Introduction to the chemistry of fractionally charged atoms: Electronegativity

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The behavior of massive fractionally charged particles in matter is governed by the laws of chemistry if electromagnetic interactions dominate at atomic distances. Chemical properties of such "quark atoms" can be predicted by interpolating isoelectronic sequences. The properties of quark atoms lie between those of a neutral atom and an ion. Electronegativity helps in the qualitative understanding of quark chemistry. Electronegativities, together with ionization potentials and electron affinities, are computed for the quark elements. The concepts of chemical analogy and isomorphism are introduced. Analogies based on shell structure and electronegativity are established. Many quark elements cannot be compared to a single ordinary element. They are chemical chimeras. An understanding of quark chemistry is essential for the design and interpretation of quark-search experiments. The impact of chemical reactions on quark impurities in matter can be monitored by observing the behavior of more abundant isomorphic control elements. Contrary to common belief, the chemical differences between a quark element and its ordinary counterpart are substantial.

I. INTRODUCTION

It is generally recognized that quarks form the basis for the theory of hadrons where the unit of electric charge is $\frac{1}{3}e$.[1,2] Therefore the existence of some kind of free particle with fractional charge should not be too surprising. In fact, recent experiments present evidence for the existence of free fractionally charged particles.[3,4]

An effective search in matter for free quarks or other fractionally charged particles requires an understanding of the chemistry of atoms with fractionally charged nuclei, here referred to as "quark atoms." A better understanding of this chemistry suggests where quark atoms might be found, how their content in ordinary matter can be enriched, and ultimately how they can be isolated from their more conventional neighbors. Knowledge of this chemistry also makes a critique of previous quark-search experiments possible.

The "big bang" provides a potential source of fractionally charged particles, for example, free quarks.[5-15] Presumably there was a time very early in the history of the universe when the mean separation between quarks was much less than their mean separation in hadrons. As the universe expanded and cooled, quarks eventually clustered in groups of three, forming protons and neutrons. In a universe with free quarks, not all quarks found partners. These isolated quarks (or their fractionally charged decay products) interacted with nucleons and the helium and lithium nuclei present, possibly forming complex systems of relatively small fractional charge. Subsequently a substantial fraction of the matter from the early universe entered stars, enabling quarks or other fractionally charged particles to interact with heavier nuclei.

Fractionally charged particles might be found in isolation or in association with particular nuclei. It is currently not possible to predict which nuclei these might be. The search for fractionally charged particles must therefore be extensive, covering many possible cases. There are, however, two relatively simple possibilities. First, since the solar system contains a significant quantity of material that has never been in stars, a search for quark atoms with small nuclear charge is appropriate. Second, heavy elements appear to be formed by successive neutron capture.[16] If this process is not disrupted by the presence of a fractionally charged particle, it may be sufficient in the search for quark atoms with large nuclear charge to look only for a small number of representative heavy quark elements.

Under reasonable assumption one can show that a quark atom consists of a fractionally charged nucleus surrounded by an electron cloud of ordinary atomic dimensions. The center of a quark atom consists of either a single particle of positive fractional charge, or a fractionally charged particle bound to strongly interacting particles, such that the net center charge is positive. For the case of a free quark bound to nucleons by electromagnetic or strong forces, the length scale l_{em} defined by the electromagnetic interaction is given by the Bohr radius of the quark-nucleon system

$$l_{\text{em}} \equiv \frac{\hbar^2}{Z_q Z_n m_R e^2} . \tag{1}$$

Z_q and Z_n are the absolute values of the quark charge and the total nucleonic charge. The reduced mass is m_R. When the reduced mass is much greater than the electron mass, the electromagnetic length scale l_{em} is much smaller than the Bohr radius α_e of the electron,

$$l_{\text{em}} \ll \alpha_e , \tag{2}$$

where

$$\alpha_e = \frac{\hbar^2}{m_e e^2} . \tag{3}$$

For example, if the quark mass is greater than one third of the proton mass,

$$l_{em} \lesssim \frac{\alpha_e}{150} \; . \tag{4}$$

Of course, $Z_q Z_N$ has been taken greater than or equal to $\frac{1}{3}$.

Although the nature of the strong interaction between free quarks and nucleons is essentially unknown, its associated length scale l_{strong} is presumably significantly less than the Bohr radius of the electron,

$$l_{strong} \ll \alpha_e \; . \tag{5}$$

The maximum of the two length scales l_{em} and l_{strong} gives an approximate upper limit to the size of the quark-nucleon system. This size is therefore expected to be much less than the Bohr radius of the electron. Consequently, such a quark atom consists of a relatively small positively charged nuclear center surrounded by an electron cloud of ordinary atomic dimensions. Its interactions with ordinary atoms are therefore governed by the familiar laws of chemistry.

Note that this conclusion only depends on two assumptions: the mass of a free quark is much greater than that of an electron [Eq. (2)], and the nonelectromagnetic interaction of a free quark with nuclear matter is negligible at atomic distances [Eq. (5)].

The following discussion applies, in fact, to any massive fractionally charged particle whose long-range interactions are dominated by electromagnetism. (Of course, we do not discuss the case where quarks have a magnetic charge.) No further assumptions concerning the nature of fractionally charged particles will be made in this paper. Such particles could be quarks, diquarks, or more exotic objects such as hadronic color singlets, leptons, or even quark constituents.[1,2,17-23]

Since the interactions between quark atoms and ordinary atoms are governed solely by the laws of chemistry, these interactions are in principle predictable. The chemical properties of a quark atom depend only on the fractional charge Z of its nucleus and the number N of its electrons. In practice, however, it is difficult to start from first principles and predict the chemical properties of ordinary atoms, let alone those containing quarks.

This work suggests an approach to quark chemistry.[24,25] (Certain aspects of quark chemistry have been described in Refs. 26–36.) Chemical properties of atoms with fractional nuclear charges $Z = N \pm \frac{1}{3}$ and $Z = N \pm \frac{2}{3}$ are found by interpolating these properties within isoelectronic sequences of states, that is, states with the same number of electrons but different nuclear charge. Thus the chemistry of a quark atom is described in terms of the known chemistry of the neutral atom, $Z = N$, and the known chemistry of the ions, $Z = N \pm 1$. By comparing the chemical properties of quark atoms with those of ordinary atoms, much of the chemical behavior of quark atoms can be predicted. Such qualitative considerations may be supplemented in specific cases by more detailed calculations following from first principles.

This first paper of a series outlines principles of quark chemistry and determines the electronegativities of quark atoms. Subsequent papers establish their ionic crystal radii, list the ordinary elements which can be replaced by them in minerals, and discuss their molecular and crystal chemistry. The geochemistry of quark atoms will be considered and minerals which can act as hosts for quarks will be identified. The implications of this work for past and future quark searches in matter will be discussed.

II. ELECTRONEGATIVITY OF ORDINARY ATOMS

One of the early triumphs of chemistry was the discovery that many properties of molecules could be simply related to a single number X, called the electronegativity, assigned to each element.[37,38] The electronegativity of an atom is an intrinsic property that is independent of the other atoms to which it may be bound. Roughly speaking, electronegativity is the power of an atom in a molecule to attract electrons to itself.[37]

The nature of the chemical bond between atoms A and B is characterized by their difference in electronegativity, $X_A - X_B$. Small values of this difference indicate a covalent bond, large values an ionic bond. If X_A is significantly greater than X_B, the bond is ionic due to atom A's greater power to attract electrons.

The concept of electronegativity has led to the correlation of a vast number of atomic and molecular properties. Some quantities that have been related to the electronegativities of the elements are[37,39] the screened nuclear charge seen by outer electrons, the radius of electron clouds, the work function of metals, the electrode potential of elements, the bond energy of molecules, the dipole moment of molecules, and the force constants of molecules. In addition, the electronegativity together with the shell structure determines the possible oxidation states of an atom.

We shall use the widely accepted definition of electronegativity given by Mulliken.[38] It can easily be generalized to fractionally charged atoms. He averaged the ionization potential (IP), the energy required for the removal of an electron from an isolated atom, and the electron affinity (EA), the energy released by the addition of an electron to the atom, to define its electronegativity X,

$$X \equiv \frac{IP + EA}{2} \; . \tag{6}$$

To motivate this definition consider a molecule AB, where A and B are both univalent. If A and B bind ionically as $A^- B^+$ the other configuration $A^+ B^-$ has much higher energy. In this case,

$$IP_A - EA_B \gg IP_B - EA_A \; . \tag{7}$$

Since electron affinities are much smaller than ionization potentials,

$$IP_A + EA_A \gg IP_B + EA_B \; . \tag{8}$$

This suggests that the electronegativity of an atom can be defined as some function of the sum of the ionization potential and electron affinity. Mulliken's simple choice is given in Eq. (6).

Another interpretation of the electronegativity is found by considering the ground-state energy E_N of an atom with N electrons and fixed center charge. In terms of E_N, the ionization potential, electron affinity, and electronegativity of a netural atom are

$$IP = E_{N-1} - E_N \; ,$$
$$EA = E_N - E_{N+1} \; ,$$

(9)

and

$$\chi = -\frac{E_{N+1} - E_{N-1}}{2} \equiv \frac{\Delta E_N}{\Delta N} \; .$$

(10)

Therefore the electronegativity is the negative rate of change of the energy of an atom with respect to the number of electrons in that atom. Since this energy is not a smooth function of the number of electrons, the rate of change is defined by finite differences as in Eq. (10).

A quantity which is occasionally of interest is the rate of change of the electronegativity χ with respect to the number of electrons N. This is related to

$$\chi' \equiv \frac{IP - EA}{2}$$

(11)

by

$$\frac{\Delta \chi}{\Delta N} = -\frac{\Delta^2 E_N}{\Delta N^2} = -(E_{N+1} - 2E_N + E_{N-1}) = -2\chi' \; .$$

(12)

If an atom has a large χ', then its power to attract electrons diminishes rapidly as the probability of finding an additional electron around it increases.

Table I gives χ, χ', IP, and EA for ordinary atoms. χ and χ' are computed from measurements[40–45] of IP and EA. (Estimates of the electron affinities are given in a few cases where measured values are not available. Details are contained in the Appendix.) Figure 1 is a scatter plot of χ versus EA for all elements.

An inspection of this table and figure reveals systematic trends for these numbers. The strength with which an electron is bound to an atom depends both on its mean distance from the nucleus and the effective nuclear charge it feels. While moving up a column in the periodic table, the atomic radius decreases for nontransition elements leading to an increase in ionization potential and electronegativity. While moving across a row in the periodic table, filling the s, p, or d shells, the ionization potential and electronegativity grow because the increasing nuclear charge is not completely screened by the additional electrons. The discontinuities in IP and χ at completed or half completed shells are at least partially explained by the more effective screening in these spherically symmetric configurations. EA is particularly sensitive to screening effects and therefore strongly reflects the shell structure of the elements. Spherically symmetric electron configurations have very low or even negative electron affinities. (In the latter case, the atoms can form resonances.)

