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LARGE AMOUNTS OF ANTIPROTON PRODUCTION BY HEAVY ION COLLISION

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ABSTRACT

To produce large amounts of antiprotons, on the order of several grams/year, use of machines to produce nuclear collisions are studied. These can be of either proton-proton, proton-nucleus and nucleus-nucleus in nature. To achieve high luminosity colliding beams, on the order of 10^{41} m/cm^2, a self-colliding machine is required, rather than a conventional circular colliding type. The self-colliding machine can produce additional antiprotons through successive collisions of secondary particles, such as spectator nucleons. A key problem is how to collect the produced antiprotons without capture by beam nuclei in the collision zone.

Production costs for anti-matter are projected for various energy source options and technology levels. Dedicated facilities using heavy ion collisions could produce antiproton at substantially less than 1 million \$/milligram. With co-production of other valuable products, e.g., nuclear fuel for power reactors, antiproton costs could be reduced to even lower values.

INTRODUCTION

Reduction of antiproton production cost is a key objective for antiproton technology (1,2). Antiprotons are presently produced by collision of a high-energy proton beam with a fixed target of tungsten or copper (3,4,5) The most efficient proton energy for antiproton production in fixed targets is 200 GeV, with a broad peak (1,3). At much higher energies, the efficiency of antiproton production decreases, because the center of mass energy ($\sqrt{S}$) in the collision process increases only as the square root of the laboratory energy E_L. A 200 GeV proton energy on a fixed target corresponds to a center of mass energy $\sqrt{S}$ = 20 GeV; a colliding machine thus reduces energy cost by approximately a factor of 10 compared to a fixed target.

Furthermore in colliding machines, the most efficient proton energy for antiproton production is much higher than 20 GeV. Energy cost can then be further reduced by operating at a higher beam energy.

Present P-P colliders for the high energy physics experiments, however, have too small a luminosity to make a substantial amount of antiprotons. One approach to increase luminosity is the use of heavy ions instead of protons. This substantially increases the effective luminosity.

In this paper, mechanisms of antiproton production in nucleon-nucleon, nucleon-nucleus collisions are discussed, conceptual approaches for antiproton production from relativistic heavy ion collisions are then examined. These include self colliding machines (5,6) using relativistic heavy ions.

ANTIPROTON PRODUCTION

Before examining antiproton production by high energy heavy ion collisions, let us discuss mechanism for producing antiprotons ($\bar{P}$).

$\bar{P}$ can be produced in several ways. One way is high energy electron-positron collision (7,8) (Figure 1). The high energy annihilation of electron and positron produces a virtual photon (γ) that subsequently creates a quark (q_1) and antiquark pair ($\bar{q}_2$).

A color string (described as dotted line) is stretched between the quark and antiquark pair, and this string then fragments into mesons, baryons and antibaryons in the hadronization process (8,9) Instead of a virtual photon, if an extremely high intensity laser (10) creates the quark and antiquark pair, antiprotons can be created by the same mechanism as electron and positron anihilation (Fig. 2). However, such an extremely high intensity laser is not possible with present technology.

The energy cost of antiproton production by electron positron annihilation reactions is slightly smaller than that for proton-proton collision. Figure 3 shows the antiproton production yield from $(e\ \bar{e})$ and (P,P) collisions. However, the antiproton production cross section for electron-positron annihilation is extremely small compared with that of proton-proton collision, on the order of nanobarn. Thus, e-$\bar{e}$ annihilation is not practical.

The most practical method for antiproton production is nucleon-nucleon or nucleon-nucleus collision. When a nucleon collides with another nucleon or a nucleus, a quark in a beam nucleon collides with a quark in a target nucleon or nucleus, producing a colour string that stretches between the quarks (Figure 4) (11,12). Antiprotons are then produced by hadronization of the color string similar to high energy electron-positron annihilation. Since the mechanism is the same and plentiful experimental data are available for phenomenological analyses, they provide a way to evaluate antiproton production by nucleon-nucleon and nucleon-nucleus collisions.

The antibaryon production cross section for hadron-hadron collision has been analyzed using the quark cascade recombination model (13). This model successfully analyzes the inclusive spectra of hadron for small P_T (transverse momentum) events, such as $P+PX\ K^{\pm}X$, $\pi^{\pm}\pi^{\pm}X$, $\Delta^{\pm}X$, ---, $\pi^{\pm}+\pi^{\pm}X$, $K^{\pm}X$, $\pi^{\pm}\pi^{\pm}X$ and $e^+e^-\to\pi^{\pm}X$, $K^{\pm}X$. Most of the predictions from this model nicely fit the experimental data, including leading particle spectra such as $\pi^+P\to\pi^+X$, $PP\to PX$ and two particle correlation. However, the model is too simple to predict the antibaryon inclusive spectra in baryon fragmentation and the baryon and anti-baryon spectra in meson fragmentation.

In order to analyze these hadron spectra, the quark cascade recombination model is extended by introducing diquark states (14). Hadrons are emitted through the processes of $(\bar{q}\bar{q})\to\bar{B}+q$. $(\bar{q}q)\to m+(\bar{q}\bar{q})$, $q\to B+(\bar{q}\bar{q})$, besides the usual successive meson emission from quarks $q\to m+q$.

