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Chemical Signatures for Superheavy Elementary Particles

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All tangible matter appears to be composed of protons, neutrons, and electrons. The presence, however, of trace amounts of superheavy [say 100 GeV to 100 TeV (*1*)] stable particles has not been completely excluded. Recent work involving electrolysis and subsequent analysis of a large sample of heavy water has set stringent limits on the occurrence of very heavy isotopes (*2*) of hydrogen in water (*3*). For masses up to 1 TeV, the limit is one part in about 10^{30}. Between 1 and 100 TeV, the limit is between one part in 10^{14} and one part in 10^{15}. There remain the possibilities that superheavy particles exist, but in concentrations less than one part in 10^{15} or so, and that superheavy particles exist in even greater concentrations, but for geophysical reasons were absent from the sample of heavy water in the study mentioned above. We insist that there is substantial motivation for continuing and extending mass searches both on general grounds and on indications from some models of unified weak, electromagnetic, and strong interactions.

Summary. Models of unified fundamental interactions suggest the existence of many particles in the mass range 10×10^9 to 100×10^{12} electron volts. Among these may be charged particles, $X^{\pm}$, that are stable or nearly so. The X^+'s would form superheavy hydrogen, while the X^-'s would bind to nuclei. Chemical isolation of naturally occurring technetium, promethium, actinium, protactinium, neptunium, or americium would indicate the presence of superheavy particles in the forms RuX^-, SmX^-, $^{232}ThX^-$, $^{235,236,238}UX^-$, $^{244}PuX^-$, or $^{247}CmX^-$. Other substances worth searching for include superheavy elements with the chemical properties of boron, fluorine, manganese, beryllium, scandium, vanadium, lithium, neon, and thallium.

We will outline a variety of chemical approaches that could lead to the isolation and identification of superheavy matter (*4*). These means would complement the hydrogen search already completed. Every search for rare heavy isotopes is subject to the uncertainties of the geophysical and geochemical history of the earth. The searches suggested below will be influenced by factors different from those affecting the search in heavy water. In addition, a combination of chemical and physical separation techniques may be able to achieve a higher level of sensitivity than that reached for hydrogen in the mass range above 1 TeV.

Historically, the chemical search for new varieties of stable matter on the earth terminated with the development of a successful model of the atomic nucleus in the 1930's. Under the constraint that all matter is composed of electrons and nucleons, there is little incentive to search for such things as naturally occurring "isotopes" of lithium or americium with atomic weights of thousands. The dogma of recent decades has it that new particles are to be found only at large accelerators or in cosmic rays by particle physicists, and certainly not in mines by chemists. However, our understanding of fundamental theory remains so limited that we dare not exclude the possible existence of very heavy stable particles as rare but natural constituents of atomic nuclei. They may be far too heavy to produce and study with existing accelerators. Perhaps these new particles do exist, are of potential technological significance, and cohabit with us on the earth. It is an important truism that if we do not search for these particles, we will not find them. In this connection, we should recall the belated discovery of argon as a 1 percent constituent of the atmosphere. Its discovery, less than a century ago, is the kind of outrageous surprise we may still anticipate today.

Motivation

Modern theories of fundamental interactions provide strong motivation for searching for stable elementary particles much heavier than a proton. The weak interactions, such as beta decay, are described generally by Fermi's theory in which four spin-1/2 particles (fermions) are coupled together, as for example in neutron (n) decay: $n \rightarrow pe\bar{\nu}_e$, where the products are a proton, an electron, and an antineutrino, respectively. This interaction is characterized by a coupling constant that has the rather small measured value $G_F \cong 10^{-5}\ M_p^{-2}$, where $M_p \approx 1$ GeV is the proton mass. In the remarkably successful theory that unifies weak and electromagnetic interactions (*5*), the interaction of the four fermions arises because pairs of fermions are coupled to a particle called the W boson. The mass of the W boson is related to the Fermi coupling constant by $M_W^2 = \pi\alpha/\sqrt{2}\, G_F \sin^2\theta_W \approx (80\ \text{GeV})^2$. Here $\alpha \approx 1/137$ is the fine structure constant and θ_W is the weak mixing angle. It has been measured in several ways with

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the result $\sin^2\theta_W \approx 0.2$. Although the electroweak theory yields a prediction for the mass of the W boson, it does not really explain its magnitude, since the value of G_F is not predicted but instead is measured experimentally.