From the preceding discussion it follows that the smallest values of χ and IP are found in the left-hand column of the periodic table; the minima are at the bottom of the periodic
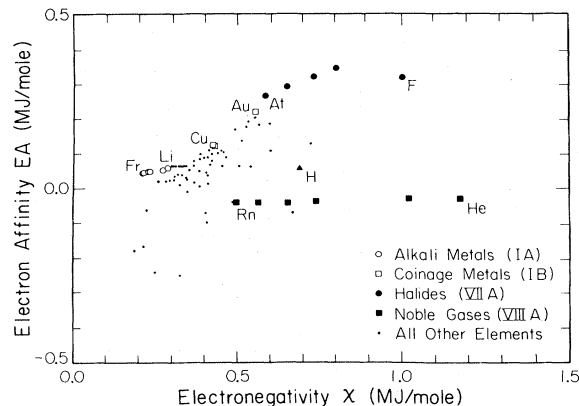
FIG. 1. Scatter plot of electronegativity versus electron affinity illustrating the variation of these quantities for the elements within the periodic table. Moving across the periodic table from left to right increases χ and EA as shown here for the sequence of columns I A (alkali metals), I B (coinage metals), and VII A (halides). The noble gases (VIII A) are exceptions in that their closed shells are responsible for particularly small electron affinities. In fact, a negative electron affinity indicates a closed shell, and vice versa; the only exception is nitrogen whose shell is half filled. Hydrogen with an electron shell half-way between closed and empty appears centered in the scatter plot. Generally, moving up a column for the nontransition elements in the periodic table increases χ, as exemplified here for the I A, VII A, and VIII A columns. Note that the variation of χ within a column also increases across the periodic table. A convenient conversion factor is 1 MJ/mole ≈ 10.4 eV per atom. Pauling's electronegativity scale is related to the one used here by $\chi_{\text{Pauling}} \approx 3.5\chi - 0.2$.

column. The largest values are found diagonally across the table in the upper right-hand corner. A similar pattern is exhibited by χ'.

Empirically, the elements in the first row of the periodic table have a relatively large χ'. This is connected with their small size. Their tendency to be negatively ionized is less than would be expected from their electronegativities.

Although Mulliken's definition of electronegativity provides a good approximation to the power of an atom in a molecule to attract electrons, a better approximation takes the hybridization of the atomic electron orbitals into account.[39,46–49] For example, the carbon atom in a molecule usually is not in its ground state ($s^2 p^2$) but rather in an excited state, where the electron orbitals are linear combinations of the s and p states. There exist several such hybrids for carbon. (The carbon-hydrogen bond can involve three different hybrids: sp^3 as in ethane H_3C-CH_3; sp^2 as in ethylene $H_2C=CH_2$; sp^1 as in acetylene $HC\equiv CH$. The electron-attracting ability of an sp^n hybrid centered on carbon increases as the percentage of s character in the orbital increases.) In Eq. (6), IP and EA should be taken to be the ionization potential and electron affinity of the hybrid state, rather than the ground state. In general, several electronegativities are assigned to an atom, one for each hybrid state. The energies of hybrid states are calculated from experimental data.[46–49]

TABLE I. The electronegativity χ, χ' [Eq. (11)], ionization potential IP, and electron affinity EA for the ordinary elements. Here the nuclear charge Z of an element is equal to the number of its electrons, N. All quantities are given in units of MJ/mole, where 1 MJ/mole$\approx$10.4 eV per atom. The conversion to Pauling's electronegativity scale is given by $\chi_{\text{Pauling}} \approx 3.5\chi - 0.2$.

PERIODIC TABLE   Z = N

Key for each cell:

$$\begin{array}{cc} \chi & \chi' \\ \multicolumn{2}{c}{\text{ELT}_N} \\ IP & EA \end{array}$$

Each entry below is given as: Symbol$_N$ — χ / χ' — IP / EA

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
H$_1$ .69/.62 1.31/.07																	He$_2$ 1.18/1.20 2.37/-.02
Li$_3$ .29/.23 .52/.06	Be$_4$ .33/.57 .90/-.24											B$_5$ .41/.39 .80/.02	C$_6$ .60/.48 1.09/.12	N$_7$ .67/.73 1.40/-.06	O$_8$ .73/.59 1.31/.14	F$_9$ 1.00/.68 1.68/.32	Ne$_{10}$ 1.03/1.05 2.08/-.03
Na$_{11}$ .27/.22 .50/.05	Mg$_{12}$ .25/.48 .74/-.23											Al$_{13}$ .31/.27 .58/.04	Si$_{14}$ .45/.33 .79/.12	P$_{15}$ .54/.47 1.01/.07	S$_{16}$ .60/.40 1.00/.20	Cl$_{17}$ .80/.45 1.25/.35	Ar$_{18}$ .74/.78 1.52/-.04
K$_{19}$ .23/.19 .42/.05	Ca$_{20}$ .22/.37 .59/-.16	Sc$_{21}$ .33/.31 .63/.02	Ti$_{22}$ .35/.31 .66/.04	V$_{23}$ .37/.28 .65/.09	Cr$_{24}$ .36/.30 .65/.06	Mn$_{25}$ .37/.35 .72/.03	Fe$_{26}$ .41/.35 .76/.06	Co$_{27}$ .42/.33 .76/.09	Ni$_{28}$ .42/.31 .74/.11	Cu$_{29}$ .43/.31 .75/.12	Zn$_{30}$ .41/.50 .91/-.09	Ga$_{31}$ .31/.27 .58/.04	Ge$_{32}$ .44/.32 .76/.12	As$_{33}$ .51/.43 .94/.08	Se$_{34}$ .57/.37 .94/.20	Br$_{35}$ .73/.41 1.14/.33	Kr$_{36}$ .66/.70 1.35/-.04
Rb$_{37}$ .22/.18 .40/.05	Sr$_{38}$ .19/.36 .55/-.17	Y$_{39}$ .33/.28 .62/.05	Zr$_{40}$ .37/.29 .66/.08	Nb$_{41}$ .39/.28 .66/.11	Mo$_{42}$ .39/.30 .69/.10	Tc$_{43}$ .35/.35 .70/.00	Ru$_{44}$ .39/.33 .71/.06	Rh$_{45}$ .41/.31 .72/.10	Pd$_{46}$ .46/.35 .81/.12	Ag$_{47}$ .43/.30 .73/.13	Cd$_{48}$ .40/.46 .87/-.06	In$_{49}$ .30/.26 .56/.03	Sn$_{50}$ .41/.29 .71/.12	Sb$_{51}$ .47/.37 .83/.10	Te$_{52}$ .53/.34 .87/.19	I$_{53}$ .65/.36 1.01/.30	Xe$_{54}$ .56/.61 1.17/-.04
Cs$_{55}$ .21/.17 .38/.05	Ba$_{56}$ .23/.28 .50/-.05	La$_{57}$ .28/.25 .54/.05	Hf$_{72}$ .35/.31 .65/.04	Ta$_{73}$ .42/.34 .76/.08	W$_{74}$ .41/.36 .77/.05	Re$_{75}$ .39/.37 .76/.02	Os$_{76}$ .46/.38 .84/.08	Ir$_{77}$ .52/.37 .88/.15	Pt$_{78}$ .54/.33 .87/.21	Au$_{79}$ .56/.33 .89/.22	Hg$_{80}$ .49/.52 1.00/-.03	Tl$_{81}$ .32/.27 .59/.05	Pb$_{82}$ .41/.31 .72/.05	Bi$_{83}$ .40/.30 .70/.10	Po$_{84}$ .50/.32 .81/.18	At$_{85}$ .59/.32 .90/.27	Rn$_{86}$ .50/.54 1.04/-.04
Fr$_{87}$ .21/.16 .37/.04	Ra$_{88}$ .23/.28 .51/-.05	Ac$_{89}$ .26/.23 .49/.03															

Lanthanide series														
Ce$_{58}$ .30/.23 .53/.08	Pr$_{59}$ .30/.22 .52/.08	Nd$_{60}$ .30/.23 .53/.08	Pm$_{61}$ .31/.23 .54/.08	Sm$_{62}$ .31/.23 .54/.08	Eu$_{63}$ .31/.24 .55/.08	Gd$_{64}$ .33/.26 .59/.08	Tb$_{65}$ .32/.32 .56/.08	Dy$_{66}$ .32/.25 .57/.08	Ho$_{67}$ .33/.26 .58/.08	Er$_{68}$ .34/.26 .59/.08	Tm$_{69}$ .34/.26 .60/.08	Yb$_{70}$ .34/.26 .60/.08	Lu$_{71}$ .30/.22 .52/.08	

Actinide series		
Th$_{90}$ .33/.26 .59/.08	Pa$_{91}$ .32/.25 .57/.08	U$_{92}$ .33/.26 .59/.08

III. ISOELECTRONIC SEQUENCES

The chemical properties of a quark atom lie between those of a neutral atom and an ion. They may be found by interpolation. This interpolation should involve an isoelectronic sequence of states, that is, states with the same number of electrons but different nuclear charge. This guarantees that the quantities interpolated vary smoothly. In contrast, quantities associated with a sequence of states having different electron number change discontinuously. Isoelectronic sequences have been used extensively in spectroscopy to organize atomic energy levels.[50] These data have been used to predict spectral lines,[51-53] ionization potentials, and electron affinities[54] of some quark atoms.

The ionization potential serves to illustrate the use of isoelectronic sequences. Figure 2 shows the extraordinary smoothness of IP within such a sequence. The ionization potential as a function of both center charge Z and electron number N is displayed in Fig. 3. The irregular behavior as N varies is evident. It reflects the electron shell structure. Changes in the electron shell structure may also occur within an isoelectronic sequence, as illustrated in Fig. 4. Although the ionization energy of a given electron configuration is a smooth function of center charge, the ground state of the atom may change its electron configuration, thereby giving rise to discontinuities in the slope of the ionization potential. In spite of this complication, Fig. 4 demonstrates that accurate interpolation is still possible.

Interpolation along isoelectronic sequences may be used to establish many chemical properties of quark atoms.

FIG. 3. A collection of isoelectronic sequences of the ionization potential $IP_N(Z)$. On each sequence the number of electrons N is fixed while the net charge $Z - N$ varies between -1 and 1. Element names are used to label isoelectronic sequences, indicating the electron numbers.

Ionic radii, partition coefficients for crystals[55] and chelating compounds, and hydration energies may all be obtained by interpolation. Isoelectronic sequences also exist for molecules; for example, $PO_n{}^{3-}$, $SO_n{}^{2-}$, $ClO_n{}^-$ with $n = 2$, 3, or 4. Binding energies, spectra, and dissociation

FIG. 2. The ionization potential as a function of the charge Z at the center of an atom with 10 electrons. The inset is a graph of the difference in ionization potential between states whose center charge differs by one. This difference approximates the slope of the ionization potential curve. The measured values of the ionization potential at integral charge Z have been connected by a sequence of quadratic interpolations discussed in the Appendix. The electron shell structure is always $1s^2 2s^2 2p^6$. The overall shape of the curve is very close to that of a parabola, as can be seen from the nearly linear rise of the first differences shown in the inset. Note the wealth of experimental data. 1 MJ/mole $\approx$ 10.4 eV per atom.


