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COLD NUCLEAR FUSION IN THE EARTH

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ABSTRACT

Evidence that p-d or d-d fusion could be occurring in the earth stimulated the original laboratory search for cold fusion. That evidence is reviewed here. It is found that the geologic ratio of heat to ^{3}He is too high to be explained by the usually accepted fusion processes. Laboratory evidence indicates that fusion can be made to occur in processes of fracture and high strain rate similar to earth processes. An extension of the Oppenheimer-Phillips theory of neutron tunneling is advanced to illustrate alternate fusion paths which could explain the high heat/^{3}He ratio. The search for fusion as a source for additional heat and non-primordial ^{3}He is further stimulated by recent data and analysis indicating that radioactivity can supply less than five percent of the earth's heat budget. Evidence of deep convection suggests that primordial ^{3}He should have been lost in early earth formation and in ongoing outgassing. In this paper, only surface-related (seawater) deuterium is considered.

INTRODUCTION

A laboratory search for hydrogen-isotope fusion in solid matter was suggested by evidence that such fusion occurs in the earth.[1] The locations and concentrations of the fusion product ^{3}He hinted that some combined action of pressure, temperature, and catalyst could be occurring in some deep-earth situations to produce fusion analogous with cold muon-catalyzed fusion.[2] A muon acts as a heavy electron and binds the hydrogen atoms in a molecule close together causing fusion in about 10^{-9} sec and giving the products $^3\mathrm{He} + \gamma$ for p-d fusion and either $^3\mathrm{He} + \mathrm{n}$ or $\mathrm{t} + \mathrm{p}$ for d-d fusion. The radioactive tritium decays into ^{3}He with a half life of 12.4 yr. If the analogy with muon-catalyzed fusion were correct, the ^{3}He could have come from fusion in the earth, and earth processes could be mimicked in the laboratory.

Deuterium is the prominent candidate as a fusion fuel in the earth because of its relative ease of fusion and its adequate abundance. Deuterium from sea water is incorporated in crystal structure, trapped in sediments and crustal rock, and is subducted into the earth's upper mantle at converging plate margins. It is conducted deep into the crust in cracks at spreading regions.[3] The amount of deuterium contained in a rock determines the total possible production of energy and fusion products, and the fusion rate constant in any particular geologic milieu determines whether measurable concentrations of heat and nuclear products can be generated in an applicable time period.

The purposes of this paper are to examine evidences of fusion in the earth, to relate these to laboratory and theoretical reports, and to advance arguments that fusion is a possible and a likely explanation for several geologic phenomena. Quantitative estimates are made for a few processes and show that low-rate fusion could produce the observed heat from the deuterium present in rocks with only minimal depletion of the fuel. However, the observed concentration of nuclear products is too low to be compatible with observed heat production if the standard p-d or d-d fusion model given above is the only process acting. The reasons to continue to press the investigation of fusion, in spite of this discrepancy, are that tantalizing geologic evidences continue to exist, laboratory and theoretical work are beginning to produce relevant information, and the long-entrenched dogma that U/Th/K radioactivity produces the earth heat is being seriously questioned. This work will be briefly reviewed. Fusion in core and mantle and other energy sources such as latent energy of phase change need to be continually reexamined, but only mantle fusion will be considered here. Possible observations and experiments to help resolve questions will be noted throughout the paper.

VOLCANISM

A typical geologic phenomenon is volcanism at subducting plate margins. The energy required to heat and melt a sedimentary rock and produce magma is about $2X10^6$ J/kg, and friction has been proposed as the source of this energy. The maximum mechanical energy available comes from gravitational potential energy over a height not much more than from mid-ocean ridge to deep trench. This is about $2X10^5$ J/kg, enough to deform rock but not enough to melt it. It is unlikely that any process can concentrate this diffuse energy source into an active volcano. Heat flow from surrounding rock is possible, but the thermal energy supply from the cold cores of continents is limited, and the constant subduction of material cools any underlying hot mantle rock. A possible source of energy internal to the rock is attractive.

A kilogram of subducting sedimentary rock contains about 30 g water containing about $2X10^{20}$ deuterons.[4] Since each p-d fusion produces 5.4 MeV energy ($8.7X10^{-13}$ J), about $2X10^{18}$ p-d fusions per kilogram are required to produce magma. Even if fusion produces all of the heat of volcanism, only about one percent of the available fuel is used in the process, and much is left for other deep-earth thermal processes.

To estimate the rate of fuel consumption requires an estimate of the time of production of the heat. Assume that this is the time of transit of the subducting rock on a slant path through a zone of volcanism from about 100-km to 300-km depth. This could require about $4X10^7$ years or $1X10^{15}$ sec. Using these numbers, a fractional rate of fusion (meaning the fraction of the deuterons present which actually fuse in the given time period) can be estimated.

$$(2X10^{18} \text{ atoms fusing})/(2X10^{20} \text{ atoms present X } 1X10^{15} \text{ sec}) = 1X10^{-17} \text{ sec}^{-1}.$$

This fractional rate of fusion is equivalent to a first-order reaction rate constant and can be expressed as "deuteron fusions per sec. per available deuteron." Note the assumption made here, that fusion dominates the energy processes in converging-plate volcanism.

This estimated fractional depletion of the deuterium fuel, based on heat production, can be compared with depletion estimated from measurements of the ^3He fusion product. Outgassed lavas at the surface often contain small amounts of ^3He, about $3X10^{13}$ atom/kg.[5] A rough estimate of the content before outgassing might be about 100 times this or $3X10^{15}$ atom/kg. This postulated ^3He production would require fusion of $3X10^{15}$ deuterons which is about 1/1000 of the number calculated as necessary to produce the magma. The fusion rate to produce this estimated ^3He product is about $1X10^{-20}$ fusions per sec. per deuteron.

A better estimate of rate constants cannot be made at this time because the rate of fusion is only barely observable and cannot be varied for study in either earth or laboratory. Differences between p-d and d-d fusion cannot be determined yet. Geologic information applicable to this rate problem is available at hot spots everywhere on earth in the form of data on the material input, the geologic processes occurring, and the output products. Materials being subducted and water influx are partially known; deformation and material transport at depth are partially known; heat, radioactivity, and fusion-product output are partially known. These data need to be reexamined and new data collected with a search for fusion in mind.

EARTH HEAT LOSS

The fusion rate constants estimated above are local constants considering only the results of fusion in a particular material. Global constants can be estimated by relating average heat-loss rates and ^3He production rates of the whole earth to the total active deuterium fuel source. Again, assume that the source is just the deuterium in sediment subduction and related to sea water.

The number of hydrogen atoms being subducted per second per meter of length of a subduction zone can be estimated by conservation of mass.

$$N = T\ S\ \rho\ f_1\ f_2\ A/M$$

where T is the thickness of the water-bearing sediment, S is the rate of subduction, ρ is the density of the rock, f_1 is the fractional weight of water in the rock, f_2 ($=1/9$) is the ratio of hydrogen to oxygen in water, A is Avagadro's number, and M is the atomic weight of hydrogen. Assuming values of $T=1000$ m, $S=0.025$ m/year, $\rho=2.2X10^6$ g/m^3, and $f_1=0.03$, gives $N=4X10^{21}$ hydrogen atoms subducted per second per meter of length of the subduction zone. A deuterium/hydrogen ratio of $1.5X10^{-4}$ results in a crudely estimated subduction rate of $7X10^{17}$ deuterium atoms per second per meter of plate margin.

This rate of subduction can be extrapolated to the entire earth by assuming all the broken-up subduction zones of the earth to have a total length of about one circumference of the earth or $4X10^7$ m. This gives a total rate of $3X10^{25}$ subducted deuterons per second. For an upper limit on fusion power, suppose a steady state were achieved and all this deuterium eventually fused in cycles of hundreds of millions of years from time of subduction to upwelling. For p-d fusion, the rate of energy production would be $2.4X10^{13}$ W. Averaging this power over the area of the earth, $5.1X10^{14}$ m^2, gives 0.05 W/m^2. Comparing this with an estimate of the actual average heat flux of 0.06 W/m^2,[6] indicates that fusion could be a significant energy source for the total earth heat budget even neglecting possible core hydrides.

