Semileptonic $\Xi_c$ baryon decays in the relativistic quark model

R. N. Faustov and V. O. Galkin

Institute of Cybernetics and Informatics in Education, FRC CSC RAS, Vavilov Street 40, 119333 Moscow, Russia

The form factors of the weak $\Xi_c \rightarrow \Xi(\Lambda)$ transitions are calculated in the framework of the relativistic quark model based on the quasipotential approach. All relativistic effects including transformations of the baryon wave functions from the rest to moving reference frame and contributions of the intermediate negative energy states are systematically taken into account. The explicit analytic expressions which reliably approximate the momentum transfer $q^2$ dependence of the form factors in the whole accessible kinematical range are given. The calculated form factors are applied for the evaluation of the semileptonic $\Xi_c \rightarrow \Xi \ell \nu_\ell$ and $\Xi_c \rightarrow \Lambda \ell \nu_\ell$ ($\ell = e, \mu$) decay rates, different asymmetry and polarization parameters within helicity formalism. The obtained results are compared with available experimental data and previous calculations.

I. INTRODUCTION

This year significant experimental progress has been achieved in studying weak decays of the charmed $\Xi_c$ baryons. Until now the absolute branching fractions of both neutral $\Xi^0_c$ and charged $\Xi^+_c$ baryons were not measured. All decay modes were only measured relative to $\Xi^0_c \rightarrow \Xi^- \pi^+$ and $\Xi^+_c \rightarrow \Xi^- \pi^+ \pi^+$ modes [1]. This fact significantly complicated comparison of theoretical predictions with experimental data. However, recently the Belle Collaboration presented the first measurement of absolute branching fractions of the neutral $\Xi^0_c$ baryon in three decay modes including $\Xi^0_c \rightarrow \Xi^- \pi^+$ one [2]. Its branching fraction is $Br(\Xi^0_c \rightarrow \Xi^- \pi^+) = (1.80 \pm 0.50 \pm 0.14)\%$. Then the absolute branching fractions of its charged partner $\Xi^+_c$ were also reported [3] for three decay modes including $\Xi^+_c \rightarrow \Xi^- \pi^+ \pi^+$ with $Br(\Xi^+_c \rightarrow \Xi^- \pi^+ \pi^+) = (2.86 \pm 1.21 \pm 0.38)\%$. These results can be combined with $\Xi_c$ branching fractions measured relative to corresponding modes to get other absolute $\Xi_c$ branching fractions. Thus the experimental values of $\Xi_c$ semileptonic branching fractions can be determined.

In this paper we calculate the weak $\Xi_c \rightarrow \Xi(\Lambda)$ transition form factors in the framework of the relativistic quark model based on the quasipotential approach and use them to evaluate the semileptonic branching fractions of the $\Xi_c$ baryon. This model was successfully applied for studying semileptonic decays of bottom $\Lambda_b$ [4] and $\Xi_b$ [5] and charmed $\Lambda_c$ [6] baryons. The form factors are expressed as the overlap integrals of the baryon wave functions. The important advantage of the employed model is the comprehensive inclusion of the relativistic effects which allows us to explicitly determine the $q^2$ dependence of the form factors in the whole kinematical range, thus increasing reliability of the results. The calculated form factors can be then used for the determination of branching fractions and other important observables which can be measured experimentally. The results can be confronted with previous theoretical predictions and new experimental data.
TABLE I: Form factors of the weak $\Xi_c \rightarrow \Xi$ transitions.

| $f(0)$ | $f_1^V(q^2)$ | $f_2^V(q^2)$ | $f_3^V(q^2)$ | $f_1^A(q^2)$ | $f_2^A(q^2)$ | $f_3^A(q^2)$ |
|--------|---------------|---------------|---------------|---------------|---------------|---------------|
| 0.499  | 0.371         | 0.329         | 0.492         | -0.156        | -0.961        |
| $f(q_{\text{max}})$ | 0.653         | 0.663         | 0.504         | 0.654         | -0.335        | -1.697        |
| $a_0$  | 0.452         | 0.457         | 0.405         | 0.513         | -0.267        | -1.089        |
| $a_1$  | 1.121         | -1.645        | -0.560        | -0.409        | 1.605         | 2.690         |
| $a_2$  | -5.54         | 4.70          | -10.98        | -1.32         | 3.55          | -12.22        |