This model requires information on the structure of hadrons, their decay schemes and recombination behavior. A second model for analyzing antibaryon production from hadron-hadron collision also considers the quark and diquark states in the cascade process. However, the structural function of protons in the initial state is treated differently. The second model, assumes that the incident proton first breaks up into one quark and one diquark (qq). In the second step, they directly emit particles and resonances via a cascade mechanism as a consequence of the confined interaction. In the final step the cascade terminates at the target. The primodial emission process of quark and diquark is similar to the previous model.

When a nucleon-collides with the nucleus, more than one string is stretched between the quark in the beam nucleon and quarks in a nucleon of the target nucleus (Figure 5).

The first application of the constituent quark model to hadron nucleus collisions is based on the additive quark approach. The difference between hadron-hadron and hadron-nucleus collision is due to the possibility that more than one quark of the initial hadron can interact and that multiple collision with quarks belonging to different nucleons in the same nucleus can occur. Final-state hadrons thus can result from four sources (neglecting cascade effects)

(1) fragmentation of non-interacting ("spectator") quark of the incident hadron.

(2) fragmentation of interacting ("wounded") quarks of the incident hadron.

(3) breaking of "color string" which join wounded quarks from beam and target hadron, responsible for the central region (between "beam fragmentation" and "target fragmentation" region).

(4) fragmentation of interacting and non-interacting quarks from target nucleons, which have participated in the collision.

Independent of detailed assumptions, one can deduce the main features from this scheme. With increasing A, the average number of spectators in the beam hadron decreases, resulting in a decrease of contribution (1) and the attenuation of hadron spectra at high rapidities. The number of wounded quarks and color strings attached to them increase, causing a slow rise of density at moderate rapidity in the forward center of mass hemisphere and for the central region. However, the ratio of rapidity distributions in nucleon target to that in the proton target should not exceed the number of constituent quarks in the beam hadrons (i.e., 2 for meson and 3 for baryons).

For relativistic heavy ion-heavy ion collisions large numbers of color strings are stretched between the wounded quarks (Figure 6), and generalization of the additive quark approach to nucleus-nucleus events is possible. However, the additive quark model does not relate nuclear data to the actual parton structure of hadrons. It merely assumes that the constituent quarks are the smallest objects which act independently. The possible fine structure of constituent quarks in terms of partons may be reflected in the detailed spectra (e.g., the different fragmentation of spectator and wounded quarks), but this has not been elaborated in existing models.

That is, the collective effects which may occur in nuclei are neglected. The existence of such effects e.g., in nucleon-nucleus interactions, is controversial. It is interesting to extend the investigation of this problem to nucleus-nucleus interactions.

In the case of nucleon-nucleus collision a fundamental role is played by the number of collisions (ν) of the incident nucleon with the nucleons in the target nucleus. However, the generalization of this concept to nucleus-nucleus collision is not unique.

It has been proposed that the nucleus-nucleus collision be described in terms of the number of wounded nucleons (w) i.e., the number of nucleons which underwent at least one inelastic collision in this process. For instance in the case of nucleon-nucleus collisions, there are ν "wounded" nucleus in the target nucleus and one wounded incident nucleon. Consequently, in this case, there is simple relation between ν and w. $w = 1 + \nu$. Thus, either of them can be used.

Because of the interaction between the stretched strings, the color strings in the small phase space are combined in the form of a color tube, and which may create a quark gluon plasma phase.

There has been considerable interest recently in the properties of hadronic matter at extreme temperature and pressure. There is theoretical evidence that matter made of gluons undergoes a first order phase transition at a critical temperature of about 200 MeV from a low temperature confining phase to a high-temperature quark-gluon plasma phase (16). Figure 7 shows the phase diagram of matter (in the temperature, baryon density phase) with indication of the regions that might be reached in the different physical situation.

Antibaryons are good signal for interesting physics in relativistic heavy-ion central collision, because any $\bar{P}/\pi^-$ signal greater than a few percent or showing unusual properties, must be due to a nonequilibrium process. It has been considered that baryon production is due to the chiral symmetry breaking transition. The mechanism of baryon production in the chiral transition proceeds exactly like monopole production in the early universe through the Kibble mechanism.

The number of baryons and antibaryons which actually escape to be detected is much less than the number that is originally made. Most of the baryons and antibaryons which are produced in the transition annihilate against one another. However, since the hadron state cools and expands rapidly after the transition, not all of the baryons and antibaryons annihilate and the density of baryon does not approach thermal equilibrium. In particular, one expects that B's and $\bar{B}$ produced by collisions near the the surface of plasma are more likely to survive than those produced in the interior.

The theory is still in the speculative stage, but antibaryon production may be estimated by using the MIT bag model and the chiral bag model. The effectiveness of the heavy ion collision for producing antiproton should be examined.

Collider Machine

The most efficient way to reduce the energy cost of antiproton production is to use a colliding machine instead of the fixed target approach. However, for large amounts of antiproton production (e.g., on the order of 1 gram per year) the luminosity required in the colliding machine is order of 10^{41} m/cm^2 sec, or about 10^{11} times higher than the present high energy physics collider. This high luminosity requires that the density of particles in the beam become very high. Such a machine cannot be designed by a simple extension of colliders presently used and planned for high energy physics. In particular, plasma physics problems that will be encountered in the particle beams are similar to those in fusion reactors.

