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Interfacial chemistry as a foundation for future iontronics

Richard N. Zare*

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INTERFACES AS ACTIVE CHEMICAL ENVIRONMENTS

Interfaces are often regarded as passive boundaries between phases. However, increasing evidence from microdroplet chemistry and gas-water interfacial systems suggests that interfaces are highly active chemical environments that can fundamentally reshape reaction pathways and energy conversion processes[1].

From the perspective of molecular reaction dynamics, chemical outcomes depend on how energy is deposited, redistributed, and directed during molecular encounters. Interfaces introduce additional complexity through broken symmetry, strong electric fields, charge separation, restricted solvation, and steep compositional gradients. These features create environments that differ significantly from homogeneous bulk phases and can enable reaction pathways that are otherwise inefficient or inaccessible.

Recent studies of microdroplets and microbubbles further reinforce this view. Interfaces can act as microscopic reactors in which reactants experience strong interfacial electric fields, partial solvation, and transient charge imbalance. These conditions can facilitate bond activation, electron transfer, redox chemistry, and radical formation under ambient conditions, often without external catalysts or applied voltage. In many cases, interfacial regions exhibit enhanced formation of reactive intermediates driven by local field effects and nonequilibrium charge redistribution. In this sense, the interface itself becomes an energetic and reactive medium[1].

MICRODROPLETS, NONEQUILIBRIUM CHEMISTRY, AND INTERFACIAL REACTIVITY

Microdroplet and gas-water interfacial systems highlight the importance of nonequilibrium chemistry at interfaces. These environments challenge the traditional view of solution-phase reactions occurring in homogeneous equilibrium conditions. Instead, interfacial systems emphasize the roles of local electric fields, transient charge separation, interfacial polarization, and short-lived reactive intermediates that

Department of Chemistry, Stanford University, Stanford, CA 94305, USA.

*Correspondence to: Prof. Richard N. Zare, Department of Chemistry, Stanford University, Stanford, CA 94305, USA. E-mail: zare@stanford.edu

are often absent in bulk descriptions[1].

Such observations suggest that interfaces are not merely spatial boundaries but dynamic chemical environments where matter, charge, and energy flow are strongly coupled. The continuous generation and relaxation of interfacial charge distributions can sustain reaction channels that deviate significantly from thermodynamic expectations in bulk phases. This perspective provides a more complete understanding of how chemical transformations can be accelerated or redirected at small length scales[1].

IONS, ELECTRIC FIELDS, AND INTERFACIAL ENERGY TRANSDUCTION

A key implication of interfacial chemistry is the active role of ions. In iontronic systems, ions are not simply charge carriers analogous to electrons in electronics. They are chemically active species whose motion, hydration, solvation structure, and interfacial organization are tightly coupled to reactivity and energy transduction.

At interfaces, ion distributions are strongly influenced by local electric fields and confinement effects, leading to spatial charge separation and dynamic electrical double layers. These interfacial ion configurations can mediate coupling between chemical transformations and electrical responses, providing a mechanistic basis for ion-electron interaction across phases[2].

Interfacial ion distributions and electric fields may therefore serve not only chemical functions but also roles in signal transduction and information processing. Microdroplets provide a useful conceptual model for how ion gradients and electric fields can couple matter transport with energy conversion at interfaces, particularly under nonequilibrium conditions.

This suggests a broader view in which interfacial systems may serve as functional units for future iontronic technologies, integrating chemical reactivity with ionic transport, adaptive electrical behavior, and environment-responsive functionality.

FROM LABORATORY INTERFACES TO SCALABLE SYSTEMS

A central challenge is scalability. While interfacial reactions are well demonstrated at laboratory scales, practical applications require strategies to generate and maintain large interfacial areas efficiently, while preserving their nonequilibrium characteristics. Rather than scaling individual droplets, future approaches may rely on massively parallel interfacial architectures in which large ensembles of microdroplets or microbubbles operate collectively.

Nature provides a useful analogy: breaking ocean waves continuously generate droplets and bubbles over vast spatial scales, driving atmospheric chemistry, aerosol formation, and gas exchange. These naturally occurring interfacial systems operate as distributed chemical reactors under ambient conditions. Engineered analogs of such systems could enable distributed chemical processing for applications such as carbon dioxide conversion, nitrogen fixation, methane activation, and water purification under environmentally benign conditions.

However, challenges remain in energy efficiency, reactor design, selectivity control, and mechanistic understanding. Interfacial systems involve coupled mass transport, charge separation, and radical chemistry, making reaction pathways difficult to control quantitatively. Many elementary processes at gas-liquid interfaces remain incompletely characterized, requiring improved theoretical descriptions of interfacial electric fields as well as advanced in situ spectroscopic and imaging techniques. Progress will depend on close integration of chemistry, physics, materials science, and engineering.

WHY IONTRONICS MATTERS NOW

Iontronics lies at the intersection of physics, chemistry, materials science, biology, and engineering. It is emerging as a field in which ionic processes are not only used for charge transport, but also for coupling energy, matter, and information in complex systems across multiple scales.

Unlike electrons, ions are directly involved in chemical and biological function, from metabolism to neural signaling and membrane transport. Their behavior is inherently coupled to solvation structure and interfacial chemistry, making them fundamentally different from electronic charge carriers. As a result, iontronics provides a framework that extends beyond device physics toward chemically active, adaptive, and bioinspired systems.

The development of a coherent iontronics community is therefore important. A shared conceptual language is needed to connect interfacial chemistry, ion transport, and functional materials across disciplines. Such integration may be essential for the long-term development of iontronics as a unified and impactful field.

CONCLUDING PERSPECTIVE

Interfaces represent environments where chemistry, physics, and materials science converge. They are not passive boundaries but active regions where ions, electric fields, polarization effects, and molecular organization collectively govern chemical transformations.

Understanding and controlling interfacial processes may therefore play a central role not only in advancing iontronics, but also in developing scalable and sustainable approaches to energy conversion, chemical synthesis, and functional materials. In this broader sense, iontronics may provide a unifying framework for translating interfacial ionic phenomena into practical chemical and electronic systems.

DECLARATIONS

Authors' contributions

The author contributed solely to this work.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool ChatGPT (GPT-5.3-mini, released 2026-4-9) was used solely for language editing and grammatical polishing. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. The author takes full responsibility for the accuracy, integrity, and final content of the manuscript.

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Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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