This whole-earth rate of utilization of fuel is modest as it was in the case of volcanism. The oceans contain about 10^{43} deuterons, enough for 30 billion years of fusion at this rate of depletion. Higher estimates of hydrogen subduction have been made based on the rate of creation of new sea bed at spreading regions with concurrent subduction of water in sedimentary rocks.[4] All estimates indicate that deuterium fuel is in adequate supply.

These data allow the calculation of an upper-limit fusion-rate constant for the whole earth. Again assume a simple first-order rate constant.

$$\Delta N = k_1 N \Delta t$$

ΔN is proportional to the actual heat-loss rate (use 0.06 W/m^2); N is proportional to the possible heat loss rate (use 0.1 W/m^2); Δt is an earth convection-cell time (use $6X10^8$ years or $2X10^{16}$ sec). These values gives a rate constant k_1 of $5X10^{-17}$ sec^{-1}. The agreement here with the previously calculated rate constant is fortuitous considering the rough estimates used for input values. A number for a rate constant for whole-earth fusion can be calculated by the same method as above but based on ^3He rather than heat. The average outgoing flux of ^3He is reported as $8X10^5$ m^{-2} sec^{-1} or $4X10^{20}$ sec^{-1} for the whole earth.[5] The possible maximum flux, neglecting core hydrides, is equal to the deuterium subduction rate, perhaps $3X10^{25}$ sec^{-1}. Assuming the time scale again of $2X10^{16}$ sec, the rate constant is $6X10^{-22}$ fusions per deuteron per sec. This is 10^{-5} below the whole-earth rate constant calculated using heat. As with subducting-margin volcanism, the rate calculated using heat is several orders of magnitude higher than the rate obtained using fusion products.

TRITIUM

Tritium, a d-d-fusion product with a half life of 12.4 years, is found in volcanic gases and hot-spring waters. Concentrations above those in the normal atmosphere were measured before H-bomb testing as well as since.[7]

An interesting event was the atmospheric tritium "pulse" recorded during the eruption of Mt. Ulu on Hawaii in Feb.-Mar. 1972. This eruption produced what was possibly the greatest lava flow ever recorded[8] as well as an extensive and long-duration tritium plume averaging 70 tritum atoms per milligram of air.[9] The width of the plume, encompassing the Mauna Loa monitoring station to the north-west and Oahu in an arc to the north-east, and an unusual reported wind of about 8 mph toward Honolulu, allow a rough estimate to be made of the amount of tritium released, about 10^{23} atoms or 5000 Ci. This is an unlikely radiation "leak" from a man-made source and is not consistent with Soviet H-bomb tests made five months earlier.[9] This tritium is not consistent with the volcanic release of stored H-bomb-contaminated rain water which would require a 7.5-cm (3-inch) rainfall containing 3000 TU (tritium units) to cover an area 80 X 80 km (50 X 50 mi) and all the collected water to be released in one eruption. 3000 TU is in the upper range of contamination levels recorded in rainfall and was not recorded at Manua Loa.

If this tritium were from d-d fusion in the earth, it must have resulted from injection of seawater into a body of magma supplying the volcano. The short half life of tritium precludes travel in a slow mantle convection system or from the core. The amount of tritium is too small to prove fusion as a source of earth heat. Bullard[8] gives an estimate of $3.5X10^8$ m^3 of lava from the Mauna Ulu eruption over a 39-month period. Suppose that one-eighth of this, $4.4X10^7$ m^3 or $1X10^{11}$ kg, came during the most active time when the wind blew toward the monitoring station. Assuming that the tritium released, 10^{23} atoms, was a large fraction of the tritium contained in the 10^{11} kg lava, gives 10^{12} tritium atoms per kg of lava. To produce this would require 10^{12} d-d fusions per kilogram of lava, far below the 10^{18} fusions calculated previously as necessary to produce magma. The 10^{12} tritium atoms per kg of rock is a lower-limit estimate; some would remain in the rock and not be measured, and most would probably decay after formation before being ejected from the volcano.

If this tritium observation is not due to contamination or faulty measurements, it is of great significance. It would demonstrate earth fusion and would indicate a shallow source for this particular type fusion. Such measurements could help differentiate between p-d and d-d fusion by simultaneous ^{3}He and tritium measurements. They could help distinguish between sea water leakage into magma and slow subduction of deuterium, and they could furnish data for rate calculations. Many more such measurements need to be made with particular attention paid to careful collection of concurrent ^{3}He and tritium data.

EVALUATION OF FUSION-RATE DATA

The standard geologic explanation for all these observations is that radioactivity in the core produces the heat, a primordial source of ^{3}He was collected in the original formation of the earth and is now revealed by slow outgassing of the mantle, and tritium is a contaminant from the nuclear age.[10] Further, if the heat is not from radioactivity, it is from gravitational potential energy expressed in latent heat of phase change at mantle, liquid-core, and solid-core interfaces. This is thought to adequately explain the heat and the fact that the nuclear product ^{3}He appears at a level 10^{-3} to 10^{-5} below that necessary to agree with the heat data. No fusion is indicated in the standard model.

In examining the possibility of fusion in the earth to supplement or contradict this model, two facts stand out: (1) There is an abundance of the fuel of choice, deuterium. Only sea-water deuterium has been considered here, and a total amount of 10^{43} atoms can be estimated. Estimates of core deuterium indicate up to 100 times this amount,[11] and this is concentrated in the region of highest temperature and pressure, the most likely region for fusion. A store of mantle deuterium has not been considered here. (2) If heat data and ^{3}He data are reasonably valid, fusion analogous to muon-catalyzed fusion is not the dominant heat source because ^{3}He concentrations appear to be too low to agree with heat data; other fusion processes need to be examined.

OPPENHEIMER-PHILLIPS REACTION

Nuclear reactions, not analogous with muon-catalyzed fusion, can possibly produce both heat and fusion products in the ratios observed, and they are more probable since they require less activation energy. One such process is the Oppenheimer-Phillips reaction described in more detail, and with some extensions, in the Appendix.[12] In this, an energetic deuteron reacts with a target nucleus and dissociates. The neutron tunnels into the target nucleus, and the proton is ejected with high energy. This is the main exothermic reaction which produces the heat. In a small fraction of the events, the energetic proton goes on to react with a deuteron to produce ^{3}He; otherwise it loses its energy in the host material. This type reaction should produce heat and ^{3}He in roughly the observed ratios. In an even smaller fraction of the events, the first excited deuteron can react with another deuteron in fusion analogous to muon-catalyzed fusion and produce tritium and neutrons in addition to ^{3}He.

A test comparing fusion following the Oppenheimer-Phillips model with fusion analogous to muon-catalyzed fusion, can be made using deuteron ion bombardment on targets of pure materials and earth-like materials which are loaded with deuterium and hydrogen. This was the method used by Lawrence, McMillan, and Thornton in the experimental work leading to the Oppenheimer-Phillips theory;[12] it has been used in the measurement of deuterium loading of materials in "hot-fusion" research;[13] and it was used in one fusion-rate-constant measurement noted in the next section.[14] Modern particle detectors can measure all the nuclear products, their energies, and their production threshold energy. This work has not been aggressively pursued.