The luminosity of a fusion plasma is close to that in a collider producing 1 gram per year of antiproton. Collective modes could be resent in the high intensity beam, and the instabilities associated with these many collective modes has to be studied as part of the design.

In order to increase luminosity, it has been proposed to use U^{238} colliding beams with energy of 10 GeV/amu in a storage type collider (17). This collider would have a diameter of $\sim$100 m and beam area of $\sim$1 cm^2. For 1 an antiproton production rate of 1 gram per year, a luminosity of 10^{41} 1/cm^2 sec is required. To control beam space charge, emittance should be greater than 2.5×10^{-3} m rad. This value is very large compared to emittance in conventional proton colliders. In this design, the length of the colliding section is assumed to be approximately 10% of the circumference of the collider. Although such a U^{238} colliding beam can increase effective luminosity, it introduces another cumbersome problem.

When the heavy ion-heavy ion collision is off center as shown in Figure 8. Most nucleons are spectators and do not participate in antiproton production. Therefore, most of the energy carried by the spectator nucleon is wasted, unless the nuclei carrying the spectators stay in the colliding beam track and make collisions later. However, debris carrying the spectator nucleous tends to be scattered out of the collision region. Control of such debris is a severe design problem for the collider and collector.

On this point, a self-colliding beam machine has an advantage over conventional colliders. Self colliding machines for the antiproton production also have advantages compared to fusion reactors.

In a fusion plasma, the most collisions occur as coulomb scattering. In the energy range of below 1 MeV, which is characteristic of fusion reactors, the cross section for coulomb scattering is much larger than that for nuclear collision, i.e., a fusion reaction.

Even if the phase space of the injected particles is initially very small, it soon will be broadened by coulomb scattering. The luminosity of a self colliding machine will thus decrease unless a self acting phase-space reduction mechanism is built in or some other mechanism such as electron cooling or stochastic cooling is used. Beam cooling techniques appear to work for beams in which phase space is well defined, but it is probably very difficult to apply such approaches to beams in self colliding machines. The advantage of self colliding machines for anti-proton compared to fusion reactors is that beam energy in the former is greater than 10 GeV/AMU, much higher than in fusion reactors. In this high energy region, the coulomb collision cross section is very small compared to the nuclear collision cross section. Thus, collisions mostly occur as nuclear collisions which produce antiprotons. Therefore, collisions increase phase space to a much smaller extent than fusion reactors.

The recent discovery and preliminary work on high temperature super conductors indicate (18) that these materials could have critical magnetic fields on the order of 100 Tesla, though the critical current density may be smaller than conventional super conductors (e.g., NbTi or Nb_3Sn) because of their two dimensional crystal structure. Very high magnetic fields substantially reduce machine size, but the magnetic pressure at 100 Tesla (4×10^4 atom) is beyond present structural technology. Reducing the magnetic field to 20 Tesla decreases magnetic pressure to 1.6×10^3 atm, which is practical with present mechanical structures. A 20 Tesla magnetic field can bend fully ionized U^{238} particles having 10 GeV/amu energy ion in a Larmor radius of 4.2 meter. The diameter of a self collider then is on the order of 20 meters. This is not so very much larger than some presently proposed fusion reactor concepts.

A major advantage of a self-collider over a colliding beam storage ring is that spectator nucleons generated by heavy ion collisions can also produce antiprotons. In the self collider, spectator nucleon debris can collide with heavy ions or other debris to create antiprotons.

Antiprotons produced in nuclear-nuclear collisions have very small longitudinal momentum compared with the leading proton and spectator nucleons. Consequently, antiprotons produced in the colliding region tend to stay at the center of the mirror field, with a small Larmor radius. They will quickly collide with the other particles unless they are removed from the colliding region. Utilizing the momentum characteristics of the produced antiprotons, they could be extracted by electric or magnetic fields created by a high intensity laser or by separate charged particle beam. This is the key for a successful self-collider.

Moir and Chapline propose a mirror type self-collider for producing pions, whose decay product muons would be used to catalyze fusion reactions. The pion(s) would be produced by collision of 600 MeV tritons. The π^--mesons produced on the axis of the magnetic mirror would then be transported to the fusion chamber along the axis of mirror. A similar approach can be used for antiproton production, but machine size is much larger than that for π-meson production, because of the much higher ion energy.

Figure 3 shows antiproton yield for proton-proton collision(s) in the center of mass frame (which equals the Laboratory system coordinate in the colliding machine). Compared to the fixed target case, antiproton yield increases much faster with incident energy E_c below 30 GeV. Above 30 GeV, antiproton yield is proportional to incident energy.

If heavy ion collisions are used, antiproton yield can be increased, by effectively reducing luminosity requirements. We assume that the antiproton yield for heavy (y) ions with mass number A is

$$y = kA^{\alpha}E_c^{\beta} \qquad (1)$$

where E_c is the incident energy of colliding particles per mass number A. The Larmor radius R of the fully ionized heavy ion with charge number Z in the magnetic field B is expressed by

$$RB = AE_c/Z \qquad (2)$$

Substituting E_c derived from Eq. (2) into (1), the yield becomes

$$y = KA^{\alpha-\beta}Z^{\beta}(RB)^{\beta} \quad (3)$$

Yield increases as the β power of collider diameter R and magnetic field.