II. FORM FACTORS OF THE WEAK $\Xi_c$ BARYON DECAYS

The weak $\Xi_c \rightarrow \Xi(\Lambda)$ transition matrix elements are parametrized in terms of six invariant form factors \[^7\]

\[
\langle \Xi(\Lambda)(p', s')|V^\mu|\Xi_c(p, s)\rangle = \bar{u}_{\Xi(\Lambda)}(p', s')\left[ f_1^V(q^2)\gamma^\mu - f_2^V(q^2)i\sigma^{\mu\nu} \frac{q^\nu}{M_{\Xi_c}} + f_3^V(q^2)\frac{q^\mu}{M_{\Xi_c}} \right] u_{\Xi_c}(p, s),
\]

\[
\langle \Xi(\Lambda)(p', s')|A^\mu|\Xi_c(p, s)\rangle = \bar{u}_{\Xi(\Lambda)}(p', s')\left[ f_1^A(q^2)\gamma^\mu - f_2^A(q^2)i\sigma^{\mu\nu} \frac{q^\nu}{M_{\Xi_c}} + f_3^A(q^2)\frac{q^\mu}{M_{\Xi_c}} \right] \gamma_5 u_{\Xi_c}(p, s),
\]

(1)

where $M_B$ and $u_B(p, s)$ are masses and Dirac spinors of the initial and final baryons ($B = \Xi_c, \Xi, \Lambda$), $q = p' - p$.

In the relativistic quark model these form factors are expressed through the overlap integrals of the baryon wave functions \[^4\] which are known from the calculations of the baryon mass spectra \[^8, 9\]. The explicit expressions are given in Ref. \[^4\]. They systematically take into account all relativistic effects including transformation of baryon wave functions from the rest to moving reference frame and contributions of the intermediate negative energy states.

Following Ref. \[^3\] we fit the numerically calculated form factors by the following analytic expression

\[
f(q^2) = \frac{1}{1 - q^2/M_{\text{pole}}^2} \left\{ a_0 + a_1 z(q^2) + a_2 [z(q^2)]^2 \right\},
\]

(2)

where the variable

\[
z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}},
\]

(3)

here $t_+ = (M_{D_s(D)} + M_{K(\pi)})^2$ and $t_0 = q_{\text{max}}^2 = (M_{\Xi_c} - M_{\Xi(\Lambda)})^2$. The pole masses have the following values. For $\Xi_c \rightarrow \Xi$ transitions: $M_{\text{pole}} \equiv M_{D^*} = 2.112$ GeV for $f_{1V}^1$; $M_{\text{pole}} \equiv M_{D_{s1}} = 2.535$ GeV for $f_{1V}^2$ and $f_{3V}^V$; $M_{\text{pole}} \equiv M_{D_s} = 1.969$ GeV for $f_{3V}^A$. For $\Xi_c \rightarrow \Lambda$ transitions: $M_{\text{pole}} \equiv M_{D^*} = 2.010$ GeV for $f_{1V}^1$; $M_{\text{pole}} \equiv M_{D_{s1}} = 2.423$ GeV for $f_{1V}^2$ and $f_{3V}^V$; $M_{\text{pole}} \equiv M_D = 1.870$ GeV for $f_{3V}^A$. The fitted values of the parameters $a_0$, $a_1$, $a_2$ as well as the values of form factors at maximum $q^2 = 0$ and zero recoil $q^2 = q_{\text{max}}^2$ of the final baryon are given in Tables \[^1\] \[^4\] \[^4\] \[^4\]. The difference of the fitted form factors from the calculated ones does not exceed 0.5%. The form factors are plotted in Figs. \[^4\] \[^4\] \[^4\]. We roughly estimate the total uncertainty of our form factor calculation to be about 5%.
FIG. 1: Form factors of the weak $\Xi_c \to \Xi$ transitions.