The electroweak theory can be extended to include strong interactions, such as the forces that bind protons and neutrons in the nucleus (*6*). In their simplest form, these theories still provide no insight into the mass of the W boson. However, there are proposals to extend these models so that the mass of the W boson (or equivalently, the value of G_F) is determined by the strength of other forces in the theory (*7*). These forces are analogous to the "color" forces between quarks and are called hypercolor or technicolor forces. While color forces are characterized by an energy scale of 1 GeV, technicolor forces would be characterized by a scale of 1 TeV. In addition to quarks, these theories have techniquarks. The techniquarks could bind to form technibaryons. Ordinary baryons like the proton and neutron have three quarks in them because the color force derives from the group SU(3). Technibaryons might have four or five techniquarks in them if the technicolor force was associated with an SU(4) or SU(5) group.

The simplest theories that combine weak, electromagnetic, and strong interactions predict that the proton is not absolutely stable but decays with a lifetime of approximately 10^{30} years (*8*). Analogous predictions can be made for the technibaryons. In this way, we estimate a lifetime for the SU(4) technibaryons of about 10^{16} years. Severe limits can be placed on the existence of technibaryons of this kind, since no such decays have been observed in cosmic-ray experiments (9). For the SU(5) case, we estimate a lifetime of roughly 10^{76} years (*10*). This would be stable indeed.

Of course, there might be other reasons for the existence of stable, very heavy particles. Models analogous to the technicolor models might have some conserved quantum number that prevents the decay of certain particles. The most general argument for the possibility of stable particles in the TeV range is simply that if there are particles like the W boson with such masses, there may well be other particles, and some of these might be stabilized by any of several mechanisms.

Assumed Properties of Superheavies

We will not attempt to estimate the concentration of superheavy particles (*11*), but simply assume that some are created in the big bang and that some fraction remains after particle-antiparticle annihilation. We will also assume that the surviving superheavy particles are integrally charged: $X^{\pm}$ (*12*). These particles will be assumed to have only electromagnetic interactions with conventional matter, but this assumption is probably not too important, and most of our expectations would be unaffected by including some conventional hadronic interactions. For our purposes, it will not matter whether the X's are fermions or bosons. Of course, if there are stable neutral X's the presence or absence of hadronic interactions would be of primary importance for them (*13*).

The X^+ particles would behave as protons, (possibly) lacking hadronic interactions. They would thus be found as superheavy hydrogen.

Table 1. Electrostatic binding energies of X^- to various nuclides. The X^- is taken to be much more massive than the nucleus. See Eqs. 4 to 6.

Nucleus	E_b (MeV)
^{1}H	0.025
^{2}H	0.050
^{3}H	0.075
^{3}He	0.270
^{4}He	0.311
^{5}Li	0.842
^{5}He	0.431
^{6}Li	0.914
^{7}Li	0.952
^{7}Be	1.49
^{8}Be	1.55

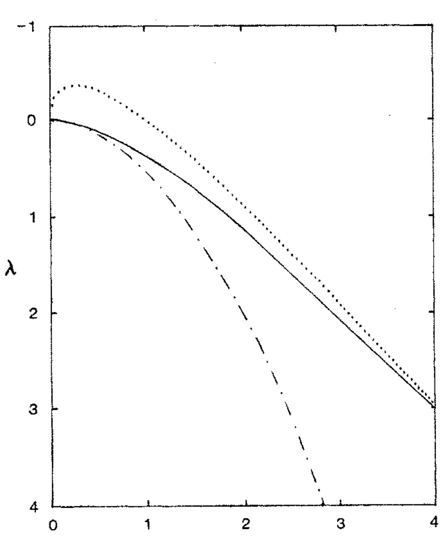

Fig. 1. The dimensionless function $\lambda(a)$, which gives the binding energy for the hybrid Coulomb–harmonic oscillator problem. The dot-dash curve is the solution to the pure Coulombic problem, the dotted curve the solution to the harmonic oscillator problem, and the solid curve the solution to the hybrid problem. See Eqs. 1 to 6.