FIG. 4. The ionization potential as a function of the charge at the center of an atom with 25 electrons. The solid circles are measured values, the line segments quadratic interpolations (discussed in the Appendix), and the asterisks predicted values for quark atoms. The outer electron shell structure for certain states is also given. The inset is a graph of the difference in ionization potential between states whose center charge differs by one. This difference approximates the slope of the ionization potential curve. The large discontinuity in slope is a reflection of the change in the outer shell structure with changing center charge. The dashed part of the curve in the inset is an extrapolation for states whose electrons have the $3d^7$ outer shell structure. Note that with increasing center charge the relative importance of the mutual electron interactions decreases and the energy levels of the same principal quantum number ($3s$, $3p$, and $3d$) come together. Therefore as the $3d$ level approaches the $3s$, its energy must fall below that of the $4s$ level. This occurs here for an ionic charge between one and two. 1 MJ/mole $\approx$ 10.4 eV per atom.

constants for molecules containing one quark atom can be found by interpolation in such molecular isoelectronic sequences.

IV. ELECTRONEGATIVITY OF FRACTIONALLY CHARGED ATOMS

Electronegativity is an example of a concept whose definition and applications can be extended to include quark elements. Such extensions make a comparison of quark elements with ordinary elements possible. Chemical analogies may be established, leading to a qualitative picture of quark chemistry.

The electronegativity of a quark atom is computed by averaging its ionization potential and electron affinity. These, in turn, are determined by interpolating isoelectronic sequences as has been exemplified in Figs. 2—4. Figure 5 shows isoelectronic curves of ionization potential and electron affinity for an entire row of the periodic table. Since we will be considering quark atoms with net charge between $\pm \frac{2}{3}e$, only restricted portions of the isoelectronic curves are shown. Similar curves have been found for all the elements, but are not displayed here. From these curves the ionization potential and electron affinity of all quark atoms with nuclear charge less than 93 have been determined, and are listed in Tables II through V. $\mathcal{X}$ and $\mathcal{X}'$ are also given.

Note that a given center charge Z occurs twice in Tables II through V. It is listed once as an atom with positive net charge and again as another atom, having one more electron, with negative net charge. For example, C_6 with a net charge of $\frac{1}{3}e$ (Table II) has the same center charge as N_7 with a net charge of $-\frac{2}{3}e$ (Table V). The electron affinity of the positively charged quark atom is identical to the ionization potential of the negatively charged atom with the same center charge.

A quark atom does not have chemical properties between those of its neutral neighbors in the periodic table. For example, although the electronegativities of the ordinary lanthanides are nearly equal, as are those of the quark lanthanides, these two sets of electronegativities are quite different from each other. The quark atom, however, does have chemical properties between those of two isoelectronic neighbors, a neutral atom and an ion.

The same systematic trends found in Table I (Sec. II) for the ordinary atoms are found for quark atoms in Tables II through V.

For a fixed number of electrons, the electronegativity increases with increasing center charge. Quark atoms with a net positive charge may have electronegativities corresponding to those of atoms to the right, or higher up in the same column of the periodic table. For example, the alkalis with a net charge of $\frac{1}{3}e$ (column I A, Table II) have electronegativities similar to those of ordinary elements found in the center of the periodic table. Adding a second $\frac{1}{3}e$ to the center charge (Table III) leads to electronegativities like those of ordinary halides.

Increasing the center charge of the halides, column VII A, leads to electronegativities greater than those of any ordinary element. Such quark atoms will be referred to as "superhalides."
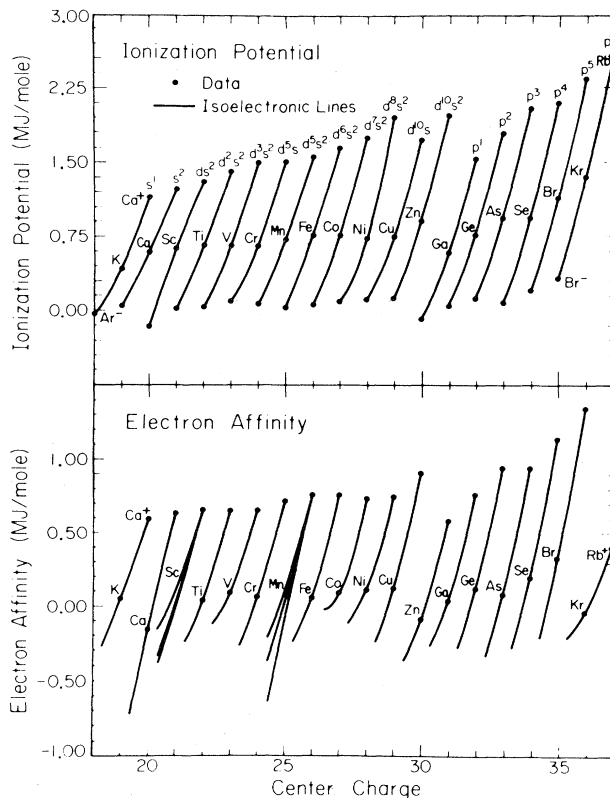

FIG. 5. Organization of ionization potentials and electron affinities into isoelectronic sequences for the first long row of the periodic table. The solid circles are measured values, the lines quadratic interpolations of both plotted and unplotted data. The outer electron shell structure for the neutral atom in each isoelectronic sequence is given at the top of the corresponding line. The positive ions have a simpler shell structure, first filling the $3d$ shell completely before filling the $4s$. The filling or half filling of every outer electron shell is evident from a reduction in ionization potential after a shell is completed. Measurements of the electron affinity of Sc and Mn are not available; interpolated values from their neighbors in the periodic table are used together with estimates of the errors in this interpolation to determine the three lines given for these elements. Since electron affinities are always much smaller than ionization potentials, such uncertainties are not important in computing electronegativities. 1 MJ/mole ≈ 10.4 eV per atom.

Decreasing the center charge reverses the trend. Halides with a net charge $-\frac{1}{3}e$ have electronegativities as are found in the center of the periodic table. Removing a second $\frac{1}{3}e$ from the center charge (Table V) gives quark halides with electronegativities lower than any in the ordinary periodic table. Decreasing the center charge of the alkalis transforms them into "superalkalis."

With a few notable exceptions, the variation of electronegativities within a column of the ordinary periodic table is too small to permit matches in electronegativity of quark atoms and ordinary atoms of the same column. These exceptions, which will be discussed later, occur in the right-hand columns of the periodic table.

The effect of changing the center charge on the elec-

TABLE II. Symbols and units as in Table I. Values given within each square are for a quark element whose net charge is $\frac{1}{3}e$. The number N of electrons it has is given by the subscript. For example, H_1 has one electron and a nuclear charge of $\frac{4}{3}e$.

PERIODIC TABLE $Z = N + 1/3$

Legend for each square:

$$\begin{array}{cc} X & X' \\ \multicolumn{2}{c}{ELT_N} \\ IP & EA \end{array}$$

Each cell below is given as: X X' / ELT$_N$ / IP EA

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1.44 .89 H$_1$ 2.33 .55																	1.90 1.82 He$_2$ 3.72 .08
.56 .30 Li$_3$ .86 .26	.69 .64 Be$_4$ 1.33 .05											.81 .51 B$_5$ 1.32 .30	1.04 .56 C$_6$ 1.60 .47	1.16 .83 N$_7$ 1.99 .32	1.25 .68 O$_8$ 1.92 .57	1.59 .77 F$_9$ 2.36 .83	1.46 1.37 Ne$_{10}$ 2.83 .10
.53 .29 Na$_{11}$ .81 .24	.54 .52 Mg$_{12}$ 1.06 .02											.58 .33 Al$_{13}$ .91 .25	.75 .37 Si$_{14}$ 1.12 .38	.86 .52 P$_{15}$ 1.39 .34	.95 .44 S$_{16}$ 1.39 .51	1.19 .49 Cl$_{17}$ 1.69 .70	1.04 .95 Ar$_{18}$ 1.99 .09
.44 .22 K$_{19}$ .66 .22	.46 .34 Ca$_{20}$ .80 .12	.54 .32 Sc$_{21}$ .86 .22	.56 .35 Ti$_{22}$ .91 .22	.59 .34 V$_{23}$ .93 .25	.60 .34 Cr$_{24}$ .94 .26	.63 .37 Mn$_{25}$ 1.00 .25	.66 .40 Fe$_{26}$ 1.05 .26	.67 .42 Co$_{27}$ 1.09 .24	.68 .39 Ni$_{28}$ 1.07 .28	.71 .36 Cu$_{29}$ 1.07 .35	.68 .57 Zn$_{30}$ 1.24 .10	.56 .31 Ga$_{31}$ .87 .24	.73 .37 Ge$_{32}$ 1.11 .36	.80 .47 As$_{33}$ 1.27 .33	.89 .41 Se$_{34}$ 1.29 .48	1.07 .43 Br$_{35}$ 1.51 .64	.91 .83 Kr$_{36}$ 1.75 .08
.40 .20 Rb$_{37}$ .60 .20	.54 .33 Sr$_{38}$ .76 .11	.54 .30 Y$_{39}$ .83 .24	.57 .33 Zr$_{40}$ .90 .24	.62 .34 Nb$_{41}$ .96 .28	.61 .34 Mo$_{42}$ .95 .26	.60 .40 Tc$_{43}$ 1.01 .20	.62 .39 Ru$_{44}$ 1.01 .23	.69 .42 Rh$_{45}$ 1.11 .27	.76 .47 Pd$_{46}$ 1.23 .29	.69 .34 Ag$_{47}$ 1.03 .35	.64 .52 Cd$_{48}$ 1.17 .12	.53 .29 In$_{49}$ .82 .24	.66 .32 Sn$_{50}$ .98 .33	.74 .41 Sb$_{51}$ 1.15 .33	.80 .36 Te$_{52}$ 1.16 .44	.95 .38 I$_{53}$ 1.33 .57	.79 .71 Xe$_{54}$ 1.51 .08
.38 .19 Cs$_{55}$ .57 .19	.42 .27 Ba$_{56}$ .69 .15	.45 .26 La$_{57}$ .71 .20	.59 .32 Hf$_{72}$ .91 .27	.66 .36 Ta$_{73}$ 1.02 .29	.65 .39 W$_{74}$ 1.04 .26	.66 .38 Re$_{75}$ 1.04 .28	.73 .40 Os$_{76}$ 1.13 .33	.76 .41 Ir$_{77}$ 1.17 .35	.82 .42 Pt$_{78}$ 1.24 .41	.82 .36 Au$_{79}$ 1.18 .46	.73 .58 Hg$_{80}$ 1.31 .15	.56 .31 Tl$_{81}$ .88 .25	.63 .36 Pb$_{82}$ .99 .27	.65 .32 Bi$_{83}$ .97 .33	.74 .33 Po$_{84}$ 1.07 .41	.84 .33 At$_{85}$ 1.17 .52	.69 .62 Rn$_{86}$ 1.31 .08
.36 .19 Fr$_{87}$ .55 .18	.42 .30 Ra$_{88}$ .73 .12	.45 .23 Ac$_{89}$ .69 .22															

Lanthanide series	.45 .24 Ce$_{58}$ .69 .22	.46 .24 Pr$_{59}$ .70 .22	.46 .24 Nd$_{60}$ .70 .22	.47 .25 Pm$_{61}$ .71 .22	.47 .25 Sm$_{62}$ .72 .22	.49 .26 Eu$_{63}$ .75 .25	.50 .27 Gd$_{64}$ .77 .23	.49 .26 Tb$_{65}$ .75 .23	.50 .26 Dy$_{66}$ .76 .24	.51 .27 Ho$_{67}$ .77 .24	.51 .27 Er$_{68}$ .78 .24	.51 .28 Tm$_{69}$ .79 .23	.50 .33 Yb$_{70}$ .83 .17	.51 .27 Lu$_{71}$ .78 .24
Actinide series	.50 .26 Th$_{90}$ .77 .24	.49 .25 Pa$_{91}$ .74 .25	.50 .26 U$_{92}$ .76 .25											

TABLE III. As in Table II, but with a net charge of $\frac{2}{3}e$.