The choice of a charge number (Z) for the heavy ion arises from confinement considerations. In the collision region where there is a high electron concentration (along with positions and other particles created by collisions), fully ionized heavy ions can capture electrons. If these partially ionized particles escape from the collider and strike the vessel wall, they can produce intense radiation, as well as severe radiation damage. Alternatively, approaches to reduce the electron capture by heavy ions could be considered.

The self collider approach appears to have high potential for minimizing the energy cost involved in antiproton production. Other important factors are involved, however.

In addition to high production efficiency, low cost electricity and use of co-production systems will substantially reduce the cost of antiprotons. Figure 9 lists some options in these last two categories. Also, potentially significant is the capital cost of the self-collider. This has not been investigated in detail, but preliminary examination indicates that it does not appear to be as important as the three factors listed above.

Figure 10 illustrates the effect of production efficiency, electricity cost, and collider capital cost on antiproton cost. Collider cost has only a small effect compared to efficiency and electricity cost.

An efficiency of 1% corresponds to 200 GeV of electrical energy investment for 2 GeV if antiproton/proton annihilation energy, while an efficiency of 0.1% corresponds to 2 TeV of electrical energy investment.

Estimates of nuclear reaction processes in colliding beams indicate that 0.5 TeV of energy investment will be required, or roughly midway between the two groups of curves.

Large scale hydro power (Figure 11) potentially has the lowest energy cost. At 1 cent/KWH production cost would only be about $300,000 per milligram of $\bar{p}$.

There are a number of sites with large amounts of hydro, for which transmission costs and losses are so high that their construction would make them uneconomic for supplying conventional load markets.

Locating an anti-proton production facility at remote hydro sites appears practical. The sites themselves could be built without acceptable environmental guidelines.

If hydro-power is not available, advanced fission power sources could provide large scale power, at a cost on the order of 2 cents per KWH.

Figures 12-16 describe one option for low cost fission power which is based on HTGR (High Temperature Graphite Reactor) technology. The key to low-power cost is to minimize capital cost of through the use of a compact, high power density reactor.

This approach, teamed the Particle Bed Reactor (PBR), packed bed elements of small high fuel particles (diameter of 500 microns) are directly cooled by pressurized helium (Figures 13-14). Design bed power density is 3 megawatts per liter, allowing a very compact reactor. These power densities appear readily achievable. Heat transfer experiments on PBR fuel elements have demonstrated 10 megawatts per liter.

The high power density also results in a short residence time (days) in the reader, and a much lower radioactive inventory than for conventional commercial power reactors - about 1/100th of an LWR (Light Water Reactor). This enhances reactor safety and environmental acceptance.

Figure 15 shows a full size model of a 200 MW(th) PBR for nuclear rocket applications. The reactor would generate at a bed power density of 10 megawatts per liter, cove diameter is 0.5 meters (cove volume 0.1 m).

A commercial version of the PBR would probably have a power on the order of 1000 MW(th), and a cove volume of ~1 m^3, at substantially lower power density and (3 MW/liter) outlet temperature (1100 K).

With a direct cycle gas turbine, such a reactor would have a thermal efficiency of ~40% (thermal to electric).

There do not appear to be any major new technology required for such a system; the fuel particles, materials, and power conversion equipment required either already exists, or could be engineered from existing systems.

The compact size and high efficiency of such a system could lead to low cost power. Cost projections indicate that 2¢/KWH should be achievable (Figure 16).

A very important feature that allows such low cost power is the ability to mass produce complete power system components in a factory. The components could then be shipped to the desired site and integrated with minimal field construction.

A principal cause for the high cost of present nuclear power systems is the large amount of field construction. This is very expensive, since it does not allow for the economics of numbers and design repetitiveness possible with mass production. In effect, present nuclear plant construction is akin to production of Rolls Royces rather than Toyotas.

A very attractive advantage of anti-matter production is the ability to remotely site a production facility. One can readily go where the power is cheapest, without worrying about transmission or shipping costs and restrictions. This was the case for large scale hydro, and is the case for nuclear power. Many of the siting problems associated with nuclear disappear if one is free to site remotely.

Large scale photovoltaic (PV) is another intriguing possibility. Thin film PV is projected to cost approximately 50 cents/per watt by the mid 90's. Averaging over daily and seasonal variations, along with the additional cost requirements associated with energy storage and conditioning, (Figure 17) one arrives at an energy cost of ~4 to 5 cents/KWH.

While more expensive than either large scale hydro or advanced fusion, large scale PV would still allow relatively low cost production of anti-matter at an energy investment of 0.5 TeV/proton, production cost would be ~0.6M$/milligram, a very tolerable value.

As with the other energy sources, the particular site limitations of PV (i.e., the southwest is favored) pose no problems for anti-matter production, since they can be easily sited remotely.

Finally, even if power tests were to equal present costs, ~10¢/KWH, anti-matter production cost would still be acceptable. At 0.5 TeV per $\bar{p}$, total cost would be ~1.5 m$/milligrams.

