K$^+$ vs. Na$^+$ Driving Force of Prebiotic Peptide Emergence

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Inorganics → Organic World

Discharge experiment 1953

Alexander I. Oparin 1894 - 1980
Harold C. Urey 1893 - 1981
Stanley L. Miller 1930 - 2007
Prebiotic Polymerization Problem

$\text{R} \quad \text{H} \quad \text{H} \quad \text{N} \quad \text{C} \quad \text{C} \quad \text{C} \quad \text{O} \quad \text{O} \quad \text{R} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H}

$\text{R} \quad \text{H} \quad \text{H} \quad \text{N} \quad \text{C} \quad \text{C} \quad \text{C} \quad \text{O} \quad \text{O} \quad \text{R} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H}

$\Delta T \quad \Delta P \quad \text{CDI} \quad \text{COS} \quad \text{Me} \quad \text{etc.}$

$\text{R} \quad \text{H} \quad \text{H} \quad \text{N} \quad \text{C} \quad \text{C} \quad \text{C} \quad \text{O} \quad \text{O} \quad \text{R} \quad \text{H} \quad \text{H} \quad \text{H} \quad \text{H}

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Sidney W. Fox
1912 - 1998

Leslie E. Orgel
1927 - 2007

Andre Brack
b. 1938
Salt-Induced Peptide Formation
Copper-Catalyzed

Bernd M. Rode  
b. 1946

Analytical Sciences (1989)
Sodium vs. Potassium Contradictions

A commonly believed thought:

First protocell could have emerged in salty seawater

Seawater:

\[ K^+ \sim 0.01 \text{ mol/L} \quad Na^+ \sim 0.46 \text{ mol/L} \]

Cell cytoplasm (all “modern” living cells):

\[ K^+ \sim 0.10 \text{ mol/L} \quad Na^+ \sim 0.01 \text{ mol/L} \]

Natochin’s hypothesis:

First protocell could not emerge in NaCl solutions, but in KCl
# Sodium vs. Potassium Contradictions

## Physical-chemical properties

<table>
<thead>
<tr>
<th></th>
<th>Atomic weight</th>
<th>Ionization Energy, eV</th>
<th>Ionic radius, Å</th>
<th>Diffusion coefficient, $x10^{-5}$ cm$^2$/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$^+$</td>
<td>22.9897</td>
<td>5.1391</td>
<td>0.95</td>
<td>1.334</td>
</tr>
<tr>
<td>K$^+$</td>
<td>39.0983</td>
<td>4.3407</td>
<td>1.33</td>
<td>1.957</td>
</tr>
</tbody>
</table>

## Biological properties

<table>
<thead>
<tr>
<th></th>
<th>DNA amplification</th>
<th>Ribosomal peptide synthesis</th>
<th>Active transport across cell membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$^+$</td>
<td>inhibition</td>
<td>decreasing</td>
<td>outside</td>
</tr>
<tr>
<td>K$^+$</td>
<td>facilitation</td>
<td>increasing</td>
<td>inside</td>
</tr>
</tbody>
</table>
Na$^+$- or K$^+$-mediated (0.5M, 1M, 2M) CDI-induced L-Glu oligopeptide formation
K$^+$ and Na$^+$ in the CDI-induced L-Glu oligopeptide formation: chromatograms

K\(^+\) predominates over Na\(^+\) in the CDI-induced L-Glu oligopeptide formation: \textit{HPLC-MS/MS}

<table>
<thead>
<tr>
<th>(N_{\text{res}})</th>
<th>L-Glu oligs + 1.0 M NaCl</th>
<th>L-Glu oligos + 1.0 M KCl</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MS [M+H](^+) ([M+Na](^+))</td>
<td>HPLC</td>
</tr>
<tr>
<td></td>
<td>Found, Da</td>
<td>Peak area</td>
</tr>
<tr>
<td>2</td>
<td>277.101 (299.085)</td>
<td>963</td>
</tr>
<tr>
<td>3</td>
<td>406.146 (428.127)</td>
<td>1060</td>
</tr>
<tr>
<td>4</td>
<td>535.187 (557.172)</td>
<td>770</td>
</tr>
<tr>
<td>5</td>
<td>664.230 (686.212)</td>
<td>408</td>
</tr>
<tr>
<td>6</td>
<td>793.272 (815.252)</td>
<td>174</td>
</tr>
<tr>
<td>7</td>
<td>922.315 (944.285)</td>
<td>61</td>
</tr>
<tr>
<td>8</td>
<td>1051.352</td>
<td>18</td>
</tr>
<tr>
<td>9</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Physical-chemical model of K$^+$ vs. Na$^+$ mediated oligopeptide formation

Quasi-chemical nucleation model

1$^{st}$ stage

K$^+$ + \text{Oligopeptide} \rightarrow \text{K+ bound oligopeptide}

2$^{nd}$ stage

K$^+$ + \text{Oligopeptide} \rightarrow \text{K+ bound oligopeptide}

Equilibrium solution

\[
\frac{[\text{Peptide}_{K}]}{[\text{Peptide}_{Na}]} = \left( \frac{D_K}{D_{Na}} \right)^{\text{LENGTH}-1}
\]

Metal ion diffusion, hydration and coordination to amino acids

![Graph showing diffusion coefficient and hydration free energy for various metal ions.](image)
Conclusion

K$^+$ predominates over Na$^+$ in the prebiotic formation of peptides

The following conditions could have enforced the first step in the chemical evolution of self-assembling organic molecules:

(1) aqueous media contained the building blocks of organic matter and positive inorganic ions, which are *geochemically abundant*

(2) *binding reversibility* to amino acids and the moderate hydration energy of the ions in liquid phase at 0-100 °C

(3) *high diffusion* and *specific ion coordination* to oxygen atoms of amino acids in zwitterion form, which enhances the ion-dependent yields of oligomerization

K$^+$ complies with all the above-listed requirements, which is unique in contrast to other mono- and divalent metallic ions
Thanks to the project team!

Sergey Vyazmin  
Chemistry

Vitali Boitsov  
Chemistry

Ivan Terterov  
Mathematics

Yuri Natochin  
Physiology

Yuri Trushin  
Physics

Maxim Lubov  
Physics

Vladimir Dubrovskii  
Physics

Igor Eliseev  
Physics
Thoughts and on-going research

The emergence of the ancient metabolic and information systems of the protocells could have occurred in potassium-rich habitats.

Thus it seems evident that all the living cells would have evolved to preserve the initial ion gradients by using energy-dependent membrane pumps in sodium aqueous media (seawater).

*If the same predominance of $K^+$ over $Na^+$ in CDI-induced polymerization of all amino acids?*

*Is SIPF without $Cu^{2+}$ (with $K^+$ only) possible?*

*What were terrestrial or extra-terrestrial sources of potassium-rich water reservoirs on prebiotic Earth?*