### TABLE II: Form factors of the weak $\Xi_c \to \Lambda$ transitions.

|   | $f_1^V(q^2)$ | $f_2^V(q^2)$ | $f_3^V(q^2)$ | $f_1^A(q^2)$ | $f_2^A(q^2)$ | $f_3^A(q^2)$ |
|---|---------------|---------------|---------------|---------------|---------------|---------------|
| $f(0)$ | 0.414         | 0.337         | 0.246         | 0.409         | -0.111        | -0.871        |
| $f(q^2_{\text{max}})$ | 0.621         | 0.756         | 0.533         | 0.562         | -0.439        | -1.95         |
| $a_0$ | 0.339         | 0.412         | 0.366         | 0.368         | -0.301        | -0.924        |
| $a_1$ | 0.821         | -0.290        | -0.186        | 0.314         | 0.983         | -0.172        |
| $a_2$ | -2.12         | -1.33         | -4.08         | -1.05         | 1.87          | 3.44          |

In Table III we compare our results for the values of form factors at $q^2 = 0$ with previous calculations. Results [10] are based on the light-front approach. In this paper form factors $f_3^{V,A}(0)$ were not evaluated. We find reasonable agreement for the form factors parametrizing the $\Xi_c \to \Xi$ weak transitions, while in the case of the $\Xi_c \to \Lambda$ transition our form factors are

FIG. 2: Form factors of the weak $\Xi_c \to \Lambda$ transitions.

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1 In Table III we present the “physical transition form factors” from Ref. [10] which include overlapping factors.
TABLE III: Comparison of the theoretical predictions for form factors of the Ξ_c baryon weak transitions at $q^2 = 0$.

|                  | $f_1^V(0)$ | $f_2^V(0)$ | $f_3^V(0)$ | $f_1^A(0)$ | $f_2^A(0)$ | $f_3^A(0)$ |
|------------------|------------|------------|------------|------------|------------|------------|
| Ξ_c → Ξ         |            |            |            |            |            |            |
| present work     | 0.499      | 0.371      | 0.329      | 0.492      | -0.156     | -0.961     |
| [10]             | 0.567      | 0.305      |            | 0.491      | 0.046      |            |
| [11]             | 0.194 ± 0.050 | 0.880 ± 0.227 | -1.14 ± 0.30 | 0.311 ± 0.081 | 0.373 ± 0.094 | -0.771 ± 0.200 |
| Ξ_c → Λ         |            |            |            |            |            |            |
| present work     | 0.414      | 0.337      | 0.246      | 0.409      | -0.111     | -0.871     |
| [10]             | 0.253      | 0.149      |            | 0.217      | 0.019      |            |

about a factor of 2 larger. In Ref. [11] the light cone QCD sum rules were employed for the calculation of the Ξ_c → Ξ transition form factors. Their form factors $f_{1,2,3}^V(0)$ parametrizing the vector current significantly differ from our results. The central values [11] of the form factor $f_1^V(0)$ is about 2 times smaller while those for $f_{2,3}^V(0)$ are a factor of about 3 larger than other predictions.

III. SEMILEPTONIC Ξ_c → Ξℓν_ℓ AND Ξ_c → Λℓν_ℓ DECAYS

The differential and total semileptonic decay rates, branching fractions and different asymmetry and polarization parameters can be calculated using the decay form factors and the helicity formalism [10]. The relation between helicity amplitudes and decay form factors are the following.

$$H_{+1/2,0}^{V,A} = \frac{\sqrt{(M_{\Xi_c} \pm M_{\Xi(\Lambda)})^2 - q^2}}{\sqrt{M_{\Xi_c}^2}} \left[ (M_{\Xi_c} \pm M_{\Xi(\Lambda)}) f_1^{V,A}(q^2) \pm \frac{q^2}{M_{\Xi_c}} f_2^{V,A}(q^2) \right],$$

$$H_{+1/2,1}^{V,A} = \frac{\sqrt{2}}{\sqrt{M_{\Xi_c}^2}} \left[ (M_{\Xi_c} \pm M_{\Xi(\Lambda)}) f_1^{V,A}(q^2) \pm \frac{M_{\Xi_c} \pm M_{\Xi(\Lambda)}}{M_{\Xi_c}} f_2^{V,A}(q^2) \right],$$