There are other, more advanced power source possibilities that may eventually result in low cost power. Fusion is one such possibility (Figure 18). Removing the constraint on power output level from single units opens up new possibilities for achieving fusion power, in particular using advanced fusion fuel like dd (deuterium-deuterium). This could greatly simplify reactor technology requirements.

Co-production of other high value products offers attractive possibilities for reducing anti-matter costs particularly these than nuclear reactions (Figure 19). A single accelerator system producing 1 gm of $\bar{p}$/year, for example, could sustain the makeup fuel requirements for 25 LWR's or 45 HGR's (1000 mw(e) each) using U^{238} or Th^{232} as raw material to breed Pu^{239} or U^{233} (Figure 14). Ten $\bar{p}$ facilities could supply nuclear fuel for the entire U.S. economy. Revenue from the scale of this fuel could substantially reduce anti-matter cost-efficient, it could become a low cost by-product of nuclear fuel production.

Such a facility could produce very large quantities of special nuclear material (Pu^{239}, tritrium, and other materials). In fact, one $\bar{p}$ facility would produce amounts in excess of U.S. requirements.

Neutrons from the target in a p facility could also transmit nuclear waste products, including actinides Sr^{90}, and Cs^{137} (Figure 21), as well as produce low cost commercial isotopes (e.g., Co^{60}). One $\bar{p}$ facility, for example, could transmit wastes from 50-1000 MW(e) LWR's.

Other possibilities for co-production exist including desalinazation, peaking power, and the chemical heat pipe (Figures 20 and 21). While attractive, they probably do not have as great a revenue potential as the nuclear fuel production or waste transmutation options.

CONCLUSION

The antiproton production cross section for proton-proton collisions indicate that production efficiency is substantially higher for a colliding machine, compared to a fixed target approach. To increase production rate from 1 mg/year to 1 g/year, beam luminosity must be increased to $\sim 10^{41}/cm^2$ sec, far beyond present accelerator technology. Using heavy ions instead of protons, luminosity can be increased, but off centered collisions waste energy tied up in spectator nucleons. However, unless a quark-gluon plasma phase could be created in head-on collisions to produce large quantities of antiprotons, conventional circular colliders are not efficient. Antiproton production rates can be estimated with reasonable accuracy by the additive quark model, multichain model and quark cascade model for proton-proton and proton-nucleus collisions. Antiproton production rate from quark-gluon plasmas is not yet well understood; conservative estimates of antiproton production can be made by extending methods for proton-proton and nucleon-nucleus collisions to nucleus-nucleus collisions.

In the case of conventional circular colliders, the debris containing spectator nucleons will be emitted from the collision zone. Control and reinjection of this debris into circular orbits in the collider can be considered, but it appear to be very difficult with present accelerator technology. On the other hand, a self collider similar to those proposed for fusion plasmas and for muon production (which would be used for muon catalyzed fusion) appears suitable for antiproton production. Because of the very high particle energies required for effective production of antiprotons. The size of such a self-collider will be considerably larger than that for fusion applications. At the high energy, Coulomb scattering cross sections are much smaller than nuclear reaction cross sections. This condition, plus the very high stiffness of an accelerated particle beam compared to a fusion device, makes the self collider much more suited to antiproton production. Spectator nucleons which did not produce antiprotons in the primary collision can make antiprotons in subsequent collisions. The key to the self-collider is to increase luminosity in the collision region, efficiently collect the produced antiprotons, and avoid electron capture by fully ionized heavy ions. These issues should be studied to see how antiproton production rate increases for high nuclei collisions.

Cost estimates indicate that the heavy ion collision approach for $\bar{p}$ production should result in the low cost anti-matter, e.g., on the order of 1 gram per year of $\bar{P}$ at a cost well below 1 million $ per milligram. Co-products, particularly nuclear fuel and waste transmutation could further reduce these costs substantially.

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FIGURES

Figure 16. Large scale fission-economics.

Figure 17. Large scale photovoltaic.

Figure 18. Large scale magnetic fusion.

Figure 19. Accelerator breeder-products.

Figure 20. Accelerator breeder-scale and costs.

Figure 21. Accelerator breeder-transmutation.