The X^- particles, should they exist, would be distributed among the various nuclei. The binding of the X^-'s to nuclei can be estimated by using a simple model in which the nucleus is regarded as a sphere with uniform charge density and in which the mass of the X^- is assumed to be much larger than that of the nucleus. The Hamiltonian is then

$$H = \frac{P^2}{2M_N} - \frac{3Z\alpha}{2r_0} + \frac{Z\alpha}{2r_0}\left(\frac{r}{r_0}\right)^2 \quad , r < r_0 \tag{1a}$$

$$= \frac{P^2}{2M_N} - \frac{Z\alpha}{r} \quad , r > r_0 \tag{1b}$$

Here P is momentum; Z is the atomic number; $r_0 \approx 1.2\, A^{1/3}$ fermi is the nuclear radius, where A is the mass number and 1 fermi $= 10^{-15}$ m; and M_N is the mass of the nucleus. For large nuclei, the X^- is always inside the nuclear radius, and the problem is just that of a simple harmonic oscillator. The binding energy is

$$E_b = \frac{3}{2}\frac{Z\alpha}{r_0} - \frac{3}{2}\left(\frac{Z\alpha}{M_N r_0^3}\right)^{1/2} \tag{2}$$
$$= (1.8ZA^{-1/3} - 8.8Z^{1/2}A^{-1}) \text{ MeV}$$

For fixed A, this pushes stability toward higher Z:

$$\frac{\partial E_b}{\partial Z} = (1.8A^{-1/3} - 4.4Z^{-1/2}A^{-1}) \text{ MeV} \tag{3}$$

For $A \approx 100$, $\partial E_b/\partial Z \approx 0.4$ MeV.

In the limit of small nuclei, the problem is Coulombic and the binding energy is simply

$$E_b = \frac{1}{2}(Z\alpha)^2 M_N \tag{4}$$

In between these extremes it suffices to treat the problem variationally, using a wave function of the form $\psi \sim e^{-\gamma r/r_0}$. The result is that

$$E_b = (M_N r_0^2)^{-1}\, \lambda(Z\alpha M_N r_0) \tag{5}$$

where the function $\lambda(a)$ has limits

$$\lambda(a) \rightarrow \frac{1}{2}a^2 - \frac{2}{5}a^4 \; (a \rightarrow 0) \tag{6a}$$

$$\lambda(a) \rightarrow \frac{3}{2}a - \sqrt{3a} \quad (a \rightarrow \infty) \tag{6b}$$

The $a \rightarrow 0$ limit gives the correct first-order perturbation, since the trial wave function is exact for the Coulomb problem. The $a \rightarrow \infty$ limit is very nearly correct ($\sqrt{3} \approx 3/2$). The function $\lambda(a)$ is shown in Fig. 1. Electrostatic binding energies for a few low-A nuclides are shown in Table 1.

As a general rule, the X^- will bind to the highest Z nuclei accessible. During the big bang, X^-'s would have bound to ^{4}He as soon as it was formed. Moreover, while

$$^8\text{Be} \rightarrow 2\ ^4\text{He} + 92\ \text{keV}$$

Table 1 shows that the supernucleus ^{8}BeX$^-$ would be stable against the decay

$$^8\text{BeX}^- \rightarrow\ ^4\text{HeX}^- +\ ^4\text{He}$$

Thus, even in the big bang the X$^-$'s could be processed into high-Z nuclei:

$$\text{X}^- +\ ^4\text{He} \rightarrow\ ^4\text{HeX}^-$$

$$^4\text{He} +\ ^4\text{HeX}^- \rightarrow\ ^8\text{BeX}^-$$

$$^4\text{He} +\ ^8\text{BeX}^- \rightarrow\ ^{12}\text{CX}^-$$

$$^4\text{He} +\ ^{12}\text{CX}^- \rightarrow\ ^{16}\text{OX}^-$$

Of course, the X$^-$'s would also be processed into heavy nuclei in the other processes that are responsible for ordinary nucleosynthesis.