$$H_{+1/2,t}^{V,A} = \frac{\sqrt{(M_{\Xi_c} \pm M_{\Xi(\Lambda)})^2 - q^2}}{\sqrt{M_{\Xi_c}^2}} \left[ (M_{\Xi_c} \pm M_{\Xi(\Lambda)}) f_1^{V,A}(q^2) \pm \frac{q^2}{M_{\Xi_c}} f_3^{V,A}(q^2) \right],$$

and the amplitudes for negative values of the helicities are obtained from the relations

$$H_{-\lambda_c,-\lambda_W}^{V,A} = \pm H_{\lambda_c,\lambda_W}^{V,A}.$$

The total helicity amplitude for the $V - A$ current is given by

$$H_{\lambda_c,\lambda_W}^{V} = H_{\lambda_c,\lambda_W}^{V} - H_{\lambda_c,\lambda_W}^{A}.$$  

The differential decay rates and angular distributions are expressed in terms of the helicity structures which are the following combinations of the total helicity amplitudes [13].

$$H_U(q^2) = |H_{+1/2,0}|^2 + |H_{-1/2,0}|^2,$$

$$H_L(q^2) = |H_{+1/2,0}|^2 + |H_{-1/2,0}|^2,$$

$$H_S(q^2) = |H_{+1/2,t}|^2 + |H_{-1/2,t}|^2,$$
The expression for the differential decay rate is given by \[ \frac{d\Gamma(\Xi_c \rightarrow \Xi(\Lambda)\ell\bar{\nu}_\ell)}{dq^2} = \frac{G_F^2}{(2\pi)^3} |V_{cq}|^2 \frac{\lambda^{1/2}(q^2 - m_\ell^2)^2}{48M_{\Xi_c}^3q^2} \mathcal{H}_{tot}(q^2), \] \[ (7) \]

where \( G_F \) is the Fermi constant, \( V_{cq} \) is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element \( (q = s, d) \), \( \lambda \equiv \lambda(M_{\Xi_c}^2, M_{\Xi(\Lambda)}^2, q^2) = M_{\Xi_c}^2 + M_{\Xi(\Lambda)}^2 + q^2 - 2(M_{\Xi_c}^2 M_{\Xi(\Lambda)}^2 + M_{\Xi(\Lambda)}^2 q^2 + M_{\Xi_c}^2 q^2) \), and \( m_\ell \) is the lepton mass \( (\ell = e, \mu) \).

Substituting in these expressions the \( \Xi_c \) decay form factors calculated in the previous section we obtain the differential decay rates. We plot them for the \( \Xi_c \rightarrow \Xi\ell\nu_\ell \) (left) and \( \Xi_c \rightarrow \Lambda\ell\nu_\ell \) (right) semileptonic decays in Fig. 3.

Many important observables are expressed in terms of the helicity combinations \[ (6) \] (see [7] for details):

- The forward-backward asymmetry of the charged lepton
  \[ A_{FB}(q^2) = \frac{\frac{d\Gamma}{dq^2} \text{(forward)} - \frac{d\Gamma}{dq^2} \text{(backward)}}{\frac{d\Gamma}{dq^2} \text{(forward)}} = \frac{3}{4} \frac{\mathcal{H}_F(q^2) - 2m_\ell^2 \mathcal{H}_{SL}(q^2)}{\mathcal{H}_{tot}(q^2)}; \] \[ (9) \]

- The convexity parameter
  \[ C_F(q^2) = \frac{3}{4} \left( 1 - \frac{m_\ell^2}{q^2} \right) \frac{\mathcal{H}_U(q^2) - 2\mathcal{H}_L(q^2)}{\mathcal{H}_{tot}(q^2)}; \] \[ (10) \]
The longitudinal polarization of the final baryon Ξ_c(Λ)

\[ P_L(q^2) = \frac{[\mathcal{H}_P(q^2) + \mathcal{H}_{LP}(q^2)] (1 + \frac{m_\ell^2}{2q^2}) + 3 \frac{m_\ell^2}{2q^2} \mathcal{H}_{SP}(q^2)}{\mathcal{H}_{tot}(q^2)} \]  

(11)

The longitudinal polarization of the charged lepton \( \ell \)

\[ P_\ell(q^2) = \frac{\mathcal{H}_U(q^2) + \mathcal{H}_L(q^2) - \frac{m_\ell^2}{2q^2} [\mathcal{H}_U(q^2) + \mathcal{H}_L(q^2) + 3 \mathcal{H}_S(q^2)]]}{\mathcal{H}_{tot}(q^2)} \]  