LABORATORY MEASUREMENTS OF FUSION

Numerous reports of measurements of fusion products indicate that d-d fusion can be made to occur at low rates under conditions far removed from those in the interior of stars or in high-temperature plasma-fusion devices. Unfortunately, these measurements have not been adequately controlled and quantified and must be accepted with reservation as evidence for fusion in the earth. The first laboratory results were obtained in metals in both D_2O-containing electrolytic cells[1,15-17] and in D_2-gas pressure cells undergoing thermal stress.[18,19] Possibly of greater significance in geology are the reports of d-d fusion in deuterides undergoing moderate shock,[20,21] in energetic chemical reactions,[22] and in fusion in SiO_2 in a deuterium-gas plasma.[23]

A few laboratory measurements of a fusion rate constant have been reported. The first, from the earliest measurement of nuclear products in the laboratory,[1] gave 10^{-23} fusions per sec. per deuteron. A second, from Soviet deuteron-ion implantation experiments,[24] gave $6X10^{-19}$ fusions per sec. per deuteron. Note that both these values come from experiments using high-concentration deuterium in a metal lattice and do not apply directly to a geologic situation. In spite of this, there is some value in comparing earth and laboratory rates. Theory suggests that the p-d-fusion rate constant is 100 times greater than the comparable d-d constant for low-energy fusion.[25] Comparing only numbers, and not the possible physics involved (blindly extrapolating the rates to geologic fusion), the highest measured value implies a p-d-fusion rate high enough to produce the heat of volcanism. The low value came from an experiment having low deuterium concentration and might be approaching an unknown second-order rate constant applicable to ^3He production. These very tenuous relations between laboratory and earth science can only be considered hints, and they await development into demonstrations or refutations of earth fusion.

A different-type result, from several different types of experiments, does not give a fusion rate but gives the ratio of tritium production to neutron production.[26] This ratio is reported to be 10^8 (within a few orders of magnitude). This is in contrast to a t/n ratio of about one for muon-catalyzed fusion and for the Soviet ion-implantation studies noted above. If proven true, the circumstances leading to these strangely different results must be unravelled and related to geologic processes.

GEOGRAPHY OF ENERGY, FUSION PRODUCTS, AND RADIOACTIVITY

An appealing argument encouraging further investigation of cold fusion in the earth is that of elegant simplicity. The world-wide distribution of nuclear products very roughly divides with all the radioactivity-related materials in the old cold continents and all the fusion ashes, mainly ^3He, in the hot spots. Plate-margin and mid-plate hot spots are well known for their anomalously high ^3He concentrations, and they lack the concentrations of U/Th/K and the decay products expected if radioactivity were the heat source.[5,27] The continental granites (which were once hot spots, of course) contain the U/Th/K products.

If fusion were a major heat source, there would be no concern about different material reservoirs and different geologic processes for heat diffusion, noble-gas diffusion, and radioactive-material transport from the interior of the earth, as has been proposed.[28] Rather, the problem becomes one of analyzing fusion evidence and evaluating the core and the surface materials as sources.

If surface deuterium did supply the energy for the earth's positive heat balance, the bumpy nature of the core would indicate convection cells in the mantle extending to the core and involving it.[29] Subduction over hundreds of millions of years could build up concentrations of deuterium that would, in time, completely change the geography of heat sources. Something as deep and extensive as this is necessary to explain the shifting hot spots which split continents, form island chains, and cause magnetic reversals.

The overall lack of evidence for adequate radioactivity in the earth, and the paucity of ^4He outgassing, lead to the growing conclusion that U/Th/K can supply less than five per cent of the earth's internal heat.[27] Resolving this disagreement with standard geologic wisdom is fundamental to ongoing development of tectonic theory and to the purposes of this paper. In view of this, evidences for fusion should be thoroughly scrutinized.

The occurrence of high concentrations of ^3He in diamonds seems to be more compatible with a fusion source rather than a primordial source.[30,31] The ^3He concentration is highly variable both in individual diamonds and throughout a diamond bed. Barberi argues that this is not compatible with incorporation of ^3He from a primordial source into the diamond at the time of its formation but is compatible with fusion in hydrogen-trapping impurities. In contrast to this, ^4He is more uniformly distributed as if by incorporation from the environment.

The mineral Josephinite is iron-nickel rich and contains high concentrations of ^3He. It is thought to be a likely example of a core material which appears on the surface of the earth.[32,33] It also qualifies as an evidence for deep-earth fusion since iron-nickel alloys form hydrides which could be fusion sources.

TRIGGERING FUSION IN THE EARTH

Fission fragments and radioactive-decay products have energies well above the few keV required to overcome the Coulomb barrier for d-d or p-d fusion, and these particles might trigger fusion reactions at very low rates in deuterium-bearing materials. The energetic products from one fusion reaction might cause further chain reactions under favorable conditions. Cosmic-ray particles may cause fusions to occur, and they can produce spallation products, containing ^3He, in earth materials and in subducted meteoric dust.[34] Some of these sources might be detectable but are not significant contributers to earth heat or to major fusion-product concentrations.

Mineral deformation in the earth is known to produce electrical effects, from piezoelectricity and fracturing, with voltages in the range of the few keV required to produce fusion. "Fracto-fusion," or particle acceleration by the voltages produced in crystal fracturing, has been proposed and investigated as a fusion trigger.[20,35] Molecular "Coulomb explosions" can occur where nuclei are accelerated as their binding electons are stripped away in violent deformations or collisions.[36] These all serve as high-energy or "hot-fusion" explanations for experimental cold-fusion results.

Laboratory investigation of these effects has been limited, and controlled variation of parameters seems to be missing. Previously noted work in impact, crushing, and heating/cooling may have provided some conditions approaching those in the upper mantle of the earth. Relations between actual physical conditions in the systems and the rates of production of fusion products have not been determined. Much more work in this area can be done to either validate the hints of fusion or to provide null experiments related to geology.

SUMMARY AND RECOMMENDATIONS

The implied quest in all this is to find whether or not the heat engine driving plate tectonics is significantly dependent on hydrogen-isotope fusion for energy. If not, are the traces of fusion ashes on earth of local origin or do they come from a star? This is of more than casual interest because of the rising doubts of the major significance of U/Th/K in tectonic processes. Progress will come first from geologic research. ^{3}He must be related to all significantly different heat sources. It will be difficult to distinguish fusion products coming from the core, from surface material, from primordial sources, and from cosmic contamination. Determining patterns of relations among different source materials, source locations, subterranean processes, and observed products will continue to be the major guide in finding answers to the questions of origins of heat and fusion products.

Laboratory research must proceed from the known to the unknown, beginning with hot fusion (perhaps ion-beam bombardment of selected materials[37] or exploding wires of deuterium-containing materials[38]) where fusion results are certain, and then progressing to "cooler" fusion. Fusion observed in violent material deformation must be controlled, measured, and related to geologic processes.[39,40] Limits and bounds on fusion processes are not now available and are not being actively sought; but they can be obtained by the suggested progression from energetic to less energetic conditions. Sensitive fusion detectors, particularly neutron detectors,[41] are now available worldwide for this work. Hopefully, theorists will be motivated to examine low-rate, geologically important problems.

CONCLUSIONS

At this time, no laboratory experiment can provide a "knob" that controls any parameter and increases or decreases cold fusion at will. No theory can provide a direction to go to find and control cold fusion. Materials science cannot give detailed knowledge of hydrogen-isotope behavior in materials under the pressure, temperature, and distortion environments met in geologic processes. Hints from geology are the best sources presently available for direction in both experimental and theoretical research toward understanding fusion in solid matter.

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APPENDIX: THEORY OF CATALYZED FUSION

There are no complete theoretical results to guide geological research in cold fusion, so only the most general principles based on energy conservation will be invoked. This section is included to show that fusion paths other than those met in muon-catalyzed fusion are energetically possible and that contradictions which arise between production rates of heat and ^{3}He and in the ratios of fusion products ^{3}He, tritium, and neutrons may have simple solutions.

It is energetically possible for low-atomic-weight isotopes to fuse to produce heavier ones in conformity with the Einstein relation $E = mc^2$, and the only requirement is that the mass of the fusion products be less than the mass of the reactants. The Coulomb barrier ordinarily prevents fusion, but quantum-mechanical tunneling allows fusion, under favorable conditions, even if the nuclei do not approach each other within ordinary nuclear dimensions. Muon-catalyzed fusion results illustrate this conclusion. The deuterium nuclei separation, when bound by a muon, is about $3X10^{-13}$ m which is about 100 times the size of the nuclei involved, and tunneling is required for fusion.[2] This distance can be achieved in d-d collisions with energy of about 1.5 keV. Tunneling reactions between hydrogen isotopes and heavy elements are less likely because of the greater repulsion of the higher-charged nuclei. However, heavy elements may be important in searching for geologic fusion because they probably provide the best matrices in which to hold hydrogen isotopes together and create conditions aiding light-isotope fusion.

