}{x_1 x_2 q_0^2} \right).
\]
From formula (13) one sees that gluon propagator \( d(x, y) \) tends to infinity when the momenta of quark \( (k_1) \) or antiquark \( (l_1) \) created by this gluon tend to zero. Evidently this property has nothing to do with real situation: \( d(x, y) \to 4m_c^2/q_0^2 \) when \( x, y \to 0 \). Similar problem is seen in the expressions for quark propagators \( s(x), s(y) \). This problem appeared since the authors of paper 5 used the following expression for the quark momenta \( k_1 = (+, +, -) = (q_0x_1, 0, M_Q^2/x_1q_0) \) (and similarly for three other quarks). It is not difficult to understand that this expression can be applied if the energy of the quark is \( \sim \sqrt{s} \). If \( x \to 0 \) the energy of the quark is \( \sim q_0x_1 \ll \sqrt{s} \) and this expression becomes inapplicable. Nevertheless the calculation of the cross section of 1S, 2S charmonium mesons production can be done using equations (10)-(14) since these charmonium mesons can be considered as nonrelativistic objects. This means that the regions where expressions (13), (14) become incorrect are suppressed.

Contrary to the 1S and 2S charmonium mesons there is considerable contribution to the cross section 3S charmonium meson production from the regions where the expressions (13), (14) are incorrect. Thus these expressions must be modified. We will do this as follows. First we will disregard transverse motion of quark-antiquark pair even in the end point region \( x, y \sim 0 \) since account of the transverse motion is higher order \( v \) effect. Next if the energies of all quark \( q_0x_1, q_0y_1 \) in Fig.3 are greater than \( m_c \) than the following expression for the quarks and gluon propagators will be used:

\[
\begin{align*}
  d(x, y) &= x_1y_1, \\
  s(x) &= x_1, \\
  s(y) &= y_1.
\end{align*}
\]

If the energy \( q_0x_1 \) of quark \( k_1 \) reaches the value \( m_c \), what means that this quark is at rest, the expressions of the quark momentum \( k_1 = (q_0x_1, 0, m_c^2/x_1q_0) \) must be substituted by \( (m_c, 0, m_c) \) (and similarly for three other quarks). We will not write explicit expressions for gluon and quark propagators \( d(x, y), s(x), s(y) \) since they are rather cumbersome.

The model that will be applied in our calculation is rude but it is sufficient to apply it for the estimation of the value of the cross section. It is worth to note here that in the calculation of quark propagators \( s(x), s(y) \) we distinguish running mass \( M_Q(\mu) \) inside the quark propagators from the pole mass \( m_c \) of the external quarks \( k_1, k_2, l_1, l_2 \). Moreover in our calculation all scale dependent quantities will be taken at scale \( \mu^2 \sim s/4 \).

There are two contributions to the formfactor \( F_{vp} \) factored in formula (11). The first contribution originates from the wave function of mesons at the origin and it is proportional to \( \sim f_Vf_P \). The second contribution regards internal motion of quark-antiquark pair inside mesons and it is proportional to \( I_D \). The leading NRQCD approximation does not take into the account the contribution of the second type.

In the numerical calculation one loop expression for \( \alpha_s \) with \( \Lambda_{QCD} = 200 \text{MeV} \) will be used, \( \overline{M}_Q = 1.2 \text{GeV} \), \( m_c = 1.4 \pm 0.2 \). The functions (8) of 1S, 2S, 3S meson states at \( \mu \sim \overline{M}_Q \) are presented in Fig. 4. The constant \( f_V \) = 0.4GeV is determined from the decay width \( \Gamma(J/\psi \to e^+e^-) \). Supposing that \( X(3940) \) is \( 3^1S_0 \) meson the constant \( f_P \) can be estimated as \( f_P \sim f_V(3^3S_1) \). In turn the constant \( f_V(3^3S_1) \) can be found from the decay width \( \Gamma(\psi(4040) \to e^+e^-) \). Thus we have \( f_P \sim 0.17 \text{GeV} \). These numerical parameters lead to the value of the cross section

\[
\sigma(e^+e^- \to J/\psi X(3940)) \approx 11 \pm 3 \text{ fb}.
\]  
(15)

Experimental result for this cross section is \( \sigma \times Br(X(3940) > 2 \text{charged particles}) = (10.6 \pm 2.5 \pm 2.4) \text{fb} \) and it is in good agreement with our prediction. Sure there are a number of uncertainties connected with different reasons. For instance, one does not know the size of QCD radiative corrections and the size of \( 1/s \) corrections. In addition to these uncertainties there is an error due to the model of the light cone wave functions (7) used in our paper.