PERIODIC TABLE   Z = N + 2/3

Legend (cell format):

x	x'
\multicolumn{2}{c}{ELT$_N$}	
IP	EA

Each entry below is given as: Symbol$_N$ — (x, x'; IP, EA).

Group IA / IIA and main groups

Element	x	x'	IP	EA
H$_1$	2.48	1.17	3.65	1.31
He$_2$	2.81	2.55	5.36	.26
Li$_3$	.91	.36	1.27	.54
Be$_4$	1.12	.72	1.84	.40
B$_5$	1.24	.59	1.84	.65
C$_6$	1.54	.65	2.19	.90
N$_7$	1.72	.94	2.65	.78
O$_8$	1.85	.76	2.61	.48
F$_9$	2.27	.85	3.12	1.41
Ne$_{10}$	1.97	1.69	3.66	.27
Na$_{11}$	.80	.33	1.13	.47
Mg$_{12}$	.85	.57	1.42	.29
Al$_{13}$	.87	.37	1.24	.50
Si$_{14}$	1.08	.41	1.49	.68
P$_{15}$	1.23	.58	1.80	.65
S$_{16}$	1.34	.48	1.83	.86
Cl$_{17}$	1.62	.53	2.16	1.09
Ar$_{18}$	1.37	1.13	2.50	.24
K$_{19}$	.65	.25	.90	.40
Ca$_{20}$	.70	.32	1.02	.38
Sc$_{21}$	.76	.33	1.08	.43
Ti$_{22}$	.79	.37	1.16	.42
V$_{23}$	.82	.39	1.21	.43
Cr$_{24}$	.85	.37	1.22	.48
Mn$_{25}$	.89	.39	1.28	.50
Fe$_{26}$	.92	.43	1.35	.49
Co$_{27}$	.94	.48	1.42	.46
Ni$_{28}$	.99	.49	1.48	.49
Cu$_{29}$	1.01	.40	1.40	.61
Zn$_{30}$	.96	.63	1.59	.32
Ga$_{31}$	.84	.35	1.19	.49
Ge$_{32}$	1.05	.41	1.45	.64
As$_{33}$	1.13	.51	1.64	.62
Se$_{34}$	1.24	.44	1.68	.80
Br$_{35}$	1.44	.46	1.91	.98
Kr$_{36}$	1.20	.97	2.17	.23
Rb$_{37}$	.59	.22	.82	.37
Sr$_{38}$	.67	.30	.97	.37
Y$_{39}$	.75	.30	1.05	.44
Zr$_{40}$	.79	.35	1.14	.43
Nb$_{41}$	.86	.40	1.26	.47
Mo$_{42}$	.84	.37	1.21	.47
Tc$_{43}$	.88	.44	1.31	.44
Ru$_{44}$	.90	.46	1.36	.45
Rh$_{45}$	1.00	.49	1.49	.51
Pd$_{46}$	1.07	.58	1.65	.49
Ag$_{47}$	.96	.37	1.33	.60
Cd$_{48}$	.96		1.48	.33
In$_{49}$	.78	.32	1.11	.46
Sn$_{50}$	.92	.44	1.28	.57
Sb$_{51}$	1.03	.44	1.47	.59
Te$_{52}$	1.10	.39	1.49	.71
I$_{53}$	1.27	.41	1.68	.86
Xe$_{54}$	1.04	.82	1.86	.22
Cs$_{55}$	.55	.22	.77	.34
Ba$_{56}$	.61	.26	.88	.35
La$_{57}$	.62	.26	.88	.36
Hf$_{72}$	.85	.34	1.19	.51
Ta$_{73}$	.90	.38	1.29	.52
W$_{74}$	.91	.41	1.32	.50
Re$_{75}$	.95	.39	1.34	.56
Os$_{76}$	1.01	.41	1.43	.60
Ir$_{77}$	1.03	.44	1.48	.59
Pt$_{78}$	1.12	.49	1.61	.64
Au$_{79}$	1.11	.38	1.49	.73
Hg$_{80}$	.99	.64	1.63	.36
Tl$_{81}$	.82	.35	1.16	.47
Pb$_{82}$	.88	.41	1.29	.47
Bi$_{83}$	.92	.35	1.27	.47
Po$_{84}$	.99	.34	1.33	.65
At$_{85}$	1.11	.34	1.45	.77
Rn$_{86}$	.91	.69	1.60	.21
Fr$_{87}$	.54	.21	.75	.33
Ra$_{88}$	.63	.32	.95	.30
Ac$_{89}$	.65	.24	.89	.41

Lanthanide series

Element	x	x'	IP	EA
Ce$_{58}$	.61	.24	.85	.37
Pr$_{59}$	.62	.25	.86	.37
Nd$_{60}$	.63	.25	.88	.37
Pm$_{61}$	.63	.26	.89	.38
Sm$_{62}$	.64	.27	.90	.37
Eu$_{63}$	.69	.27	.96	.42
Gd$_{64}$	.67	.27	.94	.39
Tb$_{65}$	.67	.27	.94	.40
Dy$_{66}$	.68	.27	.95	.41
Ho$_{67}$	.67	.27	.96	.41
Er$_{68}$	.69	.28	.97	.42
Tm$_{69}$	.69	.29	.98	.40
Yb$_{70}$	.70	.38	1.08	.32
Lu$_{71}$	.76	.33	1.08	.43

Actinide series

Element	x	x'	IP	EA
Th$_{90}$	.67	.27	.94	.40
Pa$_{91}$	.67	.25	.92	.42
U$_{92}$	.67	.26	.93	.42

TABLE IV. As in Table II, but with a net charge of $-\frac{1}{3}e$.

PERIODIC TABLE $Z = N - 1/3$

Cell legend:

x	x'
ELT_N	
IP	EA

Element	x	x'	IP	EA
H_1	.24	.35	.58	-.11
He_2	.63	.68	1.31	.05
IA				
Li_3	.10	.16	.26	-.07
Na_{11}	.09	.18	.27	-.09
K_{19}	.06	.17	.24	-.11
Rb_{37}	.07	.16	.23	-.09
Cs_{55}	.07	.15	.22	-.08
Fr_{87}	.07	.14	.21	-.07
IIA				
Be_4	.03	.51	.54	-.47
Mg_{12}	.00	.46	.47	-.46
Ca_{20}	-.02	.42	.40	-.44
Sr_{38}	-.05	.41	.37	-.46
Ba_{56}	-.04	.30	.34	-.27
Ra_{88}	.06	.27	.33	-.21
IIIB				
Sc_{21}	.11	.27	.38	-.17
Y_{39}	.12	.25	.37	-.13
La_{57}	.11	.24	.35	-.14
Ac_{89}	.07	.23	.30	-.17
IVB				
Ti_{22}	.16	.27	.43	-.11
Zr_{40}	.20	.25	.44	-.05
Hf_{72}	.12	.31	.43	-.18
VB				
V_{23}	.19	.23	.42	-.03
Nb_{41}	.20	.23	.43	-.04
Ta_{73}	.20	.31	.51	-.11
VIB				
Cr_{24}	.16	.27	.43	-.11
Mo_{42}	.22	.25	.47	-.04
W_{74}	.19	.33	.52	-.14
VIIB				
Mn_{25}	.15	.33	.48	-.18
Tc_{43}	.15	.32	.47	-.16
Re_{75}	.13	.37	.50	-.25
VIIIB				
Fe_{26}	.19	.30	.50	-.11
Co_{27}	.25	.24	.49	.00
Ni_{28}	.22	.24	.46	-.02
Ru_{44}	.19	.24	.44	-.05
Rh_{45}	.22	.23	.44	-.01
Pd_{46}	.24	.27	.51	-.03
Os_{76}	.19	.36	.56	-.17
Ir_{77}	.30	.30	.60	-.00
Pt_{78}	.31	.28	.59	.03
IB				
Cu_{29}	.21	.28	.49	-.07
Ag_{47}	.21	.28	.49	-.07
Au_{79}	.32	.32	.64	.00
IIB				
Zn_{30}	.18	.43	.61	-.24
Cd_{48}	.19	.40	.60	-.21
Hg_{80}	.27	.45	.73	-.18
IIIA				
B_5	.11	.29	.40	-.17
Al_{13}	.08	.20	.29	-.12
Ga_{31}	.09	.23	.32	-.14
In_{49}	.09	.24	.33	-.14
Tl_{81}	.12	.24	.36	-.12
IVA				
C_6	.25	.40	.65	-.15
Si_{14}	.20	.30	.50	-.10
Ge_{32}	.19	.29	.49	-.10
Sn_{50}	.20	.26	.46	-.06
Pb_{82}	.22	.25	.47	-.04
VA				
N_7	.27	.63	.90	-.36
P_{15}	.26	.41	.68	-.15
As_{33}	.25	.39	.64	-.14
Sb_{51}	.23	.34	.57	-.11
Bi_{83}	.17	.30	.47	-.12
VIA				
O_8	.29	.50	.78	-.21
S_{16}	.29	.36	.65	-.07
Se_{34}	.28	.34	.62	-.06
Te_{52}	.28	.31	.59	-.03
Po_{84}	.27	.30	.57	-.03
VIIA				
F_9	.49	.59	1.09	-.10
Cl_{17}	.45	.41	.86	.04
Br_{35}	.42	.38	.80	.04
I_{53}	.38	.33	.71	.04
At_{85}	.34	.30	.65	.04
VIIIA				
Ne_{10}	.65	.76	1.41	-.11
Ar_{18}	.48	.61	1.09	-.13
Kr_{36}	.42	.56	.98	-.14
Xe_{54}	.36	.50	.86	-.14
Rn_{86}	.32	.45	.77	-.13

Lanthanide series

Element	x	x'	IP	EA
Ce_{58}	.15	.21	.36	-.06
Pr_{59}	.15	.21	.37	-.06
Nd_{60}	.15	.22	.37	-.06
Pm_{61}	.15	.22	.37	-.06
Sm_{62}	.17	.21	.38	-.05
Eu_{63}	.14	.23	.37	-.10
Gd_{64}	.17	.25	.42	-.07
Tb_{65}	.16	.23	.40	-.08
Dy_{66}	.16	.24	.40	-.08
Ho_{67}	.16	.24	.40	-.08
Er_{68}	.16	.25	.41	-.09
Tm_{69}	.18	.24	.42	-.05
Yb_{70}	.22	.19	.40	-.03
Lu_{71}	.13	.19	.32	-.06

Actinide series

Element	x	x'	IP	EA
Th_{90}	.16	.25	.41	-.08
Pa_{91}	.15	.25	.40	-.10
U_{92}	.16	.26	.42	-.10

TABLE V. As in Table II, but with a net charge of $-\frac{2}{3}e$.