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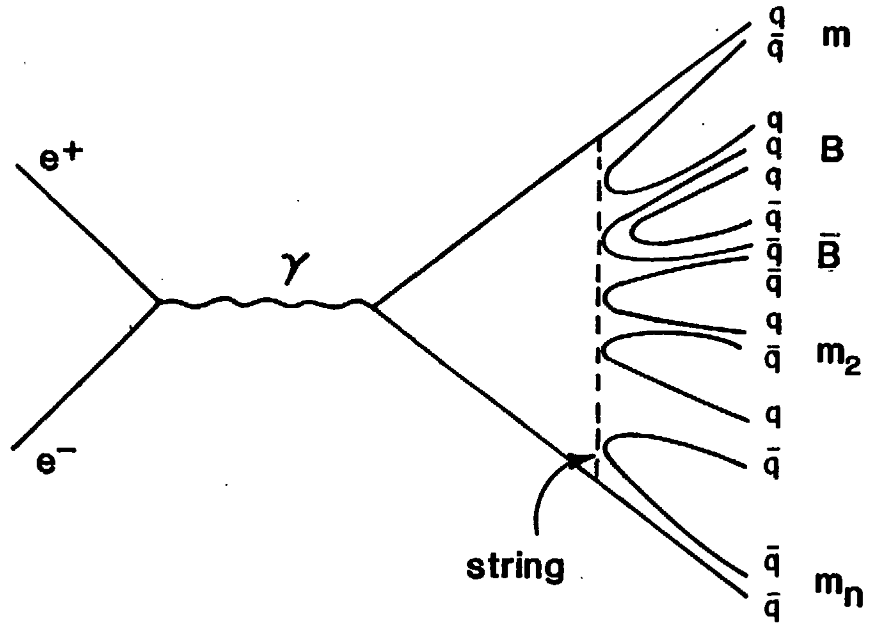
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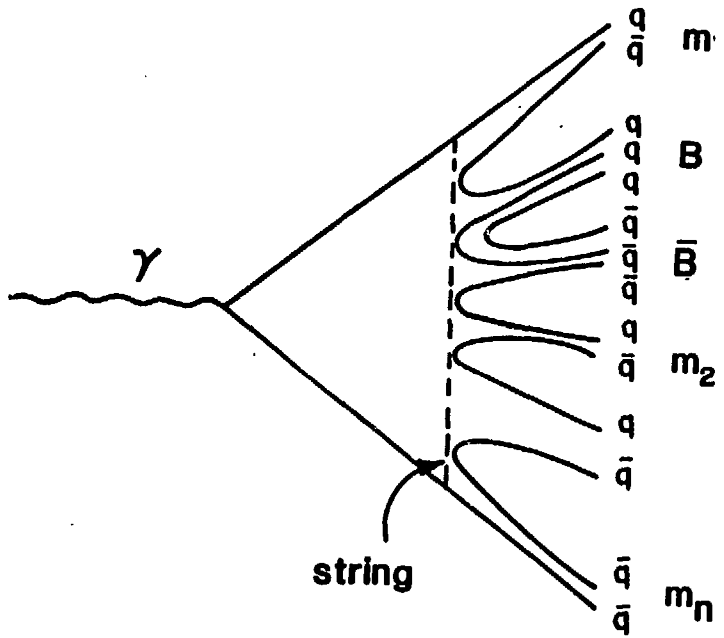
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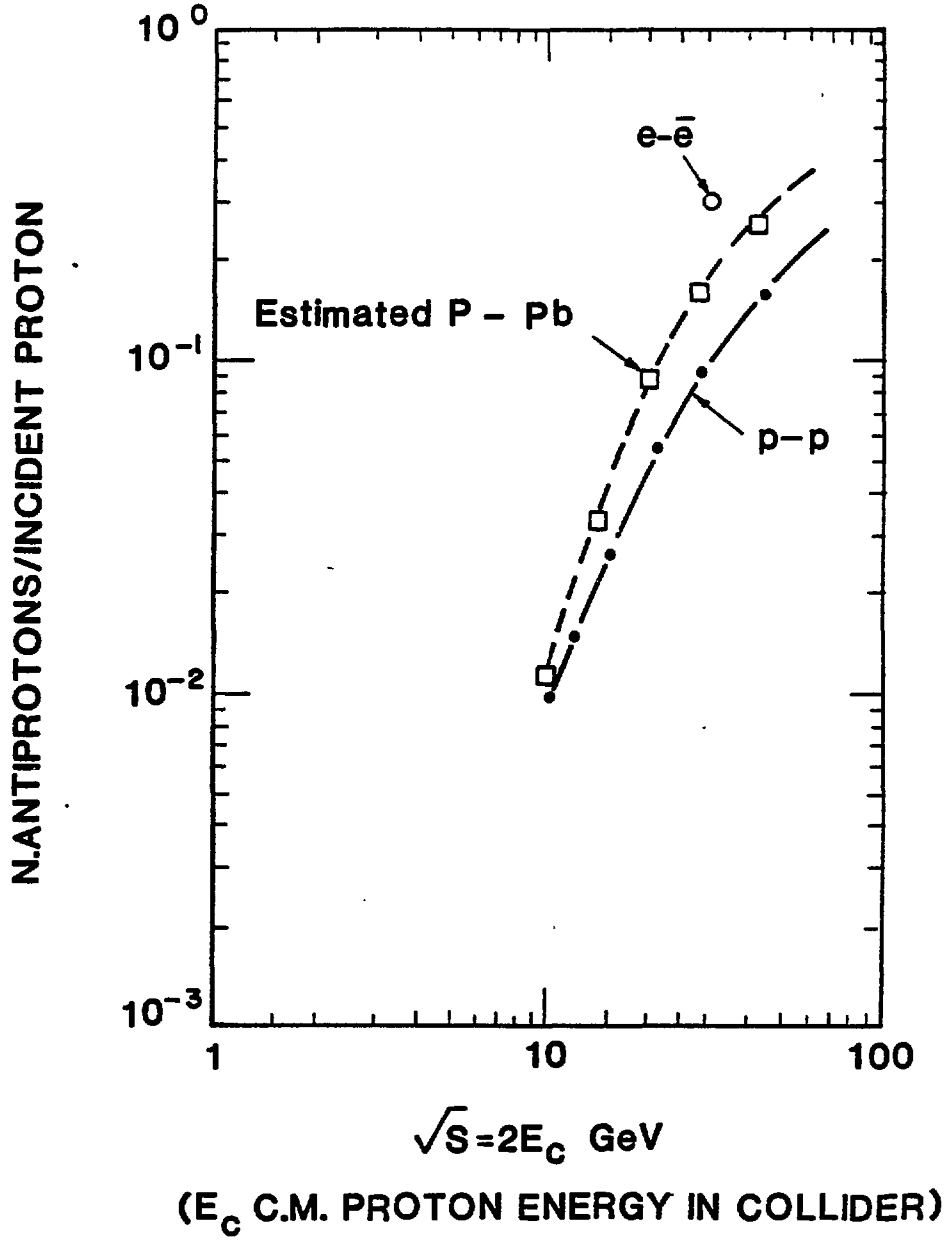