Technetium and Promethium

Through nucleosynthesis the X$^-$'s would be distributed among the nuclides. The combinations RuX$^-$ and SmX$^-$ are of special interest beause they have the charges of the nuclei technetium and promethium, which are not found in nature since their most stable isotopes have half-lives of only 4.2×10^6 years (^{98}Tc) and 17.7 years (^{145}Pm) (*14*). Thus any technetium or promethium found by chemical separation techniques should be suspected of being in fact RuX$^-$ or SmX$^-$, respectively. If a sufficiently large amount were isolated chemically, it would be possible to demonstrate the presence of superheavy material simply by density measurements. With smaller amounts, perhaps neutron activation could provide a definitive indication: the superheavy technetium would have the chemistry of technetium but not its nuclear chemistry. Also, the superheavy technetium would not be radioactive.

The best procedure for searching for technetium may be to examine material containing rhenium, which most resembles it chemically. This was the procedure which led to the spurious discovery of natural technetium by W. Noddack, I. Tacke, and O. Berg, who named it "masurium" (*15*). For promethium, the best place to look may be where the neighboring lanthanides, neodymium and samarium, are found. This, again, once led to the spurious discovery of naturally occurring promethium by B. Hopkins, who called it "illinium," and L. Rolla, who called it "florentium" (*15*).

It is necessary to check that the superheavy nuclides RuX$^-$ and SmX$^-$ would

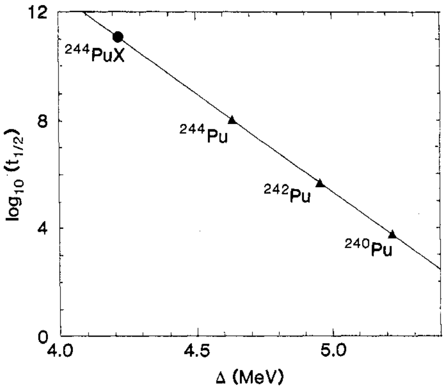

Fig. 2. Half-life, $t_{1/2}$ (in years), of plutonium isotopes plotted against Δ, the energy released in the alpha decay. The half-life of ^{244}PuX is estimated by extrapolating from measured lifetimes, using the Geiger-Nuttal law and the calculated reduction of 0.4 MeV in Δ.

be stable against beta decay, since the presence of the X$^-$ shifts stability toward higher Z. The RuX$^-$ would have about 0.4 MeV less electrostatic binding than the RhX$^-$ isobars. A check of binding energies shows that the isotopes with A = 96, 98, 99, 100, 101, 102, and 104 would indeed remain stable even with addition of X$^-$. For samarium, the electrostatic shift is about 0.34 MeV. The A = 144, 149, 150, 152, and 154 isotopes would remain stable. The A = 146, 147, and 148 isotopes of samarium are alpha emitters with half-lives of 1×10^8 years, 1×10^{11} years, and 8×10^{15} years, respectively. The superheavy analogs ^{146,147,148}SmX$^-$ would also be alpha emitters, but would release about 0.5 MeV less energy and would thus have considerably longer half-lives. We thus conclude that the superheavy analog of the stable forms of ruthenium and samarium would themselves be stable.