PERIODIC TABLE Z = N - 2/3

Legend:

x	x'
ELT_N	
IP	EA

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
H_1 .07 .07 .15 .00																	He_2 .28 .27 .55 .00
Li_3 -.02 .10 .08 -.12	Be_4 -.19 .46 .26 -.65											B_5 -.12 .17 .05 -.29	C_6 -.02 .32 .30 -.34	N_7 -.06 .53 .47 -.59	O_8 -.08 .40 .32 -.48	F_9 .06 .51 .57 -.45	Ne_{10} .34 .48 .83 -.14
Na_{11} -.04 .14 .10 -.18	Mg_{12} -.21 .45 .24 -.66											Al_{13} -.11 .13 .02 -.24	Si_{14} -.02 .27 .25 -.28	P_{15} .02 .36 .38 -.34	S_{16} .02 .32 .34 -.30	Cl_{17} .14 .37 .51 -.23	Ar_{18} .26 .44 .70 -.19
K_{19} -.08 .17 .09 -.25	Ca_{20} -.26 .48 .22 -.74	Sc_{21} -.11 .23 .12 -.34	Ti_{22} -.01 .23 .22 -.24	V_{23} .05 .17 .22 -.12	Cr_{24} -.01 .26 .25 -.27	Mn_{25} -.06 .32 .26 -.38	Fe_{26} .01 .25 .26 -.25	Co_{27} .12 .14 .26 -.02	Ni_{28} .06 .18 .24 -.12	Cu_{29} .02 .26 .28 -.24	Zn_{30} -.01 .36 .35 -.37	Ga_{31} -.09 .19 .10 -.28	Ge_{32} -.02 .26 .24 -.28	As_{33} .01 .35 .36 -.33	Se_{34} .02 .31 .33 -.29	Br_{35} .13 .35 .48 -.22	Kr_{36} .21 .42 .64 -.21
Rb_{37} -.07 .15 .08 -.22	Sr_{38} -.28 .48 .20 -.77	Y_{39} -.09 .20 .11 -.29	Zr_{40} .05 .19 .24 -.15	Nb_{41} .04 .20 .24 -.16	Mo_{42} .07 .21 .28 -.14	Tc_{43} -.02 .28 .26 -.30	Ru_{44} .05 .15 .20 -.11	Rh_{45} .08 .14 .23 -.06	Pd_{46} .07 .21 .27 -.14	Ag_{47} .02 .27 .29 -.25	Cd_{48} .01 .34 .35 -.34	In_{49} -.09 .21 .12 -.30	Sn_{50} -.01 .23 .24 -.22	Sb_{51} .02 .31 .33 -.30	Te_{52} .05 .28 .33 -.23	I_{53} .13 .31 .44 -.19	Xe_{54} .17 .39 .57 -.22
Cs_{55} -.06 .14 .08 -.20	Ba_{56} -.15 .34 .19 -.49	La_{57} -.08 .23 .15 -.31	Hf_{72} -.08 .32 .24 -.40	Ta_{73} -.01 .28 .27 -.29	W_{74} -.01 .30 .29 -.31	Re_{75} -.12 .38 .26 -.50	Os_{76} -.06 .34 .28 -.40	Ir_{77} .11 .22 .33 -.11	Pt_{78} .11 .23 .35 -.12	Au_{79} .10 .30 .41 -.20	Hg_{80} .08 .39 .46 -.31	Tl_{81} -.06 .21 .15 -.27	Pb_{82} -.05 .19 .25 -.14	Bi_{83} -.03 .30 .27 -.33	Po_{84} .05 .28 .33 -.23	At_{85} .11 .30 .41 -.19	Rn_{86} .16 .36 .52 -.20
Fr_{87} -.04 .12 .08 -.16	Ra_{88} -.09 .27 .18 -.37	Ac_{89} -.13 .25 .12 -.37															

	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
Lanthanide series	Ce_{58} .00 .19 .20 -.19	Pr_{59} .01 .20 .22 -.19	Nd_{60} .01 .20 .22 -.19	Pm_{61} .01 .21 .22 -.20	Sm_{62} .03 .19 .22 -.16	Eu_{63} -.03 .24 .22 -.27	Gd_{64} .02 .23 .25 -.21	Tb_{65} .01 .22 .23 -.22	Dy_{66} .00 .23 .23 -.23	Ho_{67} .00 .24 .24 -.23	Er_{68} -.00 .24 .24 -.24	Tm_{69} .04 .20 .24 -.16	Yb_{70} .13 .10 .23 .04	Lu_{71} .00 .17 .17 -.16		
Actinide series	Th_{90} -.01 .23 .22 -.24	Pa_{91} -.02 .25 .24 -.27	U_{92} -.01 .26 .25 -.27													

tronegativity and electron affinity is illustrated in Fig. 6 for the elements in the I A and VII A columns.

If necessary, hybridization of atomic orbitals may be taken into account by isoelectronic interpolation of ionization potentials and electron affinities of hybrid states. Data for such interpolations are available.[39,46-49]

In summary, the electronegativity of an element is substantially altered when its center charge is changed by as little as $\frac{1}{3}e$. The change in electronegativity is of the same order as typical electronegativity differences between the ordinary elements, and signals drastic changes in chemistry.

V. ANALOGIES AND ISOMORPHISMS

The easiest way to understand the chemistry of quark atoms is to compare them with ordinary atoms. In many instances exploiting analogies between ordinary atoms and quark atoms is the only way to predict their chemical properties. Direct theoretical computation is often unfeasible. Analogies are established by comparing quantities, like electronegativities or crystal radii, which are usually obtained by interpolation.

Quark atoms are always ions independent of their electron number. However, the behavior of a quark atom inside a molecule is not unlike that of an ordinary atom. The distinction between charged and neutral atoms becomes important only at distances larger than the size of their electron clouds. Therefore, the nonzero net charge of a quark atom does not preclude its comparison with ordinary atoms.

In order to draw analogies with ordinary chemistry we assign to each quark atom of nuclear charge Z two electron numbers N and $N+1$, with Z between them: $N < Z < N+1$. Each of these two states may play the role
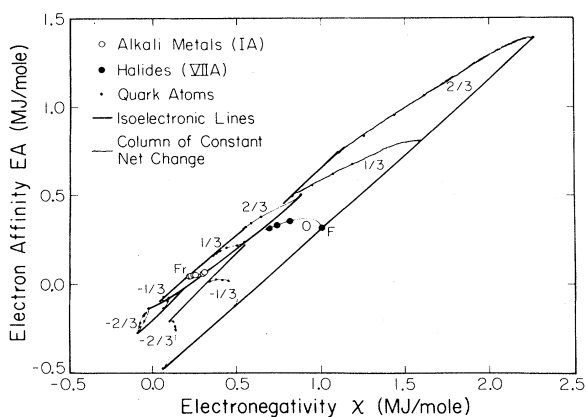
FIG. 6. The electronegativity and electron affinity of the alkalis and halides as functions of the net charge. The ordinary alkalis and halides are represented by open and full circles. The range of electronegativity of the ordinary elements is spanned by those of francium and fluorine (Fig. 1). Elements within the same column of the periodic table are connected by a light line. Quark atoms (small dots) within the same column of a periodic table are also connected by a light line labeled by their net charge in units of e. The heavy lines connect isoelectronic atoms. 1 MJ/mole ≈ 10.4 eV per atom. $\chi_{\text{Pauling}} \approx 3.5\chi - 0.2$.

of the neutral atom in ordinary chemistry. For example, the nucleus with $Z = 6\frac{1}{3}$ may have six electrons, as for $C(\frac{1}{3})$, or seven electrons, as for $N(-\frac{2}{3})$. One is free to choose between these two different physical states as analogs of a neutral atom in ordinary chemistry. If $C(\frac{1}{3})$ is taken as the analog, the system with seven electrons is understood as the first negative ionization state $C(\frac{1}{3})^-$. Similarly, the six-electron system may be viewed as $N(-\frac{2}{3})^+$. Which of the two assignments is preferable depends on the kind of analogy to be drawn with ordinary elements. In forming molecules the assignment is made so that the sum of all oxidation numbers is zero.

Analogies are always drawn with respect to a particular chemical reaction or class of reactions. Different reactions will, in general, require different analogies. The behavior of an element participating in a reaction usually depends on several factors. An ordinary element matching a quark element in one or more of these factors is said to behave analogously with respect to them. If all factors match, the ordinary element is said to be isomorphic to the quark element.

In molecular chemistry the electronegativity and shell structure are major factors affecting chemical reactions. Isomorphisms and analogies can be established on this basis. Analogies should preferably be drawn between elements with the same shell structure. These elements are found in the same column of the periodic table. Because of the similarity in shell structure between nontransition elements in the A columns and transition elements in the B columns of the periodic table, it is sometimes possible to compare elements in these corresponding columns, provided that their oxidation numbers are the same. When these kinds of analogies do not exist, analogies may still be drawn between elements in the same oxidation state, even if they come from entirely different columns of the periodic table.

Analogies with respect to reactions controlled by electronegativity and shell structure are listed in Tables VI and VII. Table VI gives the closest analogs of the quark elements. In order to understand the significance of such analogs, Table VII gives the closest analogs of the ordinary elements.

Note that a quark element $A(\pm n/3)$ never has its ordinary counterpart A as an analog. Therefore, for example, pyrolytic graphite, a substance used in quark-search experiments,[56] could not contain significant quantities of quark carbon, but may contain a quark element which behaves like carbon.

A good example of analogous elements is $Pb(\frac{1}{3})$ and carbon, both lying in column IV A. As can be seen in Table VI, their electronegativity difference is only 0.02 MJ/mole (0.2 eV per atom). Like carbon, $Pb(\frac{1}{3})$ is expected to form covalent tetrahedral bonds with hydrogen. Similarly the electronegativity of $Bi(\frac{1}{3})$ in column V A lies between that of phosphorus and nitrogen. Since both PH_3 and NH_3 exist, $Bi(\frac{1}{3})H_3$ can be formed and is expected to have properties lying between those of PH_3 and NH_3. The electronegativity of $Bi(\frac{1}{3})$ is closer to that of nitrogen, but its ability to involve d electrons in its bonds makes it more like phosphorus.

TABLE VI. Quark elements and their ordinary analogs as determined by their shell structure and electronegativity difference. $\Delta \chi$ given in MJ/mole (1 MJ/mole $\approx$ 10.4 eV per atom). Analogs are chosen from the same column and corresponding column of the periodic table. Whenever possible, the closest analogs with electronegativities just above and below that of the quark element are given. The electronegativity difference must be less than 0.15 MJ/mole for an analog to be listed. Analogs in corresponding columns have been looked for only in columns I through IV. The quark elements are listed according to their net charge. For a given net charge they are ordered in the columns of the periodic table. Hydrogen is assigned both to the I A and VII A columns.