To calculate equal time charmonium wave functions nonrelativistic potential model was applied. Our calculation shows that there is considerable contribution to the cross sections from the kinematical region where the motion of quark-antiquark pair inside charmonium cannot be regarded as nonrelativistic. To make our prediction more reliable in addition to nonrelativistic potential model we have calculated the cross section in the framework of the model where charmonium mesons are treated as a relativistic quark-antiquark bound state (12). In the framework of this model the value of the cross section is \( \sigma \sim 10 \pm 3 \text{ fb} \).
IV. DISCUSSION.

In our paper light cone formalism was applied to the process $e^+e^- \rightarrow J/\Psi X(3940)$. We considered two hypotheses about the structure of $X(3940)$ meson: $X(3940)$ is one of $\chi'_c$, $\chi'_{c1}$, $\chi'_{c2}$ mesons and $X(3940)$ is $\eta''_c$ meson. Based on experimental data we rejected the first hypothesis and proposed the conjecture why $\chi'_c$ mesons are not seen at the experiment. If this conjecture is correct we predict the suppression of $\chi'_c$ mesons production in any hard process. As to the second hypothesis we calculated the cross section of $X(3940)$ meson production if this meson is $\eta''_c$. The result of our calculation is in good agreement with the experiment.

There are a number of uncertainties of our calculation connected with different reasons. For instance, one does not know the size of QCD radiative corrections and the size of $1/s$ corrections. But we believe that the main source of uncertainty is our model for the light cone wave functions. The main problem is that in our calculation we used nonrelativistic potential model. At the same time there is considerable contribution to the amplitude under consideration from region where the motion of quark-antiquark pair inside mesons cannot be considered as a nonrelativistic.

Obviously application of nonrelativistic potential models to this region results in large error. Nevertheless we believe that if one was able to build correct description of charmonium in the relativistic region the value of the cross section [15] would be of order of 10 fb. So the estimation of the cross section [15] using nonrelativistic potential model is rather good.

Last statement is based on the following facts. First of all in addition to the nonrelativistic potential model we applied relativistic potential model [12] to the calculation of the cross section of the process $e^+e^- \rightarrow J/\psi X(3940)$. In the framework of this model we obtained the value $\sigma \sim 10 \pm 3$ fb. Moreover it is possible to estimate the cross section in a model independent way. As was noted above the amplitude of the process $e^+e^- \rightarrow J/\Psi P$ is a product of NRQCD result for this amplitude and the factor that regards internal motion of quark antiquark pair inside the mesons. For the cross section this statement can be written in the following form

$$\sigma(e^+e^- \rightarrow J/\Psi P) \sim f_P^2 |I_0(P)|^2.$$  \hfill (16)

Obviously the wave functions of higher charmonium states become wider. Consequently the factor $I_0(P)$ that regards internal motion of quark antiquark pair inside the mesons is larger for higher charmonium states. So $I_0(3S) > I_0(2S)$. Using this relation and equation (16) one can get lower bound for the cross section of $\eta''_c$ meson production

$$\sigma(e^+e^- \rightarrow J/\Psi \eta''_c) > \sigma(e^+e^- \rightarrow J/\Psi \eta''_c) \frac{f_{\eta''_c}^2}{f_{\eta''_c}^2} \sim 6 \text{ fb.}$$  \hfill (17)

Another estimation of the cross section can be obtained if one supposes that $I_0(2S)/I_0(1S) \sim I_0(3S)/I_0(2S)$. This estimation gives $\sigma \sim 8$ fb.

As it was noted earlier the motion of quark antiquark pair near to the end point regions ($x \sim 0, x \sim 1$) is relativistic and cannot be calculated reliably in the framework of nonrelativistic potential models. Recently in paper [12] it was proposed to solve this problem in the framework of NRQCD. We are not going to discuss this paper in detail. We would like to say only that the results of [12] were not applied in our paper since we don’t think that it is possible to regard relativistic motion as it was done in [12].

The interpretation of $X(3940)$ as $3^1S_0$ state was proposed in paper [14]. The problem with this interpretation consists in the fact that the mass of this meson obtained in the framework of potential approach is $4040 \sim 4060$ MeV [1]. But as it was shown in our paper relativistic motion of quark antiquark pair is important for $3^1S_0$ meson and probably potential models do not regard this motion correctly. Moreover in paper [15] it was shown that $X$ meson with the mass $3940$ MeV agrees well with Regge trajectory with quantum numbers $0^{-+}$.

This work was partially supported by Russian Foundation of Basic Research under grant 04-02-17530, Russian Education Ministry grant E02-31-96, CRDF grant MO-011-0, Scientific School grant SS-1303.2003.2. One of the authors (V.B.) was also supported by Dynasty foundation.

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