Experiments by Lawrence, McMillan, and Thornton and theory by Oppenheimer and Philips[12] showed that the neutron from a deuteron projectile having a few hundred keV energy could tunnel into relatively heavy target nuclei (Na, Al, Si, Cu) in an exothermic reaction. Neutron tunneling probably occurs at lower threshold energies than full-nucleus tunneling, and the Oppenheimer-Phillips effect, with variations, could be fundamental in cold fusion research.

The basic neutron-tunneling reaction, using deuterium, is

$$d + X(A) \rightarrow p + X(A+1) + Q_1. \quad (1)$$

The deuteron loses its neutron, and the target element X captures the neutron and increases its nuclear mass from A to A+1. In an extension of this reaction, the energetic proton or the excited target nucleus might interact individually with other deuterons, protons, or target nuclei. Also, the product-complex of proton, neutron, and target might interact as a unit with other nuclei, particularly deuterons or protons. The basic reaction of Eq.1 and a few extended reaction possibilities are shown in Fig. 1. The reactions are shown as being sequential, but that is only for clarity, and they may be multi-body reactions.

As another extension of the theory, it is energetically possible for the target nucleus to lose a neutron to the deuteron producing a triton and a target nucleus of mass A-1. This can happen with only a very few isotopes.

$$d + X(A) \rightarrow t + X(A-1) + Q_2. \quad (2)$$

Again, the energetic products might interact individually with deuterons, protons, or other target nuclei, or the product-complex might react as a whole. Various possibilities are given in Fig. 1. Because the primary reaction (2) is so rare, possible multi-body reactions are of most interest in this case. These may be related to the high t/n ratios observed in some experiments. Note that if the "target" is a proton or deuteron, the reaction is analogous to muon-catalyzed fusion and produces the same products. For "targets" of heavier elements, the nuclear products are not necessarily t and ^3He, and such products as protons and altered "neutron-rich" isotopes are produced. These would be difficult to detect in a geologic setting, even with large energy release, since the "altered" isotopes are among those already present from neutron reactions in the stars.

Table I is a listing of the energies for the different processes of Fig. 1 for a few selected elements. The common light elements of earth materials, those which have the lowest Coulomb barriers, Li, Be, B, C, N, and O, are prominent candidates to catalyze neutron-tunneling fusion. Quantum-mechanical considerations governing reaction paths and rates, and strong, electromagnetic, and weak forces, are as important as energy and Coulomb barrier in controlling fusion, but these will not be considered here.

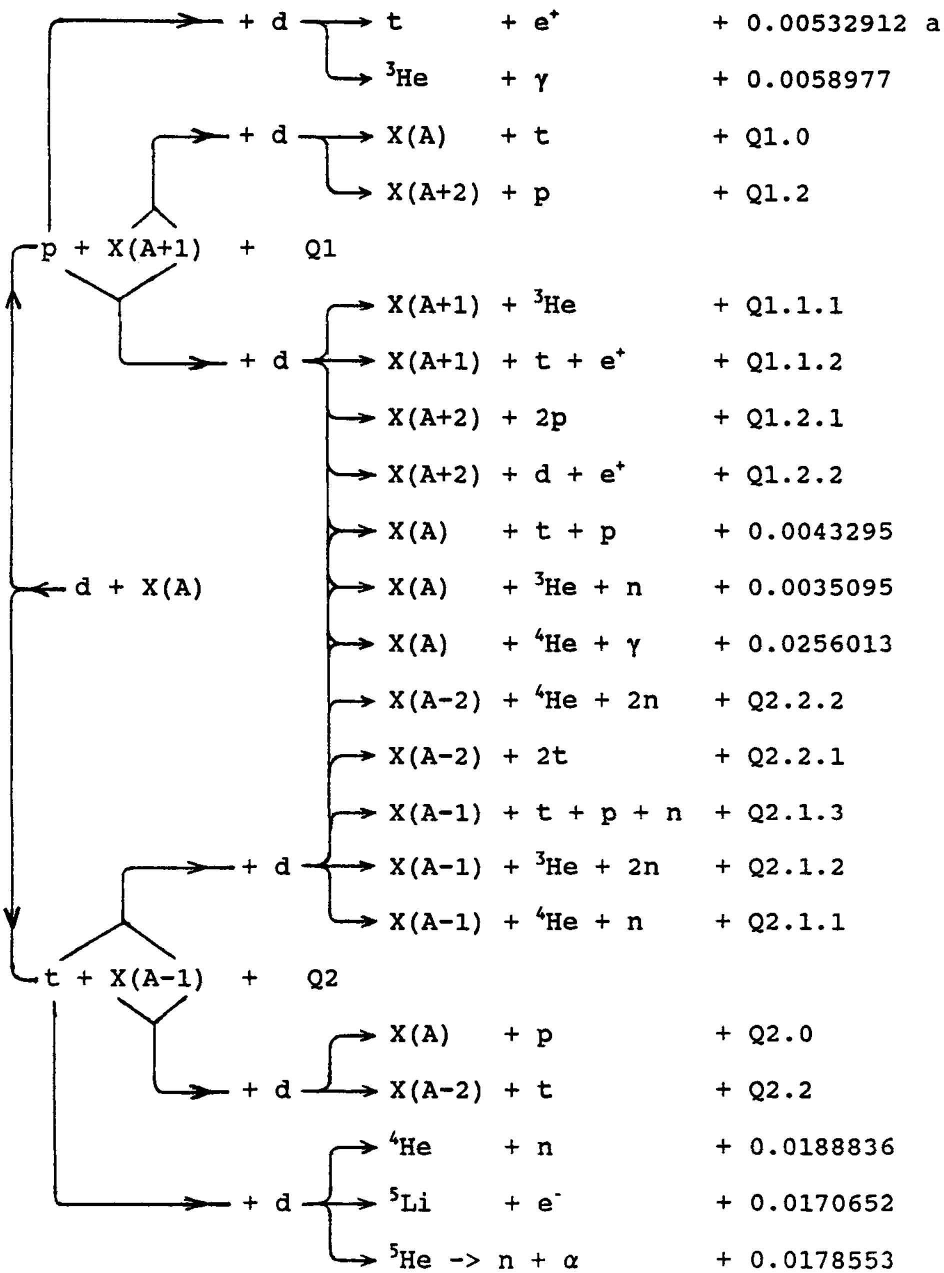

Fig.1. Possible pathways for neutron-tunneling reactions. Energy Q is given for each path segment; total energy is found by adding path-segment energies. Reactions are shown sequentially but may be multi-body. A few reactions using products from the first reaction are illustrated.

Table I

Calculated energy in atomic mass units for Eq. 1 and 2 and for reactions of Fig. 1. Multibody-reaction energy may be positive even with first-step energy negative. For example for ^{7}Li: Q2 = -0.001068 a; Q2.0 = 0.005398 a; Q2.1.1 = 0.17815 a. Thus Q2 + Q2.0 = 0.00433 a and Q2 + Q2.1.1 = 0.01675 a.