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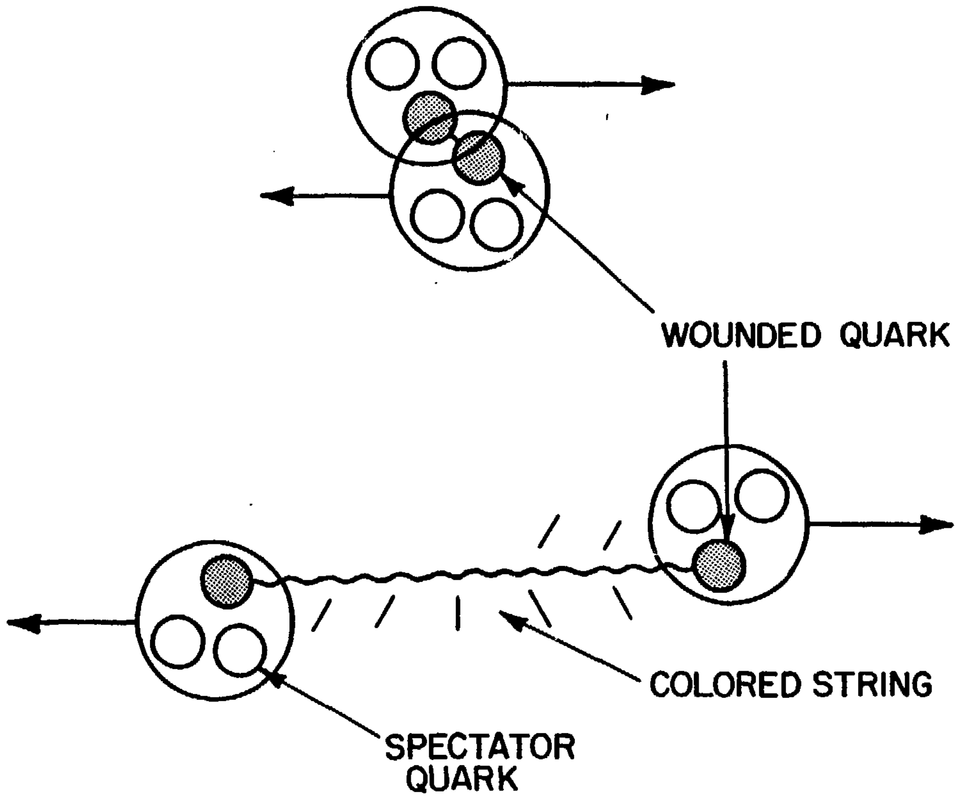
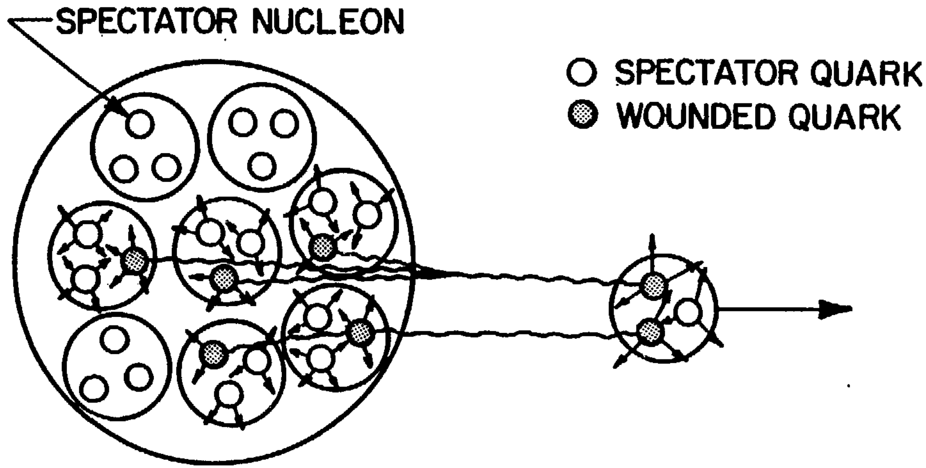