Net charge	Column	Quark element	Ordinary elements			
			Same column		Corresponding column	
			$\Delta \chi > 0$	$\Delta \chi < 0$	$\Delta \chi > 0$	$\Delta \chi < 0$
$-\frac{2}{3}$	I A	H		Fr -0.14		
	I B	Au				Fr -0.10
	II B	Hg				Sr -0.11
$-\frac{1}{3}$	I A	H	K 0.00	Na -0.04		
		Li		Fr -0.11		
		Na		Fr -0.11		
		K		Fr -0.14		
		Rb		Fr -0.14		
		Cs		Fr -0.14		
		Fr		Fr -0.14		
	II A	Ra		Sr -0.13		
	III B	Y		Ac -0.14		
	VI B	Mo		Cr -0.14		
	VIII B	Co		Ru -0.14		
		Ir		Ru -0.09		
		Pd		Ru -0.15		
		Pt		Ru -0.08		
	I B	Cu			Fr 0.00	Cs -0.00
		Ag			Fr 0.00	Cs -0.00
		Au		Ag -0.11	Li 0.03	
	II B	Zn				Sr -0.01
		Cd			Sr 0.00	Ca -0.02
		Hg		Cd -0.13	Mg 0.02	Be -0.06
	III A	B				Ac -0.15
		Tl				Ac -0.14
	IV A	C				Hf -0.09
		Si				Hf -0.15
		Sn				Hf -0.15
		Pb				Hf -0.13
	V A	N		Bi -0.13		
		P		Bi -0.14		
	VII A	F		At -0.09		
		Cl		At -0.14		
	VIII A	He	Xe 0.07	Kr -0.02		
		Ne	Xe 0.09	Kr -0.00		
		Ar		Rn -0.02		
		Kr		Rn -0.08		
		Xe		Rn -0.14		
	Lanthanides			Lan. -0.14		
	Actinides			Lan. -0.14		
$\frac{1}{3}$	I A	Li		H -0.13	Au 0.00	
		Na			Cu 0.09	Au -0.03
		K	Li 0.15		Cu 0.00	Au -0.12
		Rb	Li 0.11			Ag -0.03
		Cs	Li 0.09			Ag -0.05
		Fr	Li 0.07			Ag -0.06

TABLE VI. *(Continued.)*

Net charge	Column	Quark element	Ordinary elements Same column ΔX > 0	ΔX < 0	Corresponding column ΔX > 0	ΔX < 0
	II A	Mg			Hg 0.05	
		Ca	Be 0.13		Zn 0.05	Hg −0.03
$\frac{1}{3}$	II A	Sr	Be 0.10		Zn 0.02	Hg −0.05
		Ba	Be 0.09		Zn 0.01	Hg −0.07
		Ra	Be 0.10		Zn 0.02	Hg −0.06
	III B	Sc			B 0.13	
		Y			B 0.13	
		La	Y 0.12		B 0.04	
		Ac	Y 0.12		B 0.04	
	IV B	Ti			Si 0.11	C −0.04
		Zr			Si 0.12	C −0.04
		Hf			Si 0.14	C −0.02
	VIII B	Fe	Pt 0.12			
		Ru	Pt 0.08			
		Co	Pt 0.13			
		Ni	Pt 0.14			
	I B	Cu			H 0.02	
		Ag	Au 0.13			H −0.00
		Au			H 0.13	
	III A	Ga	B 0.15			
		In	B 0.12			
		Tl	B 0.15			
	IV A	Si	C 0.15			
		Ge	C 0.13			
		Sn	C 0.05			
		Pb	C 0.02			
	V A	As	N 0.13			
		Sb	N 0.07			
		Bi	P 0.11	N −0.02		
	VI A	Te	O 0.07			
		Po	O 0.01			
	VII A	Br	F 0.07			
		I	Cl 0.15	F −0.05		
		At	Cl 0.04			
	VIII A	Ar	Ne 0.01	He −0.14		
		Kr		Ne −0.11		
		Xe	Ar 0.5			
		Rn	Kr 0.04	Ar −0.05		
	Lanthanides		Lan. 0.14			
$\frac{2}{3}$	I A	Na	H 0.11			
		K		H −0.04	Au 0.09	
		Rb		H −0.10	Au 0.04	
		Cs		H −0.14	Cu 0.12	Au −0.00
		Fr		H −0.15	Cu 0.11	Au −0.01
	II A	Ba			Hg 0.13	
		Ra			Hg 0.14	
	VII A	At	F 0.11			
	VIII A	Kr	He 0.03			
		Xe	Ne 0.01	He −0.14		
		Rn		Ne −0.12		

Cd($-\frac{1}{3}$) in column II B is an example of a quark element whose analogs are in the corresponding II A column of the periodic table. The properties of Cd($-\frac{1}{3}$), as far as they are determined by the electronegativity, are between those of strontium and calcium.

Tables VIII and IX aid in understanding the significance of a given electronegativity difference. They list representative pairs of analogous ordinary elements classi-

TABLE VII. Ordinary elements and their analogs as determined by their shell structure and electronegativity difference, $\Delta\chi$ given in MJ/mole (1 MJ/mole$\approx$10.4 eV per atom). Entries are organized as in Table VI, with the quark atom replaced by an ordinary atom of zero net charge. The elements in the three columns labeled VIII B are divided into the iron group Fe, Co, and Ni, and the platinum group containing the remaining six elements. Whenever possible, elements in the same group have been put in correspondence.

| | | Ordinary elements | | | |
| | | Same column | | Corresponding column | |
Column	Element	$\Delta\chi>0$	$\Delta\chi<0$	$\Delta\chi>0$	$\Delta\chi<0$
I A	H			Au 0.14	
	Li	Na 0.02			Ag −0.14
	Na	K 0.04	Li −0.02		
	K	Rb 0.01	Na −0.04		
	Rb	Cs 0.01	K −0.01		
	Cs	Fr 0.00	Rb −0.01		
	Fr		Cs −0.00		
II A	Be	Mg 0.08			Cd − 0.08
	Mg	Ra 0.02	Be −0.08		
	Ca	Sr 0.03	Ba −0.01		
	Sr		Ca −0.03		
	Ba	Ca 0.01	Ra −0.00		
	Ra	Ba 0.00	Mg −0.02		
III B	Sc	La 0.04	Y −0.01	Tl 0.01	B −0.09
	Y	Sc 0.01		Tl 0.01	B −0.08
	La	Ac 0.02	Sc −0.04		In −0.01
	Ac		La −0.02		In −0.04
IV B	Ti	Hf 0.00	Zr −0.02		Pb −0.06
	Zr	Ti 0.02			Pb −0.04
	Hf		Ti −0.00		Pb −0.06
V B	V		Nb −0.02		
	Nb	V 0.02	Ta −0.03		
	Ta	Nb 0.03			
VI B	Cr		Mo −0.03		
	Mo	Cr 0.03	W −0.02		
	W	Mo 0.02			
VII B	Mn	Tc 0.02	Re −0.02		
	Tc		Mn −0.02		
	Re	Mn 0.02			
VIII B	Fe	Ru 0.02	Ni −0.02		
	Ru		Rh −0.02		
	Os	Rh 0.05	Pd −0.00		
	Co	Ni 0.00	Os −0.03		
	Rh	Ru 0.02	Os −0.05		
	Ir	Pd 0.06	Pt −0.02		
	Ni	Fe 0.02	Co −0.00		
	Pd	Os 0.00	Ir −0.06		
	Pt	Ir 0.02			
I B	Cu	Ag 0.01	Au −0.12	Li 0.14	
	Ag		Cu −0.01	Li 0.14	
	Au	Cu 0.12			H −0.14
II B	Zn	Cd 0.00	Hg −0.08	Be 0.08	
	Cd		Zn −0.00	Be 0.08	
	Hg	Zn 0.08			
III A	B	Tl 0.09		Y 0.08	
	Al	Ga 0.00	Tl −0.01	La 0.03	Sc −0.01
	Ga	In 0.01	Al −0.00	La 0.02	Sc −0.02
	In		Ga −0.01	La 0.01	Sc −0.03
	Tl	Al 0.01	B −0.09	La 0.04	Sc −0.01
IV A	Si	Ge 0.01		Zr 0.09	
	Ge	Sn 0.02	Si −0.01	Zr 0.07	
	Sn	Pb 0.01	Ge −0.02	Zr 0.05	
	Pb		Sn −0.01	Zr 0.04	

TABLE VII. *(Continued.)*

		Ordinary elements				
		Same column			Corresponding column	
Column	Element	$\Delta\chi > 0$		$\Delta\chi < 0$	$\Delta\chi > 0$	$\Delta\chi < 0$
V A	N	P	0.13			
	P	As	0.03	N	−0.13	
	As	Sb	0.04	P	−0.03	
	Sb	Bi	0.06	As	−0.04	
	Bi			Sb	−0.06	
VI A	O	S	0.13			
	S	Se	0.03	O	−0.13	
	Se	Te	0.04	S	−0.03	
	Te	Po	0.03	Se	−0.04	
	Po			Te	−0.03	
VII A	H	I	0.04	Br	−0.04	
	Cl	Br	0.07			
	Br	H	0.04	Cl	−0.07	
	I	At	0.07	H	−0.04	
	At			I	−0.07	
VIII A	He	Ne	0.15			
	Ne			He	−0.15	
	Ar	Kr	0.09			
	Kr	Xe	0.09	Ar	−0.09	
	Xe	Rn	0.07	Kr	−0.09	
	Rn			Xe	−0.07	
Lanthanides		Lan.	0.00	Lan.	−0.00	
Actinides		Act.	0.00	Act.	−0.00	

fied according to electronegativity difference. As is evident, chemical resemblances deteriorate when the electronegativity difference increases, and when analogs are not taken from the same column of the periodic table.

Figure 1 is a scatter plot of electronegativity versus electron affinity for all ordinary elements. In order to illustrate the variation of these quantities with the center

TABLE VIII. Ordinary elements and their analogs within the same column of the periodic table classified according to their difference in electronegativity, $\Delta\chi$ given in MJ/mole (1 MJ/mole $\approx$ 10.4 eV per atom). The more electronegative element of a pair is written first.

	$0.00 \le \Delta\chi \le 0.15$				
Column	0.00—0.03	0.03—0.06	0.06—0.09	0.09—0.12	0.12—0.15
I A	K-Cs	Na-K	Na-Cs		
II A	Ca-Sr	Mg-Ca	Mg-Sr	Be-Ca	Be-Sr
III B	Y-Sc	Sc-La	Y-Ac		
IV B	Zr-Ti				
V B	Nb-V	Ta-Nb			
VI B	W-Mo	Mo-Cr			
VII B	Re-Mn	Re-Tc			
VIII B	Co-Fe	Ir-Pd	Pt-Os	Ir-Rh	Ir-Ru
I B	Cu-Ag				Au-Ag
II B	Zn-Cd		Hg-Cd		
III A	Al-Ga			B-Al	
IV A	Si-Ge	Si-Sn			
V A		P-As	P-Sb	As-Bi	N-P
VI A		S-Se	S-Te	S-Po	O-S
VII A		H-I	Cl-Br	Cl-H	Cl-I
VIII A			Ar-Kr	Kr-Xe	He-Ne

charge, the isoelectronic lines for hydrogen, helium, and lithium have been drawn into the scatter plot, as shown in Fig. 7. This also facilitates a comparison of quark atoms with ordinary elements.