ELEMENT	ATOMIC NMBR.	TERMS
H	1	3
ATOMIC WT.	ATM. MASS	PERCENT
0	0	0
0	0	0
1	1.0078252	99.985
2	2.0141022	.015
3	3.0160497	.00006
4	4.0302959	0
5	5.0333771	0

	TARGET H- 1	TARGET H- 2	TARGET H- 3
Q1	-3.485871E-08	4.329466E-03	-7.969235E-03
Q1.0	.0043295	0	.0122987
Q1.2	4.329466E-03	-7.969235E-03	3.195765E-03
Q1.1.1	.0058977	.0102272	-.0020715
Q1.1.2	.0053291	.0096586	-.0026401
Q1.2.1	4.329431E-03	-3.63977E-03	-4.77347E-03
Q1.2.2	.0053291	-.0026401	-.0037738
Q2	0	.0043295	0
Q2.0	0	-3.485871E-08	4.329466E-03
Q2.2	0	0	.0043295
Q2.1.1	0	2.321313E-02	1.888362E-02
Q2.1.2	0	.0011213	-.0032082
Q2.1.3	0	.0019413	-.0023882
Q2.2.1	0	0	4.329456E-03
Q2.2.2	0	0	.0164954

ELEMENT	ATOMIC NMBR.	TERMS
HE	2	2
ATOMIC WT.	ATM. MASS	PERCENT
0	0	0
0	0	0
3	3.0160297	.00014
4	4.0026031	99.99986
5	5.0122966	0
6	6.0188928	0

	TARGET HE- 3	TARGET HE- 4
Q1	1.970357E-02	-3.416535E-03
Q1.0	-.0153741	.007746
Q1.2	-3.416535E-03	-3.192349E-04
Q1.1.1	.0256013	.0024812
Q1.1.2	.0250327	.0019126
Q1.2.1	1.628703E-02	-3.73577E-03
Q1.2.2	.0172867	-.0027361
Q2	0	-.0153741
Q2.0	0	1.970357E-02
Q2.2	0	0
Q2.1.1	0	3.509523E-03
Q2.1.2	0	-.0185823
Q2.1.3	0	-.0177623
Q2.2.1	0	0
Q2.2.2	0	0

ELEMENT	ATOMIC NMBR.	TERMS
LI	3	2
ATOMIC WT.	ATM. MASS	PERCENT
4	0	0
5	5.0125381	0
6	6.0151247	7.5
7	7.0160039	92.5
8	8.022487	0
9	9.0268015	0

	TARGET LI- 6	TARGET LI- 7
Q1	5.397765E-03	-2.061349E-04
Q1.0	-.0010683	.0045356
Q1.2	-2.061349E-04	1.962465E-03
Q1.1.1	.0112955	.0056916
Q1.1.2	.0107269	.005123
Q1.2.1	5.19163E-03	1.75633E-03
Q1.2.2	.0061913	.002756
Q2	.0006391	-.0010683
Q2.0	3.690365E-03	5.397765E-03
Q2.2	0	.0006391
Q2.1.1	1.952272E-02	1.781532E-02
Q2.1.2	-.0025691	-.0042765
Q2.1.3	-.0017491	-.0034565
Q2.2.1	0	-4.292444E-04
Q2.2.2	0	.0117367

ELEMENT	ATOMIC NMBR.	TERMS
BE	4	1
ATOMIC WT.	ATM. MASS	PERCENT
7	7.0169289	0
8	8.0053078	0
9	9.0121855	100
10	10.0135343	0
11	11.0216655	0

	TARGET BE- 9
Q1	4.928165E-03
Q1.0	-.0005987
Q1.2	-1.854235E-03
Q1.1.1	.0108259
Q1.1.2	.0102573
Q1.2.1	3.07393E-03
Q1.2.2	.0040736
Q2	.0049302
Q2.0	-6.007349E-04
Q2.2	-.0135686
Q2.1.1	2.381382E-02
Q2.1.2	.001722
Q2.1.3	.002542
Q2.2.1	-8.638444E-03
Q2.2.2	.0035275

ELEMENT	ATOMIC NMBR.	TERMS
B	5	2
ATOMIC WT.	ATM. MASS	PERCENT
8	8.0246093	0
9	9.0133321	0
10	10.0129387	19.8
11	11.0093052	80.2
12	12.0143536	0
13	13.0177798	0

	TARGET B- 10	TARGET B- 11
Q1	9.910465E-03	1.228565E-03
Q1.0	-.005581	.0031009
Q1.2	1.228565E-03	2.850765E-03
Q1.1.1	.0158082	.0071263
Q1.1.2	.0152396	.0065577
Q1.2.1	1.113903E-02	4.07933E-03
Q1.2.2	.0121387	.005079
Q2	-.0023409	-.005581
Q2.0	6.670365E-03	9.910465E-03
Q2.2	-.0132247	-.0023409
Q2.1.1	1.654272E-02	1.330262E-02
Q2.1.2	-.0055491	-8.789201E-03
Q2.1.3	-.0047291	-.0079692
Q2.2.1	-1.556564E-02	-7.921945E-03
Q2.2.2	-.0033997	.004244

ELEMENT	ATOMIC NMBR.	TERMS
C	6	2
ATOMIC WT.	ATM. MASS	PERCENT
10	10.0168098	0
11	11.0114317	0
12	12	98.9
13	13.0033544	1.1
14	14.0032419	0
15	15.0105995	0

	TARGET C- 12	TARGET C- 13
Q1	2.922565E-03	6.389465E-03
Q1.0	.0014069	-.00206
Q1.2	6.389465E-03	-1.080635E-03
Q1.1.1	.0088203	.0122872
Q1.1.2	.0082517	.0117186
Q1.2.1	9.31203E-03	5.30883E-03
Q1.2.2	.0103117	.0063085
Q2	-.0133792	.0014069
Q2.0	1.770867E-02	2.922565E-03
Q2.2	-.0073256	-.0133792
Q2.1.1	5.504424E-03	2.029052E-02
Q2.1.2	-.0165874	-.0018013
Q2.1.3	-.0157674	-.0009813
Q2.2.1	-2.070485E-02	-1.197235E-02
Q2.2.2	-.0085389	.0001936

ELEMENT	ATOMIC NMBR.	TERMS
N	7	2
ATOMIC WT.	ATM. MASS	PERCENT
12	12.0186412	0
13	13.0057384	0
14	14.0030743	99.63
15	15.0001078	.37
16	16.0061033	0
17	17.0084498	0

	TARGET N- 14	TARGET N- 15
Q1	9.243465E-03	2.814652E-04
Q1.0	-.004914	.004048
Q1.2	2.814652E-04	3.930465E-03
Q1.1.1	.0151412	.0061792
Q1.1.2	.0145726	.0056106
Q1.2.1	9.52493E-03	4.21193E-03
Q1.2.2	.0105246	.0052116
Q2	-.0046116	-.004914
Q2.0	8.941066E-03	9.243465E-03
Q2.2	-.0148503	-.0046116
Q2.1.1	1.427202E-02	1.396962E-02
Q2.1.2	-.0078198	-.0081222
Q2.1.3	-.0069998	-.0073022
Q2.2.1	-1.946195E-02	-9.525644E-03
Q2.2.2	-.007296	.0026403

ELEMENT	ATOMIC NMBR.	TERMS
O	8	3
ATOMIC WT.	ATM. MASS	PERCENT
14	14.008597	0
15	15.0030702	0
16	15.994915	99.762
17	16.9991329	.038
18	17.9991598	.2
19	19.0035777	0
20	20.0040784	0

	TARGET O- 16	TARGET O- 17	TARGET O- 18
Q1	2.059065E-03	6.250066E-03	1.859065E-03
Q1.0	.0022704	-.0019206	.0024704
Q1.2	6.250066E-03	1.859065E-03	5.776265E-03
Q1.1.1	.0079568	.0121478	.0077568
Q1.1.2	.0073882	.0115792	.0071882
Q1.2.1	8.309131E-03	8.10913E-03	7.635331E-03
Q1.2.2	.0093088	9.108801E-03	8.635001E-03
Q2	-.0101027	.0022704	-.0019206
Q2.0	1.443217E-02	2.059065E-03	6.250066E-03
Q2.2	-.0074743	-.0101027	.0022704
Q2.1.1	8.780924E-03	2.115402E-02	1.696302E-02
Q2.1.2	-.0133109	-.0009378	-.0051288
Q2.1.3	-.0124909	-.0001178	-.0043088
Q2.2.1	-1.757705E-02	-7.832345E-03	3.497557E-04
Q2.2.2	-.0054111	.0043336	.0125157