(12)

These observables are plotted for \( \Xi_c \to \Xi \ell^+ \nu_\ell \) and \( \Xi_c \to \Lambda \ell^+ \nu_\ell \) semileptonic decays in Figs. 4-7. The predictions for the decay branching fractions and asymmetry parameters are presented in Table IV. We calculated the decay branching fractions and asymmetry parameters using the CKM values |\( V_{cs} \)| = 0.995 ± 0.016, |\( V_{cd} \)| = 0.220 ± 0.005 [1]. The average values of the \( \langle A_{FB} \rangle \), \( \langle C_F \rangle \), \( \langle P_L \rangle \) and \( \langle P_\ell \rangle \) were obtained by separately integrating the numerators and denominators in Eqs. (11) and (12) over \( q^2 \). We roughly estimate uncertainties of our predictions for the branching fractions to be about 10%.

Since possible violations of the charged lepton universality are now widely discussed in the literature [12] we present predictions for the corresponding ratios for the semileptonic...
FIG. 5: Convexity parameter $C_F(q^2)$ in the $\Xi_c \rightarrow \Xi \ell^+ \nu_\ell$ (left) and $\Xi \rightarrow \Lambda \ell^+ \nu_\ell$ (right) semileptonic decays.

FIG. 6: Longitudinal polarization $P_L(q^2)$ of the final baryon in the $\Xi_c \rightarrow \Xi \ell^+ \nu_\ell$ (left) and $\Xi_c \rightarrow \Lambda \ell^+ \nu_\ell$ (right) semileptonic decays.

FIG. 7: Longitudinal polarization $P_\ell(q^2)$ of the charged lepton in the $\Xi_c \rightarrow \Xi \ell^+ \nu_\ell$ (left) and $\Xi_c \rightarrow \Lambda \ell^+ \nu_\ell$ (right) semileptonic decays.
TABLE V: Comparison of theoretical predictions for the $\Xi_c$ semileptonic decay branching fractions (in %) with available experimental data.

| Decay                  | this paper | Ref. [10] | Ref. [13] | Ref. [14] | Ref. [11] | Experiment |
|------------------------|------------|-----------|-----------|-----------|-----------|------------|
| $Br(\Xi_c^0 \to \Xi^- e^+ \nu_e)$ | 1.71       | 1.35      | 4.87 ± 1.74 | 2.4 ± 0.3 | 7.26 ± 2.54 | 5.58 ± 2.62 |
| $Br(\Xi_c^0 \to \Xi^- \mu^+ \nu_\mu)$ | 1.66       | 2.4 ± 0.3 | 7.15 ± 2.50 |
| $Br(\Xi_c^+ \to \Xi^0 e^+ \nu_e)$  | 6.75       | 5.39      | 3.38$^{+2.19}_{-2.26}$ | 9.8 ± 1.1 | 28.6 ± 10.0 | 6.58 ± 3.85 |
| $Br(\Xi_c^+ \to \Xi^0 \mu^+ \nu_\mu)$ | 6.55       | 9.8 ± 1.1 | 28.2 ± 9.9  |
| $Br(\Xi_c^+ \to \Lambda e^+ \nu_e)$  | 0.53       | 0.082     | 0.166 ± 0.018 |
| $Br(\Xi_c^+ \to \Lambda \mu^+ \nu_\mu)$ | 0.52       |           |           |

$\Xi_c$ decays involving muons and electrons

$$R_\Xi = \frac{Br(\Xi_c \to \Xi \mu \nu_\mu)}{Br(\Xi_c \to \Xi e \nu_e)} = 0.969 \pm 0.010,$$

$$R_\Lambda = \frac{Br(\Xi_c \to \Lambda \mu \nu_\mu)}{Br(\Xi_c \to \Lambda e \nu_e)} = 0.980 \pm 0.010. \quad (13)$$

Most of the theoretical uncertainties cancels in these ratios, thus we roughly estimate them to be about 1%.