Moving up the isoelectronic line of lithium in Fig. 7, the striking closeness of $\text{Li}(\frac{1}{3})$ to both gold (■) and astatine (●) becomes apparent. $\text{Li}(\frac{1}{3})$ is expected to behave like these elements when its oxidation number is matched by theirs. Gold and $\text{Li}(\frac{1}{3})$ are in corresponding columns I B and I A of the periodic table and are analogs in oxidation state + 1. Although they are not in corresponding columns, astatine and $\text{Li}(\frac{1}{3})$ have two oxidation states ±1 in common. When interacting with electropositive elements, both come in oxidation state − 1. Analogies between $\text{Li}(\frac{1}{3})$ and these two elements must be drawn with

TABLE IX. Ordinary elements and their analogs in corresponding columns classified according to their difference in electronegativity, $\Delta\chi$ given in MJ/mole (1 MJ/mole $\approx$ 10.4 eV per atom). The more electronegative element of a pair is written first.

	$0.00 \le \Delta\chi \le 0.15$				
Column	0.00—0.03	0.03—0.06	0.06—0.09	0.09—0.12	0.12—0.15
I					H-Au Cu-Li
II			Zn-Be		
III	Al-La Sc-Al	In-Ac Y-In	B-Sc		B-La
IV		Sn-Zr	Si-Zr	SiTi	
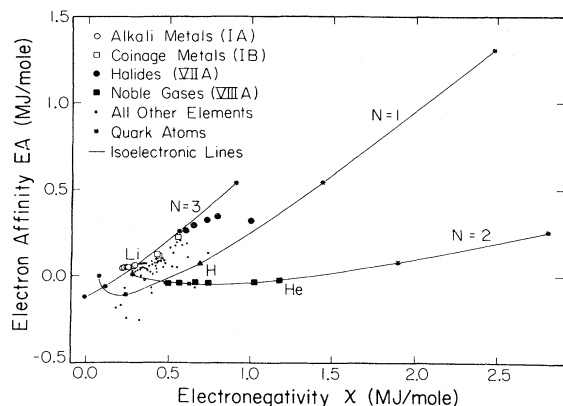
FIG. 7. The isoelectronic lines of hydrogen, helium, and lithium drawn into the scatter plot of electronegativity versus electron affinity shown in Fig. 1. The net charge of the states on the isoelectronic lines varies between $-\frac{2}{3}e$ and $\frac{2}{3}e$. The lines are labeled by their electron number N. 1 MJ/mole ≈ 10.4 eV per atom. $X_{\text{Pauling}} \approx 3.5X - 0.2$.

care. Gold with its d-shell electrons usually occurs in oxidation state $+3$, astatine sometimes in oxidation states, 3,5, and 7.

Although there is a relatively large electronegativity difference between hydrogen and $\text{Li}(\frac{1}{3})$, their similar shell structure makes them analogous elements. $\text{Li}(\frac{1}{3})$ is often expected to act like an electropositive hydrogen.

$\text{Li}(\frac{2}{3})$ is somewhat isolated from the elements in the scatter plot. Its electronegativity, however, lies between that of chlorine and fluorine. In oxidation state -1 it is therefore expected to behave like these two halides.

Moving along the isoelectronic line of lithium toward net negative charge leads to quark atoms widely separated from the ordinary elements. $\text{Li}(-\frac{1}{3})$ and $\text{Li}(-\frac{2}{3})$ are superalkalis, giving up their $2s^1$ electron when forming bonds with any other elements.

The quark atoms $\text{H}(\frac{1}{3})$ and $\text{H}(\frac{2}{3})$ with positive net charge lying on the isoelectronic line of hydrogen are superhalides. They complete their $1s$ shell when interacting with any ordinary element.

Moving along the isoelectronic line of hydrogen toward net negative charge leads to $\text{H}(-\frac{1}{3})$ which has the same electronegativity as potassium. Like potassium it never occurs in a negative oxidation state. Therefore the difference of electron affinities, separating the two elements in the scatter plot, does not destroy the analogy between these elements. For this very electropositive atom, matching ionization potentials rather than electronegativities may lead to better analogies. For ionic binding, the propensity of an electropositive atom to give up an electron may be more important than its electronegativity. Similarly, for electronegative atoms bound ionically, the electron affinity may be the more significant quantity in establishing analogies. The electronegativity is most appropriate in drawing analogies between atoms entering into covalent bonds.

Helium's isoelectronic line passes through the positions

of all noble gases. The closed shells of the states on this line is responsible for their low electron affinity and for this striking coincidence.

None of the quark atoms on the isoelectronic line of helium can be the analog of a neutral atom. Because these quark atoms have stable closed shells they never donate, accept, or share electrons. Furthermore, since they are charged, they bind electrostatically to oppositely charged ions. Therefore a nonzero oxidation number must be assigned to them. For example, $\text{He}(\frac{2}{3})$ is written as $\text{Li}(\frac{1}{3})^-$.

The form and length of the isoelectronic lines will now be discussed. The hydrogen line has a conspicuous minimum at a negative net charge corresponding to a negative value of the electron affinity. At this point the repulsion of an additional electron by the negatively charged atom is maximized. The increase of the atomic radius, due to a further decrease of the center charge, more than compensates for the increased absolute value of the net charge. As the center charge approaches zero the line must approach the origin.

With the exception of some transition elements, the length of an isoelectronic line increases when moving from left to right across a row in the periodic table. It also increases when moving toward the top of a column. This effect, which can be seen in Fig. 7 from the lines of lithium and hydrogen, is best illustrated in Fig. 6.

The rate of change of the electronegativity of an atom with respect to its center charge, i.e., essentially the length of its isoelectronic line, correlates with the possibility of finding analogs of quark atoms on this line. If the line is too long, the quark atoms at its ends are carried out of the periodic table. Therefore more analogs are found for heavy elements near the bottom of the periodic table. For example, $\text{Pb}(\frac{1}{3})$ has C as an analog, but $\text{C}(-\frac{1}{3})$ has no analog within the same column. For the same reason, it is easier to find analogs at the left rather than at the right of the periodic table. However, these analogs will not lie in the same column as the corresponding quark atoms because the variation of X and EA within a column is very small at the left of the periodic table (compare the alkalis, coinage metals, halides, and noble gases in Figs. 1 or 7).

The examples given in this section illustrate how analogies between quark elements and ordinary elements are established. The systematics of analogies based on electronegativities and shell structure were outlined. A comprehensive list of analogies has been given in Table VI.

VI. CHEMICAL CHIMERAS

Some quark elements have no analogs in molecular chemistry. Their electronegativity and possible oxidation numbers do not both match those of any ordinary element. For example $\text{C}(\frac{1}{3})$, which has the same electronegativity as fluorine, forms tetrahedral bonds like carbon, but these bonds are generally highly ionic, like those of fluorine. $\text{C}(\frac{1}{3})$ is therefore a carbon-fluorine chimera.

Although there is no single element analogous to $\text{C}(\frac{1}{3})$, properties of its molecules may still be determined by the usual interpolation procedure. For example, the isoelect-

ronic sequence CH_4, $C(\frac{1}{3})H_4$ and $NH_4{}^+$, which could also be written in the more suggestive notation $C(\frac{0}{3})H_4$, $C(\frac{1}{3})H_4$, and $C(\frac{3}{3})H_4$, may be used to determine the binding energy and molecular spectra of the quark molecule $C(\frac{1}{3})H_4$.

Even though some quark elements possess no analogs, analogs of molecules containing such quark atoms may still exist. For example, CH_4 is an analog of $C(\frac{1}{3})F_4$. This analogy is based on the similar electronegativity differences of the atoms in each molecule, together with the similarity of their bond structure. For a single bond, C—I is an even better analog of $C(\frac{1}{3})$—F than C—H, mainly because of the greater similarity in shell structure. Note that CH_4 and $C(\frac{1}{3})F_4$ do not interact with other molecules in the same way. Rather, they are structural analogs of each other.

Although C and $C(\frac{1}{3})$ are not analogs, the pairs of elements, (C,H) and $(C(\frac{1}{3}),F)$, are. Not only are their molecules structurally similar, but the way carbon reacts with hydrogen is also analogous to quark carbon's reaction with fluorine. Generally, a set of elements $(A,B,\ldots)$ is said to be analogous to another set $(A',B',\ldots)$ with respect to a particular reaction or class of reactions, if for each reaction involving elements $A,B,\ldots$ of the first set, there exists another reaction involving elements $A',B',\ldots$ from the second set with A replaced by the corresponding A', B by $B',\ldots$. For example, if a quark atom A has an ordinary analog A' then the set of elements $(A,B,C,\ldots)$ is analogous to the set $(A',B,C,\ldots)$ for any elements $B,C,\ldots$.

For molecular reactions governed by electronegativity differences, the two sets of ordinary elements (Be,C,N,O,Cl,F) and (Sr,Si,P,S,I or H,Cl) are analogous. Analogous pairs of molecules are, for example, BeF_2 and $SrCl_2$, CF_4 and $SiCl_4$, NF_3 and PCl_3, OF_2 and SCl_2, ClF and ICl. A more interesting example of analogous molecules is provided by

$$|\overline{O}-N\overset{\displaystyle F}{\underset{\displaystyle F}{\diagup}}F \quad \text{and} \quad |\overline{S}-P\overset{\displaystyle Cl}{\underset{\displaystyle Cl}{\diagup}}Cl \;.$$
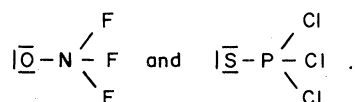
All atoms are in correspondence. If only some of the atoms correspond, the nature of the bonding, and even the structure of the molecule changes. For example, if the oxygen in the first molecule, ONF_3, is replaced by sulphur,

$$|\overline{S}-N\overset{\displaystyle F}{\underset{\displaystyle F}{\diagup}}F$$
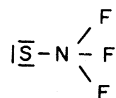
does not result. The molecules rearrange to the more stable form

$$N\equiv S\overset{\displaystyle F}{\underset{\displaystyle F}{\diagup}}F$$
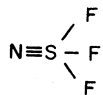
with the most electropositive element at the center.[57−59]

Chemical chimeras will react with ordinary elements in novel ways. Their existence would open a new field in chemistry, possibly providing new types of catalysts.

VII. CONTROL ELEMENTS AND TRACERS

The search for quarks in matter is complicated by their largely unknown geochemical history. In addition, man-made materials have been subjected to numerous chemical refinement procedures. It is usually impossible to compute from first principles the effect of such chemical reactions on possible quark impurities in a sample.

The impact of chemical reactions on quark impurities may, however, be monitored by observing the behavior of more abundant isomorphic elements. These isomorphic elements may be either found naturally in the sample, or tracers may be added to serve as artificial control elements.

Each type of chemical process may require its own control elements, since chemical analogies hold only for certain aspects of chemistry. For example, molecular reactions, which are particularly sensitive to electronegativity and shell structure, can be monitored with analogs given in Table VI.

VIII. RELATED WORK

The behavior of quark atoms in molecules, crystals, and solutions forms the core of quark chemistry. Electronegativity, shell structure, oxidation number, and crystal radius all help to determine this behavior. Electronegativity and crystal radius are found by interpolating isoelectronic sequences.[24,25] A complete discussion of crystal radii will be given in another paper of this series on quark chemistry.

Other papers will use these chemical indices to sketch the molecular, crystal, and aqueous chemistry of quarks, applying these to analytical chemistry and geochemistry. Later papers deal with the search for quarks in matter. An outline of the work to be covered is given in Fig. 8.