ELEMENT	ATOMIC NMBR.	TERMS
F	9	1
ATOMIC WT.	ATM. MASS	PERCENT
17	17.0020955	0
18	18.0009365	0
19	18.9984045	100
20	19.9999871	0
21	20.9999504	0

	TARGET F- 19
Q1	4.694365E-03
Q1.0	-.0003649
Q1.2	6.313666E-03
Q1.1.1	.0105921
Q1.1.2	.0100235
Q1.2.1	1.100803E-02
Q1.2.2	.0120077
Q2	-.0044795
Q2.0	8.808965E-03
Q2.2	-.0031065
Q2.1.1	1.440412E-02
Q2.1.2	-.0076877
Q2.1.3	-.0068677
Q2.2.1	-7.586045E-03
Q2.2.2	.0045799

ELEMENT	ATOMIC NMBR.	TERMS
NA	11	1
ATOMIC WT.	ATM. MASS	PERCENT
21	20.9976542	0
22	21.9944365	0
23	22.9897707	100
24	23.9909623	0
25	24.9899557	0

	TARGET NA- 23
Q1	5.085365E-03
Q1.0	-.0007559
Q1.2	7.283565E-03
Q1.1.1	.0109831
Q1.1.2	.0104145
Q1.2.1	1.236893E-02
Q1.2.2	.0133686
Q2	-.0066133
Q2.0	1.094277E-02
Q2.2	-.0051652
Q2.1.1	1.227032E-02
Q2.1.2	-.0098215
Q2.1.3	-.0090015
Q2.2.1	-1.177855E-02
Q2.2.2	.0003874

ELEMENT	ATOMIC NMBR.	TERMS
MG	12	3
ATOMIC WT.	ATM. MASS	PERCENT
22	21.9998496	0
23	22.9941249	0
24	23.9850416	78.7
25	24.9858389	10.13
26	25.9825928	11.17
27	26.9843445	0
28	27.983875	0

	TARGET MG- 24	TARGET MG- 25	TARGET MG- 26
Q1	5.479665E-03	9.523065E-03	4.525265E-03
Q1.0	-.0011502	-.0051936	-.0001958
Q1.2	9.523065E-03	4.525265E-03	6.746466E-03
Q1.1.1	.0113774	.0154208	.010423
Q1.1.2	.0108088	.0148522	9.854399E-03
Q1.2.1	1.500273E-02	1.404833E-02	1.127173E-02
Q1.2.2	.0160024	.015048	.0122714
Q2	-.0110308	-.0011502	-.0051936
Q2.0	1.536027E-02	5.479665E-03	9.523065E-03
Q2.2	-.0076722	-.0110308	-.0011502
Q2.1.1	7.852824E-03	1.773342E-02	1.369002E-02
Q2.1.2	-.014239	-.0043584	-.0084018
Q2.1.3	-.013419	-.0035384	-.0075818
Q2.2.1	-1.870304E-02	-1.218105E-02	-6.343845E-03
Q2.2.2	-.0065371	-.0000151	.0058221

ELEMENT	ATOMIC NMBR.	TERMS
AL	13	1
ATOMIC WT.	ATM. MASS	PERCENT
25	24.990412	0
26	25.9868908	0
27	26.9815388	100
28	27.9819045	0
29	28.9804418	0

	TARGET AL- 27
Q1	5.911265E-03
Q1.0	-.0015818
Q1.2	7.739665E-03
Q1.1.1	.011809
Q1.1.2	.0112404
Q1.2.1	1.365093E-02
Q1.2.2	.0146506
Q2	-.0072995
Q2.0	1.162897E-02
Q2.2	-.0054687
Q2.1.1	1.158412E-02
Q2.1.2	-.0105077
Q2.1.3	-.0096877
Q2.2.1	-1.276824E-02
Q2.2.2	-.0006023

ELEMENT	ATOMIC NMBR.	TERMS
SI	14	3
ATOMIC WT.	ATM. MASS	PERCENT
26	25.9923432	0
27	26.9867027	0
28	27.9769292	92.21
29	28.9764957	4.7
30	29.9737628	3.09
31	30.9753487	0
32	31.9740198	0

	TARGET SI- 28	TARGET SI- 29	TARGET SI- 30
Q1	6.710465E-03	9.009865E-03	4.691066E-03
Q1.0	-.002381	-.0046804	-.0003616
Q1.2	9.009865E-03	4.691066E-03	7.605865E-03
Q1.1.1	.0126082	.0149076	.0105888
Q1.1.2	.0120396	.014339	.0100202
Q1.2.1	1.572033E-02	1.370093E-02	1.229693E-02
Q1.2.2	.01672	.0147006	.0132966
Q2	-.011721	-.002381	-.0046804
Q2.0	1.605047E-02	6.710465E-03	9.009865E-03
Q2.2	-.007588	-.011721	-.002381
Q2.1.1	7.162624E-03	1.650262E-02	1.420322E-02
Q2.1.2	-.0149292	-.0055892	-.0078886
Q2.1.3	-.0141092	-.0047692	-.0070686
Q2.2.1	-1.930904E-02	-1.410205E-02	-7.061444E-03
Q2.2.2	-.0071431	-.0019361	.0051045

ELEMENT	ATOMIC NMBR.	TERMS
P	15	1
ATOMIC WT.	ATM. MASS	PERCENT
29	28.9818084	0
30	29.978317	0
31	30.9737647	100
32	31.9739094	0
33	32.9717278	0

	TARGET P- 31
Q1	6.132265E-03
Q1.0	-.0018028
Q1.2	8.458565E-03
Q1.1.1	.01203
Q1.1.2	.0114614
Q1.2.1	1.459083E-02
Q1.2.2	.0155905
Q2	-.0064998
Q2.0	1.082927E-02
Q2.2	-.0054389
Q2.1.1	1.238382E-02
Q2.1.2	-9.708001E-03
Q2.1.3	-.008888
Q2.2.1	-1.193874E-02
Q2.2.2	.0002272

ELEMENT	ATOMIC NMBR.	TERMS
S	16	5
ATOMIC WT.	ATM. MASS	PERCENT
30	29.9848733	0
31	30.9796107	0
32	31.9720736	95
33	32.9714618	.76
34	33.967864	4.22
35	34.9690304	0
36	35.9670897	.014
37	36.9710135	0
38	37.9712281	0

	TARGET S- 32
Q1	6.888765E-03
Q1.0	-.0025593
Q1.2	9.874765E-03
Q1.1.1	.0127865
Q1.1.2	.0122179
Q1.2.1	1.676353E-02
Q1.2.2	.0177632
Q2	-.0094846
Q2.0	1.381407E-02
Q2.2	-.0072101
Q2.1.1	9.399023E-03
Q2.1.2	-.0126928
Q2.1.3	-.0118728
Q2.2.1	-1.669475E-02
Q2.2.2	-.0045288

	TARGET S- 33	TARGET S- 34	TARGET S- 36
Q1	9.874765E-03	5.110565E-03	2.353165E-03
Q1.0	-.0055453	-.0007811	.0019763
Q1.2	5.110565E-03	8.217666E-03	6.062365E-03
Q1.1.1	.0157725	.0110083	.0082509
Q1.1.2	.0152039	.0104397	.0076823
Q1.2.1	1.498533E-02	1.332823E-02	8.415531E-03
Q1.2.2	.015985	.0143279	.0094152
Q2	-.0025593	-.0055453	-.0038882
Q2.0	6.888765E-03	9.874765E-03	8.217666E-03
Q2.2	-.0094846	-.0025593	-.0007811
Q2.1.1	1.632432E-02	1.333832E-02	1.499542E-02
Q2.1.2	-.0057675	-.0087535	-.0070964
Q2.1.3	-.0049475	-.0079335	-.0062764
Q2.2.1	-1.204395E-02	-8.104645E-03	-4.669345E-03
Q2.2.2	.000122	.0040613	.0074966