Theoretical predictions [10, 11, 13, 14] for the semileptonic $\Xi_c$ decay branching fractions are compared in Table V. The light-front quark model is used for the weak decay form factor and branching fraction calculations in Ref. [10]. The predictions of Refs. [13, 14] are based on the application of the SU(3) flavor symmetry, while the light-cone QCD sum rules are employed in Ref. [11]. The experimental branching fractions are obtained by multiplying the CLEO II values [15] updated by PDG [1] for the ratios $\Gamma(\Xi_c^0 \to \Xi^- e^+ \nu_e)/\Gamma(\Xi_c^0 \to \Xi^- \pi^+) = 3.1 \pm 1.1$ and $\Gamma(\Xi_c^+ \to \Xi^0 e^+ \nu_e)/\Gamma(\Xi_c^+ \to \Xi^- \pi^+ \pi^+ ) = 2.3^{+0.7}_{-0.8}$ by the recently measured by the Belle Collaboration branching fractions $Br(\Xi_c^0 \to \Xi^- \pi^+) = (1.80 \pm 0.50 \pm 0.14)\%$ [2] and $Br(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = (2.86 \pm 1.21 \pm 0.38)\%$. We find reasonable agreement of our predictions for the CKM favored $\Xi_c \to \Xi \ell \nu_\ell$ decays with the results of Refs. [10, 13, 14] and experimental data, while the light-cone QCD sum rule values for branching fractions are substantially higher and disagree with data by more than a factor of 2 for the $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ decay. Note that ARGUS Collaboration [16] measured the ratio $\Gamma(\Xi_c^0 \to \Xi^- e^+ \text{anything})/\Gamma(\Xi_c^0 \to \Xi^- \pi^+) = 1.0 \pm 0.5$ (the value updated by PDG [1]) which combined with Belle data [2] leads to the semi-inclusive branching fraction $Br(\Xi_c^0 \to \Xi^- e^+ \text{anything}) = (1.80 \pm 1.07)\%$ in good agreement with our result. There is no data yet for the CKM suppressed $\Xi_c^+ \to \Lambda \ell^+ \nu_\ell$ decays and theoretical evaluations differ substantially. Our prediction is about a factor of 6 larger than the light-cone quark model value [10] and a factor of 3 larger than the SU(3) flavor symmetry result [14]. The difference for the $Br(\Xi_c^+ \to \Lambda \ell^+ \nu_\ell)$ with Ref. [10] originates from larger values of form factors predicted by our model (see Table III).

IV. CONCLUSION

The relativistic quark model was used for the calculation of form factors of the semileptonic $\Xi_c$ transitions, both for the CKM favored $\Xi_c \to \Xi \ell^+ \nu_\ell$ and CKM suppressed $\Xi_c^+ \to \Xi^- e^+ \nu_e$. The results of our model are in good agreement with experimental data.
$\Lambda \ell^+ \nu_\ell$ decays. All relativistic effects, including baryon wave function transformations from the rest to moving reference frame and contributions of the intermediate negative-energy states, were comprehensively taken into account. This allowed us to explicitly determine the momentum transfer $q^2$ dependence of the weak form factors in the whole kinematical range without additional model assumptions or extrapolations. We give the values of parameters in the analytic expression (2) which accurately approximates the numerically calculated form factors in Tables I, II and show the form factor $q^2$ dependence in Figs. 1, 2.

Using the calculated form factors and helicity formalism we estimated important observables for the CKM favored and CKM suppressed $\Xi_c$ semileptonic decays: differential decay rates, branching fractions, different asymmetry and polarization parameters, which are given in Table IV and plotted in Figs. 4-7. Our results for the branching fractions of the $\Xi_c \to \Xi \ell \nu_\ell$ decays are in reasonable agreement with previous calculations based on the light-front quark model [10] and application of the SU(3) flavor symmetry [13, 14], but significantly lower than the light-cone QCD sum rule predictions [11]. They agree reasonably with experimental values which can be obtained combining the corresponding decay ratios from PDG [1] and recent measurements of absolute branching fractions by the Belle Collaboration [2, 3]. For the suppressed $\Xi^+_c \to \Lambda \ell^+ \nu_\ell$ decays available theoretical predictions differ significantly. Our model predicts larger values of the decay branching fractions than other calculations [10, 14]. Thus their direct experimental measurement can help to discriminate between theoretical approaches.

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