IX. AN EXAMPLE

The quark atom $H(\frac{1}{3})$ will be used to illustrate the previous discussion. This atom with one electron has a center charge of $\frac{4}{3}e$. The center could, for example, consist of the diquark uu, or the quark-nucleus system $\bar{u}He$. Such objects might be found on earth as remnants of the big bang.

Table II and Fig. 7 show the electronegativity of $H(\frac{1}{3})$ to be 1.4 MJ/mole (15 eV per atom), an electronegativity much larger than that of any ordinary element. In its interactions with ordinary matter $H(\frac{1}{3})$ acquires an additional electron, filling its 1s shell and forming the negative ion $H(\frac{1}{3})^-$. Like fluorine, $H(\frac{1}{3})$ reaches a spherically symmetric rare gas configuration in oxidation state -1. $H(\frac{1}{3})$ is a superhalide.

The crystal radius of $H(\frac{1}{3})^-$ is approximately 1.5 Å, conveniently close to that of fluorine which is 1.4 Å.[24,25] Therefore $H(\frac{1}{3})$ can substitute in crystals for fluorine. In fact, with respect to crystal chemistry, $H(\frac{1}{3})$ and F are isomorphic. Both are extremely electronegative, appear
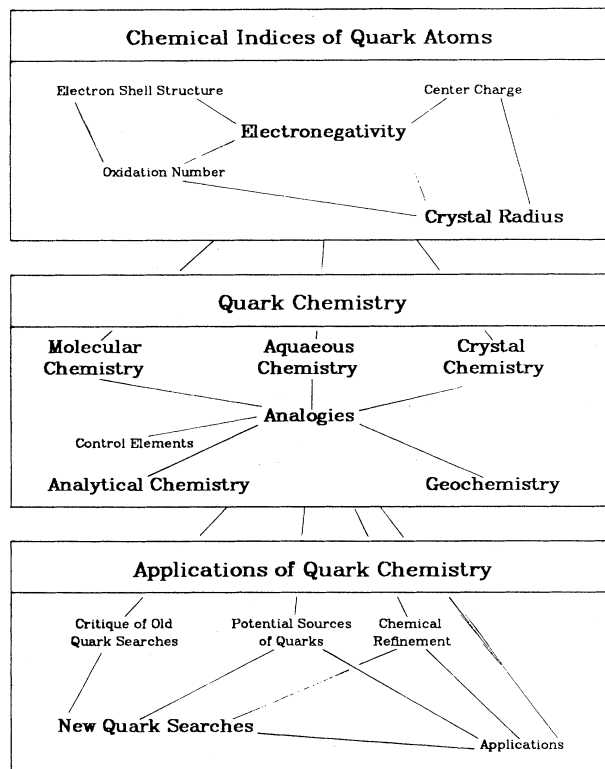
FIG. 8. Areas of quark chemistry, and their relationships, covered in this series of papers. Starting from the chemical indices of quark atoms, the quark chemistry of molecules, crystals, and solutions is developed and applied to the search for fractionally charged particles in matter.

only in oxidation state -1 with similar rare gas configurations, and have similar crystal radii.

If fractional charges occur in the form of $H(\frac{1}{3})$, then they would be found in fluorapatite. The fluorine in fluorapatite, $Ca_5(PO_4)_3F$, is often replaced by chlorine or by the hydroxide ion. The crystal radius of the chlorine ion is 1.8 Å, the radius of the hydroxide is 1.4 Å. These ions may be used as controls. Their concentration indicates the past promiscuity of the fluorine site.

The large electronegativity of $H(\frac{1}{3})$ suggests the possibility of a highly specific form of bonding that might be used for enrichment. The noble gas xenon tends to form bonds only with the most electronegative elements: fluorine, oxygen, and chlorine. The bonding of xenon to $H(\frac{1}{3})$ is therefore likely. However, detailed calculations are still necessary to establish the existence of the $H(\frac{1}{3})$-Xe bond.

Knowledge of the electron affinity and ionization potential of $H(\frac{1}{3})$ has helped in the design of recently proposed "charge spectroscopy" experiments.[60-62] These experiments involve the transfer of electrons between quark atoms and ordinary atoms. The probability of such a transfer depends on the ratio of the relative velocity of these atoms to the energy required for the transfer. For example, the probability of forming the negative ion $H(\frac{1}{3})^-$ by passing an $H(\frac{1}{3})$ atom through a target is max-

imized when the $H(\frac{1}{3})$ has a velocity.

$$v = \frac{l}{h}[IP(\text{target atom}) - EA(H(\frac{1}{3}))] , \qquad (13)$$

where l is an interaction length and h is Planck's constant.

X. SUMMARY

The behavior of massive fractionally charged particles in matter is governed by the laws of chemistry if electromagnetic interactions dominate at atomic distances. These fractionally charged particles could be free quarks, bound states of quarks and nuclei, or other fractionally charged objects.

Chemical properties of such quark atoms can be predicted by interpolating isoelectronic sequences. Isoelectronic sequences also exist for molecules. The properties of molecules containing quarks can be obtained directly from them.

Electronegativity forms the basis for much of our qualitative understanding of molecular quark chemistry. The electronegativity together with the ionization potential and electron affinity of the quark elements has been computed using isoelectronic sequences.

The concepts of chemical analogy and isomorphism were introduced. Analogies based on shell structure and electronegativity have been established.

Many quark elements cannot be compared to a single ordinary element. They are chemical chimeras whose properties can be deduced by comparing analogous sets of elements. The individual elements of these sets are no longer analogs of each other but have appropriate differences of electronegativity.

The impact of chemical reactions on quark impurities in matter can be monitored by observing the behavior of more abundant isomorphic control elements. The impact of a geochemical reaction on the history of a sample may be estimated in a similar fashion.

An understanding of quark chemistry is essential for the design and interpretation of quark-search experiments. Contrary to common belief,[63,64] the chemical differences between a quark element and its ordinary counterpart are substantial. Generally they will not be found together.

Thus, the behavior of massive fractionally charged particles in matter is governed by the laws of chemistry. Quark chemistry is quite different from ordinary chemistry, but quark chemistry can be simply understood.

ACKNOWLEDGMENT

APPENDIX

This appendix details the interpolation procedure used to determine IP and EA. The smoothness of the data and the accuracy of the interpolation is exemplified in Figs. 2 and 4. The errors in the data as well as those arising from

the interpolation are negligible. Other factors, like hybridization of atomic orbitals and radius effects, should also be considered when predicting chemical properties more accurately. Their influence overshadows uncertainties arising from numerical errors.

All data[40–45] are taken from a compilation by Huheey (Tables 2.4A and 2.5 of Ref. 39). In those cases where the electron affinity of an element was not available, we estimated its value by comparing it with the electron affinities of all its neighbors in the periodic table. These estimates, together with very conservative upper and lower limits, are given in Table X. Since the electron affinity is small, its uncertainty does not lead to large absolute errors in the electronegativity.

Several higher ionization energies are either misprinted or missing in Huheey's compilation. Misprints were easily identified by arranging ionization energies in isoelectronic sequences. Values for misprinted or missing energies were obtained by interpolation. They are listed in Table XI.

The ionization potential and electron affinity are computed either by quadratic interpolation or quadratic extrapolation using the formula

$$IP_N(Z_0+\zeta) \approx \frac{\zeta(\zeta-1)}{2}IP_N(Z_0-1)+(1-\zeta^2)IP_N(Z_0)$$

$$+\frac{\zeta(\zeta+1)}{2}IP_N(Z_0+1) \ . \qquad \text{(A1)}$$

$IP_N(Z)$ is the energy needed to remove one electron from an atom with center charge Z and N electrons. In this notation $IP_{N+1}(N)$ is the electron affinity of a neutral atom with N electrons.

The total center charge Z is divided into an integer part Z_0 and a residual charge ζ,

TABLE XI. Estimated values for the ionization potential in those cases where measurements were not available or have been misprinted in the data source (Ref. 39). The less accurately determined numbers in parentheses have been obtained by comparison with corresponding numbers of neighbors in the periodic table. All other numbers have been found by interpolating isoelectronic sequences. The corrections to the misprinted values are designated by a superscript "(m)." The ionization potential is given in units of MJ/mole (1 MJ/mole $\approx$ 10.4 eV per atom).

Element	Ionization state	Ionization potential
Mg	X	35.462[(m)]
Mn	III	2.9484[(m)]
Zn	VI	9.64
Ba	III	3.45
Ta	II	(1.5)
W	II	(1.6)
Re	II	(1.6)
Os	II	(1.7)
Ir	II	(1.7)
Tl	IV	4.87
Pb	III	3.0815[(m)]
Po	II	(1.6)
At	I	(0.9)
At	II	(1.6)
Rn	II	(1.7)
Fr	I	(0.4)
Fr	II	(1.9)
Ac	III	1.78
Pa	II	(1.1)
U	II	(1.1)
Np	I	(0.6)
Np	II	(1.1)
Pu	II	(1.1)

TABLE X. Estimates of the electron affinity in those cases where measurements were not available. All values are given in units of MJ/mole (1 MJ/mole $\approx$ 10.4 eV per atom).

Element	Electron affinity	Lower limit	Upper limit
Sc	0.02	0.0	0.1
Mn	0.027	−0.1	0.1
Y	0.05	0.0	0.2
Zr	0.075	0.0	0.2
Nb	0.11	0.0	0.2
Tc	0.0	−0.1	0.1
Ru	0.06	0.0	0.2
Rh	0.1	0.0	0.2
Pd	0.115	0.0	0.2
La	0.03	0.0	0.2
Lanthanides	0.075	0.0	0.3
Hf	0.04	0.0	0.2
Os	0.075	0.0	0.3
Ir	0.15	0.0	0.3
Hg	−0.03	−0.1	0.2
Ra	−0.05	−0.1	0.0
Ac	0.03	0.0	0.3
Actinides	0.075	0.0	0.3

$$Z \equiv Z_0+\zeta \ . \qquad \text{(A2)}$$

If Z_0 is chosen such that ζ lies in the interval $[-1,1]$, Eq. (A1) gives an interpolation for $IP_N(Z)$. Otherwise extrapolated values are obtained.

The choice of Z_0 is limited by the available data. The IP_N for Z_0-1, Z_0, and Z_0+1 must all be known. The electron affinity of quark atoms with $Z < N$ can only be found by extrapolation. On the other hand, the ionization potential of a quark atom with $Z > N$ may be found by interpolation in two independent ways, corresponding to the choice of Z_0 equal to N or $N+1$. In this case the average of the two interpolations, IP and IP' is taken, provided they differ by less than 1%. Explicitly, when

$$\frac{IP+IP'}{2} \geq 0.01 \text{ and } \left| \frac{IP-IP'}{(IP+IP')/2} \right| < 0.01 \ , \qquad \text{(A3a)}$$

or

$$\frac{IP + IP'}{2} < 0.01 \text{ and } \left| \frac{IP - IP'}{0.01} \right| < 0.02 , \qquad \text{(A3b)}$$

the average of IP and IP' is formed. Otherwise, a more conservative linear interpolation is used. This occurs,

when the shell structure changes in an isoelectronic sequence, as is illustrated in Fig. 4.

X and X' are then computed from IP and EA according to Eqs. (6) and (11).

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