Actinides

A situation analogous to that of technetium and promethium occurs for actinium and protactinium. Although no isotope of uranium or thorium is absolutely stable, ^{238}U and ^{232}Th have half-lives of 4.5×10^9 and 1.4×10^{10} years, respectively. Thus the superheavy nuclides ^{238}UX$^-$ and ^{232}ThX$^-$ should both be present if the stable X$^-$ exists. These nuclei would form atoms with the chemistry of protactinium and actinium, respectively. Neither of these elements occurs in nature, since their longest lived isotope is ^{231}Pa, with a half-life of 3.3×10^4 years. In fact, the half-lives of ^{238}UX$^-$ and ^{232}ThX$^-$ would far exceed 10^{10} years because the presence of the X$^-$ gives added stability to the parent nucleus relative to the daughter in the alpha decay. Using Eq. 2, we find that the energy of the alpha emitted in the decay is 0.4 MeV less than if the X$^-$ is not present. Using the Geiger-Nuttal law and the known half-lives of various uranium and thorium isotopes, we estimate that the half-lives of the superheavy isotopes will be about 10^3 times longer (*16*). This would be enough to make the half-lives of ^{235}UX$^-$ and ^{236}UX$^-$ comparable to the age of the universe, as well. Indeed, even ^{247}CmX$^-$ and ^{244}PuX$^-$ would have half-lives of the order of 10^{10} years (see Fig. 2). These would have the chemistry of americium and neptunium, respectively. It is possible that X$^-$ might stabilize nuclei with Z greater than 105 by suppressing spontaneous fission (*17*). In summary, a search for naturally occurring actinium, protactinium, americium, and neptunium would be an important means of looking for superheavy, charged, stable particles.

Table 2. Possible sites for enhanced X$^-$ concentration. The final column is a rough guide to the enhancement. The concentrations, N^0, are relative to Si = 10^6 and are taken from (*19*). The abundances are not for the present terrestrial composition, but for the solar system.

Z	$N^0(Z)$	$N^0(Z+1)$	A	$A\ N^0(Z+1)/N^0(Z)$
3 (Li)	5×10^1	8×10^{-1}	7	1×10^{-1}
4 (Be)	8×10^{-1}	4×10^2	9	3×10^3
5 (B)	4×10^2	1×10^7	11	3×10^5
9 (F)	2×10^3	3×10^6	19	3×10^4
10 (Ne)	3×10^6	6×10^4	20	3×10^{-1}
11 (Na)	6×10^4	1×10^6	23	4×10^2
13 (Al)	8×10^4	1×10^6	27	3×10^2
15 (P)	1×10^4	5×10^5	31	2×10^3
17 (Cl)	6×10^3	1×10^5	35	7×10^2
18 (Ar)	1×10^5	4×10^3	40	1×10^0
19 (K)	4×10^3	7×10^4	39	7×10^2
21 (Sc)	4×10^1	3×10^3	45	4×10^3
23 (V)	3×10^2	1×10^4	51	3×10^3
25 (Mn)	9×10^3	8×10^5	55	5×10^3
27 (Co)	2×10^3	5×10^4	59	1×10^3
33 (As)	7×10^0	7×10^1	75	7×10^2
36 (Kr)	5×10^1	6×10^0	84	1×10^1
54 (Xe)	5×10^0	4×10^{-1}	131	1×10^1
81 (Tl)	2×10^{-1}	4×10^0	204	4×10^3

Other Sites of Enhancement

We can identify other chemical substances in which the concentration of X^-'s is likely to be enhanced. Let us indicate by $N_X{}^0(Z, A)$ the fraction of the nuclei with X's in them that have Z protons and $A - Z$ neutrons. By the superscript zero we mean that this is an initial distribution, let us say representing the distribution at the time of the formation of the solar system. We indicate the fraction of ordinary nuclei at the same time with Z protons and $A - Z$ neutrons by $N^0(Z, A)$. We define the function $\mathbf{a}(Z, A)$ by

$$N_X{}^0(Z, A) = \mathbf{a}(Z, A) \quad N^0(Z, A) \quad (7)$$

A reasonable hypothesis is that the X's are distributed approximately as the nucleons so that $\mathbf{a} \propto A$ and

$$\mathbf{a}(Z, A) = \frac{A}{\sum\limits_{Z,A} A\, N^0(Z, A)} = \frac{A}{\bar{A}} \quad (8)$$

Certainly this is a very crude approximation, but it will suffice except for some special cases to be considered below.

Let us denote by $P(Z)$ the probability that a nucleus with a charge of Z actually has $Z + 1$ protons and one X^- (we will suppress dependences on A). This probability, in the initial distribution, is

$$P(Z) = R\, \mathbf{a}(Z + 1, A)\, N^0(Z + 1)/N^0(Z) \quad (9)$$

where R is the ratio of the number of X^-'s to the total number of nuclei.