ELEMENT	ATOMIC NMBR.	TERMS
CL	17	3
ATOMIC WT.	ATM. MASS	PERCENT
33	32.9774399	0
34	33.9737501	0
35	34.9688511	75.53
36	35.9683084	0
37	36.965898	24.47
38	37.9680042	0
39	38.9680076	0

	TARGET CL- 35	TARGET CL- 37
Q1	6.819665E-03	4.170765E-03
Q1.0	-.0024902	.0001587
Q1.2	8.687365E-03	6.273566E-03
Q1.1.1	.0127174	.0100685
Q1.1.2	.0121488	.0094999
Q1.2.1	1.550703E-02	1.044433E-02
Q1.2.2	.0165067	.011444
Q2	-.0068465	-.0043579
Q2.0	1.117597E-02	8.687365E-03
Q2.2	-.0056373	-.0024902
Q2.1.1	1.203712E-02	1.452572E-02
Q2.1.2	-.0100547	-.0075661
Q2.1.3	-9.234701E-03	-.0067461
Q2.2.1	-1.248385E-02	-6.848145E-03
Q2.2.2	-.0003179	.0053178

ELEMENT	ATOMIC NMBR.	TERMS
K	19	3
ATOMIC WT.	ATM. MASS	PERCENT
37	36.9733648	0
38	37.9690962	0
39	38.9637098	93.1
40	39.9639997	.0118
41	40.961832	6.88
42	41.9624057	0
43	42.9607301	0

	TARGET K- 39	TARGET K- 40	TARGET K- 41
Q1	5.987065E-03	8.444665E-03	5.703266E-03
Q1.0	-.0016576	-.0041152	-.0013738
Q1.2	8.444665E-03	5.703266E-03	7.952566E-03
Q1.1.1	.0118848	.0143424	.011601
Q1.1.2	.0113162	.0137738	.0110324
Q1.2.1	1.443173E-02	1.414793E-02	1.365583E-02
Q1.2.2	.0154314	.0151476	.0146555
Q2	-.0073339	-.0016576	-.0041152
Q2.0	1.166337E-02	5.987065E-03	8.444665E-03
Q2.2	-.0062161	-.0073339	-.0016576
Q2.1.1	1.154972E-02	1.722602E-02	1.476842E-02
Q2.1.2	-.0105421	-.0048658	-.0073234
Q2.1.3	-9.722099E-03	-.0040458	-.0065034
Q2.2.1	-1.355004E-02	-8.991544E-03	-5.772845E-03
Q2.2.2	-.0013841	.0031744	.0063931

ELEMENT	ATOMIC NMBR.	TERMS
CA	20	9
ATOMIC WT.	ATM. MASS	PERCENT
38	37.9767141	0
39	38.9706917	0
40	39.9625888	96.947
41	40.9622746	0
42	41.9586248	.646
43	42.9587793	.135
44	43.9554901	2.083
45	44.9561892	0
46	45.9536886	.186
47	46.9545374	0
48	47.9525313	.18
49	48.9556746	0
50	49.957519	0

	TARGET CA- 40	TARGET CA- 42	TARGET CA- 43
Q1	6.591165E-03	6.122465E-03	9.566166E-03
Q1.0	-.0022617	-.001793	-.0052367
Q1.2	9.926765E-03	9.566166E-03	5.577865E-03
Q1.1.1	.0124889	.0120202	.0154639
Q1.1.2	.0119203	.0114516	.0148953
Q1.2.1	1.651793E-02	1.568863E-02	1.514403E-02
Q1.2.2	.0175176	.0166883	.0161437
Q2	-.0100504	-.0055973	-.001793
Q2.0	1.437987E-02	9.926765E-03	6.122465E-03
Q2.2	-.0079699	-.0022617	-.0055973
Q2.1.1	8.833223E-03	1.328632E-02	1.709062E-02
Q2.1.2	-.0132586	-8.805501E-03	-.0050012
Q2.1.3	-.0124386	-.0079855	-.0041812
Q2.2.1	-1.802035E-02	-7.859045E-03	-7.390345E-03
Q2.2.2	-.0058544	.0043069	.0047756

	TARGET CA- 44	TARGET CA- 46	TARGET CA- 48
Q1	5.577865E-03	5.428165E-03	3.133665E-03
Q1.0	-.0012484	-.0010987	.0011958
Q1.2	8.777566E-03	8.283065E-03	4.432565E-03
Q1.1.1	.0114756	.0113259	.0090314
Q1.1.2	.010907	.0107573	.0084628
Q1.2.1	1.435543E-02	1.371123E-02	7.566231E-03
Q1.2.2	.0153551	.0147109	.0085659
Q2	-.0052367	-.0044481	-.0039536
Q2.0	9.566166E-03	8.777566E-03	8.283065E-03
Q2.2	-.001793	-.0012484	-.0010987
Q2.1.1	1.364692E-02	1.443552E-02	1.493002E-02
Q2.1.2	-.0084449	-.0076563	-.0071618
Q2.1.3	-.0076249	-.0068363	-.0063418
Q2.2.1	-7.029745E-03	-5.696545E-03	-5.052345E-03
Q2.2.2	.0051362	.0064694	.0071136

ELEMENT	ATOMIC NMBR.	TERMS
TI	22	5
ATOMIC WT.	ATM. MASS	PERCENT
44	43.9595714	0
45	44.9581285	0
46	45.9526315	7.93
47	46.9517684	7.28
48	47.9479499	73.94
49	48.9478703	5.51
50	49.9447856	5.34
51	50.9466028	0
52	51.9468155	0

	TARGET TI- 46	TARGET TI- 47	TARGET TI- 48
Q1	7.140065E-03	1.009547E-02	6.356566E-03
Q1.0	-.0028106	-.005766	-.0020271
Q1.2	1.009547E-02	6.356566E-03	9.361665E-03
Q1.1.1	.0130378	.0159932	.0122543
Q1.1.2	.0124692	.0154246	.0116857
Q1.2.1	1.723553E-02	1.645203E-02	1.571823E-02
Q1.2.2	.0182352	.0174517	.0167179
Q2	-.0074445	-.0028106	-.005766
Q2.0	1.177397E-02	7.140065E-03	1.009547E-02
Q2.2	-.0033904	-.0074445	-.0028106
Q2.1.1	1.143912E-02	1.607302E-02	1.311762E-02
Q2.1.2	-.0106527	-.0060188	-.0089742
Q2.1.3	-.0098327	-.0051988	-8.154201E-03
Q2.2.1	-1.083495E-02	-1.025514E-02	-8.576644E-03
Q2.2.2	.001331	.0019108	.0035893

	TARGET TI- 49	TARGET TI- 50
Q1	9.361665E-03	4.459766E-03
Q1.0	-.0050322	-.0001303
Q1.2	4.459766E-03	6.064265E-03
Q1.1.1	.0152594	.0103575
Q1.1.2	.0146908	9.788899E-03
Q1.2.1	1.382143E-02	1.052403E-02
Q1.2.2	.0148211	.0115237
Q2	-.0020271	-.0050322
Q2.0	6.356566E-03	9.361665E-03
Q2.2	-.005766	-.0020271
Q2.1.1	1.685652E-02	1.385142E-02
Q2.1.2	-.0052353	-.0082404
Q2.1.3	-.0044153	-.0074204
Q2.2.1	-7.793145E-03	-7.059345E-03
Q2.2.2	.0043728	.0051066

ELEMENT	ATOMIC NMBR.	TERMS
FE	26	5
ATOMIC WT.	ATM. MASS	PERCENT
52	51.9481168	0
53	52.9455724	0
54	53.9396167	5.82
55	54.9382982	0
56	55.934936	91.66001
57	56.9353976	2.19
58	57.9332814	.33
59	58.9348774	0
60	59.9339638	0