This probability, $P(Z)$, may not represent the present terrestrial probability because of processes that occurred during or since the formation of the earth. However, let us begin by ignoring this correction. Then, using Eq. 7, we can select good candidates for the search for superheavy particles by listing for various elements the quantity $A\, N^0(Z + 1)/N^0(Z)$. Some selected values are shown in Table 2. The odd-Z nuclei are seen to have the largest values. This simply reflects the greater nuclear stability of the even-Z nuclei, which are consequently produced in greater numbers in nucleosynthesis. An exception to this rule is beryllium, whose even-even nucleus ^{8}Be is unstable against decay into two alpha particles.

From Table 2, we see that several other elements are particularly attractive candidates for a search for superheavy matter: boron, fluorine, manganese, beryllium, scandium, and vanadium. In these cases, neutron activation might be used to identify a component whose nuclear structure was not that of the element being studied.

An exception to the approximation given by Eq. 8 is ^{8}BeX$^-$, which we would expect to be made rather easily. Limits on this supernucleus should be obtained with searches in lithium.

Another exception to Eq. 8 would be lead. Since the presence of an X^- pushes stability toward higher Z, it is likely that the X^-'s would be found preferentially in high-Z nuclei. In addition to favoring the nearly stable actinides, this would lead to a concentration in lead. The result would be PbX$^-$, with chemical properties identical to those of thallium.

The probabilities described by Eq. 9 ignore any effects that might have occurred during or since the formation of the earth. In particular, most of the volatile elements originally present were lost from the initial atmosphere. Thus neon is quite rare (18 parts per million by volume) in the atmosphere, although it is a primary component of nucleosynthesis (see Table 2). It is possible that NaX$^-$, which would be chemically a noble gas, might have survived the process that resulted in the loss of volatile elements. A list of suggested searches is given in Table 3.

Present limits on the concentrations of superheavy nuclei other than in hydrogen are rather weak. The agreement between masses measured chemically and those measured by mass spectrometry is about one part in 10^5 (*18*). Thus the concentration of 100-TeV X^-'s in matter with $A \approx 100$ must be less than one part in 10^8. Of course, it is desirable to push far beyond this scale, as has already been done in the case of heavy water.

Table 3. Suggested chemical searches for superheavy matter.

Superheavy material	Chemical behavior	Motivation for search
1. X^+e^-, $(^4\text{HeX}^-)e^-$	H	Site of all X^+; large ^{4}He abundance
2. RuX$^-$	Tc	No stable Tc isotope
3. SmX$^-$	Pm	No stable Pm isotope
4. ^{232}ThX$^-$	Ac	No stable Ac isotope
5. ^{235,236,238}UX$^-$	Pa	No stable Pa isotope
6. ^{244}PuX$^-$	Np	No stable Np isotope
7. ^{247}CmX$^-$	Am	No stable Am isotope
8. CX$^-$	B	B much scarcer than C
9. NeX$^-$	F	F much scarcer than Ne in cosmic abundance
10. FeX$^-$	Mn	Mn much scarcer than Fe
11. BX$^-$	Be	Be much scarcer than B
12. TiX$^-$	Sc	Sc much scarcer than Ti
13. PbX$^-$	Tl	Tl much scarcer than Pb
14. CrX$^-$	V	V much scarcer than Cr
15. BeX$^-$	Li	BeX$^-$ copiously produced in $^4\text{HeX}^- + {}^4\text{He} \rightarrow {}^8\text{BeX}^-$
16. NaX$^-$	Ne	Initial Ne lost from atmosphere

Conclusion

We have outlined a number of chemical searches that might lead to the discovery of new, very heavy, stable, charged particles. Any of them has the potential to find these new objects, but which search is the most promising we cannot say. That depends not only on the applicability of specialized techniques for isolating and identifying the new substances, but also on geophysical considerations that determine where the new substances might actually be found terrestrially. With such large atomic weights, these new chemicals might have undergone extensive fractionation, so they may not be distributed in the same manner as their lighter analogs.