	TARGET FE- 54	TARGET FE- 56	TARGET FE- 57	TARGET FE- 58
Q1	7.595465E-03	5.815366E-03	8.393165E-03	4.680965E-03
Q1.0	-.003266	-.0014859	-.0040637	-.0003515
Q1.2	9.639166E-03	8.393165E-03	4.680965E-03	7.190565E-03
Q1.1.1	.0134932	.0117131	.0142909	.0105787
Q1.1.2	.0129246	.0111445	.0137223	.0100101
Q1.2.1	1.723463E-02	1.420853E-02	1.307413E-02	1.187153E-02
Q1.2.2	.0182343	.0152082	.0140738	.0128712
Q2	-.0079032	-.0053097	-.0014859	-.0040637
Q2.0	1.223267E-02	9.639166E-03	5.815366E-03	8.393165E-03
Q2.2	-.0044919	-.003266	-.0053097	-.0014859
Q2.1.1	1.098042E-02	1.357392E-02	1.739772E-02	1.481992E-02
Q2.1.2	-.0111114	-8.517899E-03	-.0046941	-.0072719
Q2.1.3	-.0102914	-.0076979	-.0038741	-.0064519
Q2.2.1	-1.239515E-02	-8.575744E-03	-6.795645E-03	-5.549644E-03
Q2.2.2	-.0002292	.0035902	.0053703	.0066163

ELEMENT	ATOMIC NMBR.	TERMS
CO	27	1
ATOMIC WT.	ATM. MASS	PERCENT
57	56.9362955	0
58	57.93576	0
59	58.9331889	100
60	59.9338131	0
61	60.9324403	0

	TARGET CO- 59
Q1	5.652766E-03
Q1.0	-.0013233
Q1.2	7.649766E-03
Q1.1.1	.0115505
Q1.1.2	.0109819
Q1.2.1	1.330253E-02
Q1.2.2	.0143022
Q2	-.0045186
Q2.0	8.848066E-03
Q2.2	-.002483
Q2.1.1	1.436502E-02
Q2.1.2	-.0077268
Q2.1.3	-.0069068
Q2.2.1	-7.001645E-03
Q2.2.2	.0051643

ELEMENT	ATOMIC NMBR.	TERMS
NI	28	7
ATOMIC WT.	ATM. MASS	PERCENT
56	55.9421153	0
57	56.9397688	0
58	57.9353414	68.274
59	58.9343419	0
60	59.9307866	26.095
61	60.9310555	1.134
62	61.9283414	3.593
63	62.9296641	0
64	63.9279571	.904
65	64.9300709	0
66	65.9290857	0

	TARGET NI- 58	TARGET NI- 60	TARGET NI- 61
Q1	7.276465E-03	6.008066E-03	8.991066E-03
Q1.0	-.002947	-.0016786	-.0046616
Q1.2	9.832265E-03	8.991066E-03	4.954265E-03
Q1.1.1	.0131742	.0119058	.0148888
Q1.1.2	.0126056	.0113372	.0143202
Q1.2.1	1.710873E-02	1.499913E-02	1.394533E-02
Q1.2.2	.0181084	.0159988	.014945
Q2	-.0063749	-.0055028	-.0016786
Q2.0	1.070437E-02	9.832265E-03	6.008066E-03
Q2.2	-.004294	-.002947	-.0055028
Q2.1.1	1.250872E-02	1.338082E-02	1.720502E-02
Q2.1.2	-.0095831	-.008711	-.0048868
Q2.1.3	-.0087631	-.007891	-.0040668
Q2.2.1	-1.066895E-02	-8.449844E-03	-7.181444E-03
Q2.2.2	.001497	.0037161	.0049845

	TARGET NI- 62	TARGET NI- 64
Q1	4.954265E-03	4.163165E-03
Q1.0	-.0006248	.0001663
Q1.2	7.983965E-03	7.262165E-03
Q1.1.1	.010852	.0100609
Q1.1.2	.0102834	9.492301E-03
Q1.2.1	1.293823E-02	1.142533E-02
Q1.2.2	.0139379	.012425
Q2	-.0046616	-.0036545
Q2.0	8.991066E-03	7.983965E-03
Q2.2	-.0016786	-.0006248
Q2.1.1	1.422202E-02	1.522912E-02
Q2.1.2	-.0078698	-.0068627
Q2.1.3	-.0070498	-.0060427
Q2.2.1	-6.340245E-03	-4.279345E-03
Q2.2.2	.0058257	.0078866

ELEMENT	ATOMIC NMBR.	TERMS
PD	46	9
ATOMIC WT.	ATM. MASS	PERCENT
100	99.908527	0
101	100.908287	0
102	101.905634	1.02
103	102.906114	0
104	103.904029	11.14
105	104.905079	22.33
106	105.903478	27.33
107	0	0
108	107.903895	26.46
109	108.905954	0
110	109.905167	11.72
111	110.90766	0
112	111.907323	0

	TARGET PD- 102	TARGET PD- 104	TARGET PD- 105
Q1	5.796965E-03	5.226965E-03	7.877966E-03
Q1.0	-.0014675	-.0008975	-.0035485
Q1.2	8.361966E-03	7.877966E-03	0
Q1.1.1	.0116947	.0111247	.0137757
Q1.1.2	.0111261	.0105561	.0132071
Q1.2.1	1.415893E-02	1.310493E-02	0
Q1.2.2	.0151586	.0141046	0
Q2	-.0046005	-.0040325	-.0008975
Q2.0	8.929965E-03	8.361966E-03	5.226965E-03
Q2.2	-.0021875	-.0014675	-.0040325
Q2.1.1	1.428312E-02	1.485112E-02	1.798612E-02
Q2.1.2	-.0078087	-.0072407	-.0041057
Q2.1.3	-.0069887	-.0064207	-.0032857
Q2.2.1	-6.788044E-03	-5.500044E-03	-4.930045E-03
Q2.2.2	.0053779	.0066659	.0072359

	TARGET PD- 106	TARGET PD- 108	TARGET PD- 110
Q1	0	4.217965E-03	3.783965E-03
Q1.0	0	.0001115	.0005455
Q1.2	0	7.063966E-03	6.613965E-03
Q1.1.1	0	.0101157	.0096817
Q1.1.2	0	9.547101E-03	9.113101E-03
Q1.2.1	1.213693E-02	1.128193E-02	1.039793E-02
Q1.2.2	.0131366	.0122816	.0113976
Q2	-.0035485	0	-.0027345
Q2.0	7.877966E-03	0	7.063966E-03
Q2.2	-.0008975	0	.0001115
Q2.1.1	1.533512E-02	0	1.614912E-02
Q2.1.2	-.0067567	0	-.0059427
Q2.1.3	-.0059367	0	-.0051227
Q2.2.1	-4.446044E-03	-3.478045E-03	-2.623045E-03
Q2.2.2	.0077199	8.687901E-03	.0095429

ELEMENT	ATOMIC NMBR.	TERMS
U	92	5
ATOMIC WT.	ATM. MASS	PERCENT
232	232.03713	0
233	233.039628	0
234	234.040946	.0057
235	235.043924	.72
236	236.045562	0
237	237.048724	0
238	238.050784	99.26999
239	239.054289	0
240	240.056587	0

	TARGET U- 234	TARGET U- 235	TARGET U- 238
Q1	3.298965E-03	4.638965E-03	2.771965E-03
Q1.0	.0010305	-.0003095	.0015575
Q1.2	4.638965E-03	3.114965E-03	3.978965E-03
Q1.1.1	9.196699E-03	.0105367	8.669699E-03
Q1.1.2	.0086281	.0099681	.0081011
Q1.2.1	7.937931E-03	7.75393E-03	6.75093E-03
Q1.2.2	.0089376	8.753599E-03	.0077506
Q2	-.0006295	.0010305	.0001125
Q2.0	4.958966E-03	3.298965E-03	4.216966E-03
Q2.2	.0005505	-.0006295	.0012145
Q2.1.1	1.825412E-02	1.991412E-02	1.899612E-02
Q2.1.2	-.0038377	-.0021777	-.0030957
Q2.1.3	-.0030177	-.0013577	-.0022757
Q2.2.1	-7.904433E-05	4.009557E-04	1.326956E-03
Q2.2.2	.0120869	.0125669	.0134929