References and Notes

1. That is, particles with masses of 100×10^9 to 100×10^{12} electron volts. Throughout we use units in which the speed of light is unity. This means that masses are given in energy units. The mass of the proton is 0.94 GeV and the mass of the electron is 0.51 MeV.
2. By a hydrogen isotope we mean an atom with a nucleus with one positive charge. The nucleus might or might not contain a proton. The positive charge could be supplied by a hitherto unknown particle.
3. P. F. Smith *et al.*, in preparation [preliminary report in *CERN Courier* **21**, 18 (1981)]. See also P. F. Smith and J. R. J. Bennett, *Nucl. Phys. B* **149**, 525 (1979).
4. A great many of our conclusions were arrived at independently and nearly simultaneously by C. K. Jorgensen of the University of Geneva.
5. S. L. Glashow, *Nucl. Phys.* **22**, 579 (1961); A. Salam and J. C. Ward, *Phys. Lett.* **13**, 1681 (1964); S. Weinberg, *Phys. Rev. Lett.* **19**, 1246 (1967); A. Salam, in *Elementary Particle Physics*, N. Svartholm, Ed. (Almqvist & Wiksell, Stockholm, 1968), p. 367.
6. H. Georgi and S. L. Glashow, *Phys. Rev. Lett.* **32**, 438 (1974).
7. S. Weinberg, *Phys. Rev. D* **13**, 974 (1976); *ibid.* **19**, 1277 (1979); L. Susskind, *ibid.* **20**, 2619 (1979); E. Farhi and L. Susskind, *ibid.*, p. 3404.
8. H. Georgi, H. Quinn, S. Weinberg, *Phys. Rev. Lett.* **33**, 451 (1974).
9. P. H. Frampton and S. L. Glashow, *ibid.* **44**, 1481 (1980).
10. E. Eichten, paper presented at the International Symposium on High Energy e^+e^- Interactions, Vanderbilt University, Nashville, Tenn., May 1980.
11. See, however, C. B. Dover, T. K. Gaisser, G. Steigman, *Phys. Rev. Lett.* **42**, 1117 (1979).
12. It is not certain that the existence of an X^- requires the existence of an X^+ in nature. The X^- might be composed of a very heavy quark, H, with charge −4/3. The state Hud with charge −1 might be stable, while Hu with charge +2 might

be stable with Hd decaying to it by beta emission.
13. Perhaps neutral heavy stable particles would bind only to nuclei with $Z > 1$ and thus would not have been detected in the experiment of (3). Such behavior is known for the Λ^0, which binds to ^{4}He but not ^{1}H or ^{2}H.
14. Technetium has been detected in uranium ore, where it occurs as a product of spontaneous and neutron-induced fission, as well as in the spectra of stars [for example, see G. E. Boyd and Q. V. Larson, *J. Phys. Chem.* **60**, 707 (1956)]. Minute traces of promethium have been found in nature and attributed to neutron irradiation of neodymium [see F. Weigel, *Chem. Ztg.* **102**, 339 (1978)]. These traces are identified by their radioactivity and thus cannot be related to the superheavy isotopes we seek, which would not be radioactive..
15. See M. E. Weeks and H. M. Leicester, *The Discovery of the Elements* (Journal of Chemical Education, Easton, Pa., ed. 7, 1968), pp. 834–883.
16. See, for example, J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (Wiley, New York, 1952), figure 3.1, p. 575.
17. We are indebted to E. K. Hulet and R. Lougheed for this suggestion.
18. See, for example, R. J. Holt *et al.*, *Phys. Rev. Lett.* **36**, 183 (1976), where limits for bismuth are discussed. Their experiment set very stringent limits on the occurrence of abnormal nuclei of a particular kind, but was insensitive to the sort of matter we are discussing.
19. A. G. W. Cameron, in *Explosive Nucleosynthesis*, D. N. Schramm and W. David, Eds. (Univ. of Texas Press, Austin, 1973), p. 3.
20. We thank L. W. Alvarez, F. Asaro, R. Hagstrom, R. Muller, E. Segrè, and R. Wagoner for their assistance and advice. R.N.C. was supported in part by an A. P. Sloan fellowship and expresses his thanks to the Aspen Center for Physics, where a portion of this work was completed. S.L.G. acknowledges the kind hospitality of the Lawrence Berkeley Laboratory, where this work was begun. He also thanks C. K. Jorgensen for several enlightening conversations and communications. This research was supported in part by the High Energy Physics Division of the U.S. Department of Energy under contract W-7405-ENG-48.

Enhanced Spinal Cord Regeneration in Lamprey by Applied Electric Fields

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The notion that an imposed electrical field can enhance or direct nerve growth began with the work of Sven Ingvar in 1920 (*1*). However, various technical and procedural difficulties rendered the results of many early studies ambiguous (*2–4*). Several experiments have been reported that clearly show that an imposed steady electric field has an effect on nerve growth in culture. Elaborating on an experimental design first used by Marsh and Beams in 1946 (*5*), Jaffe and Poo (*3*) demonstrated that the outgrowth of neurites emerging from explanted chick dorsal root ganglia is increased toward the negative pole (cathode) when an electrical field is imposed across the culture chamber. More recently, Robinson and McCaig (*6*) and Hinkle *et al.* (*4*) reported that single or multiple neurites produced by individual neuroblasts in culture show accelerated growth toward the cathode and will deviate toward it, bending away from the antipode.

Summary. After a weak, steady electric current of approximately 10 microamperes was imposed across the completely severed spinal cord of the larval lamprey *Petromyzon marinus*, enhanced regeneration was observed in the severed giant reticulospinal neurons. The current was applied with implanted wick electrodes for 5 to 6 days after transection (cathode distal to lesion). The spinal cords were examined 44 to 63 days after the operation by means of intracellular fluorescent dye injections and electrophysiology. Extracellular stimulation of whole cords showed that action potentials in most of the electrically treated preparations were conducted in both directions across the lesion, but they were not conducted in either direction in most of the sham-treated controls. In most of the electrically treated animals, processes from giant axons with swollen irregular tips, indicating active growth, were seen in or across the lesion. Only a few of the sham-treated controls showed these features. It is possible that these facilitated regenerative responses were mediated by the effects of the artificially applied electric fields on the natural steady current of injury entering the spinal lesion.

Recent studies on the effects of applied electric current on the regeneration of frog forelimbs have indicated that nerve growth in vivo can also be modified by applied electric currents. Borgens *et al.* (*7, 8*) demonstrated that minute, steady electrical fields imposed within the forelimb stumps of adult frogs can initiate limb regeneration. These workers used wick electrodes to deliver current and thus avoided the possible effects of electrode products associated with implanted metal electrodes. The enhanced limb regeneration was correlated with a striking hyperinnervation of the electrically treated limbs in both *Rana* (*7, 8*) and *Xenopus* (*9*). This suggested that the induced limb regeneration might be mediated by a facilitated nerve growth within the terminal portions of the limb stump, in much the same manner that surgical hyperinnervation was shown by Singer (*10*) to initiate limb regeneration in *Rana*. Borgens *et al.* (*7, 8*) established that this induced limb regeneration and increased nerve growth was due directly to the artificially imposed current of 200 nanoamperes with the cathode oriented distally within the limb stump.

We have asked whether comparable electric fields, when imposed across the severed spinal cord of a primitive vertebrate, will enhance the regeneration of axons in the cord. For our experiments we used the ammocoete larva of the lamprey (*Petromyzon marinus*), for the following reasons: (i) The lamprey central nervous system (CNS) possesses giant reticulospinal neurons that are morphologically identifiable at various locations within the brain and spinal cord (*11*). The cell bodies of these Mauthner and Müller cells lie within the brain and project giant axons (about 40 micrometers in diameter) down the spinal cord in well-characterized tracts. This permits one to compare the reactions of these individual identified neurons to axonal transection in control and experimental animals. (ii) These giant neurons are already known to regenerate across a spinal lesion (*12, 13*). Normally, a few of the axons will regenerate across the lesion and form new synapses (*14*) and eventually, swimming is restored. (iii)

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