WOUNDED QUARK
COLORED STRING
SPECTATOR QUARK


SPECTATOR NUCLEON
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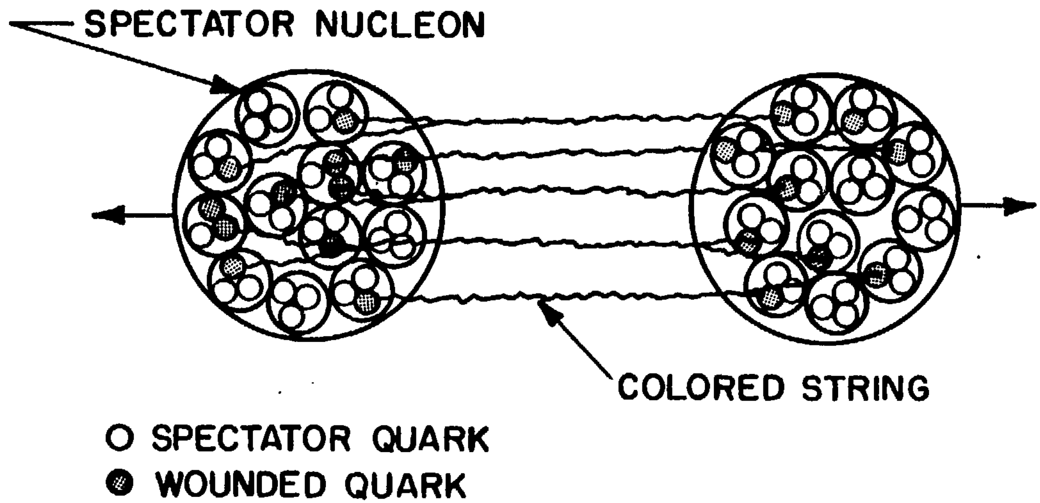
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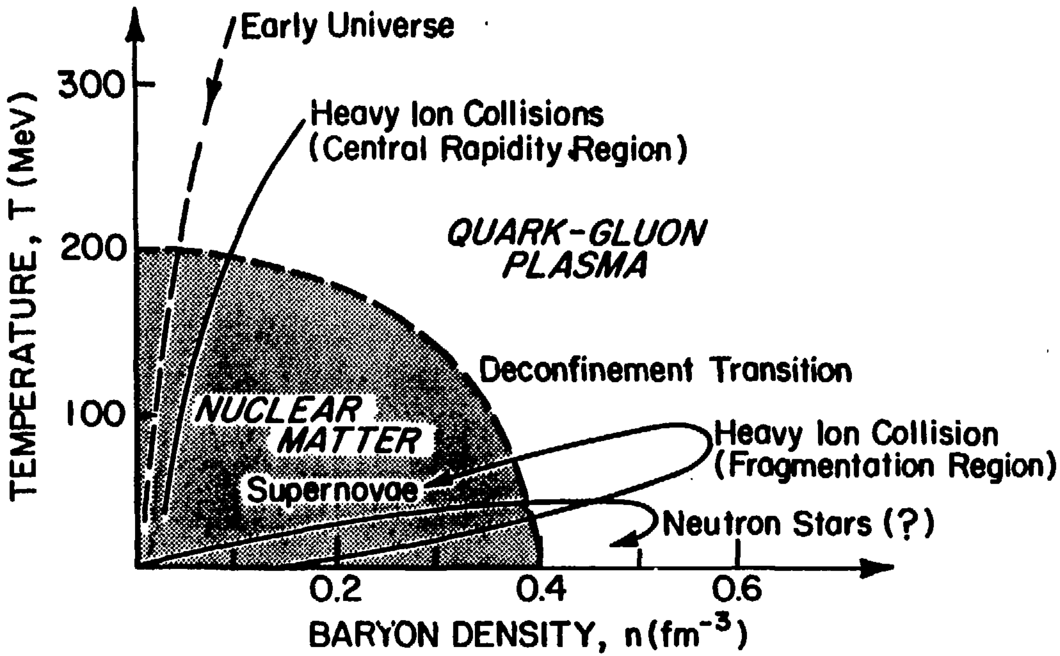
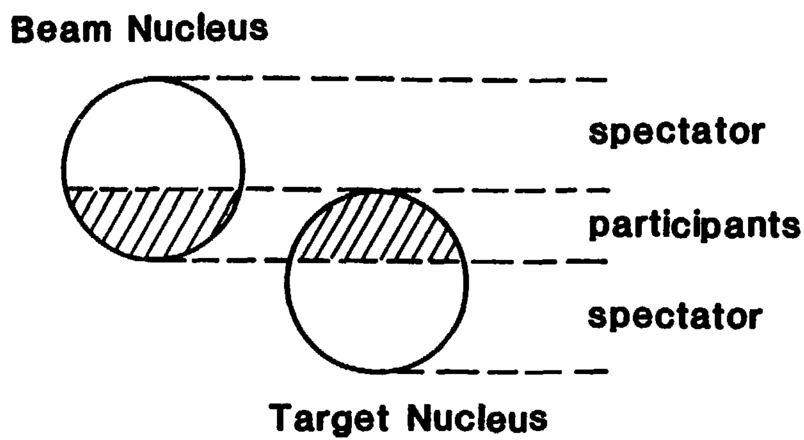
SPECTATOR QUARK
WOUNDED QUARK


Early Universe
300
Heavy Ion Collisions
(Central Rapidity Region)
200
QUARK-GLUON
PLASMA
TEMPERATURE, T (MeV)
Deconfinement Transition
100
NUCLEAR
MATTER
Heavy Ion Collision
(Fragmentation Region)
Supernovae
Neutron Stars (?)
0.2
0.4
0.6
BARYON DENSITY, n(fm^{-3})

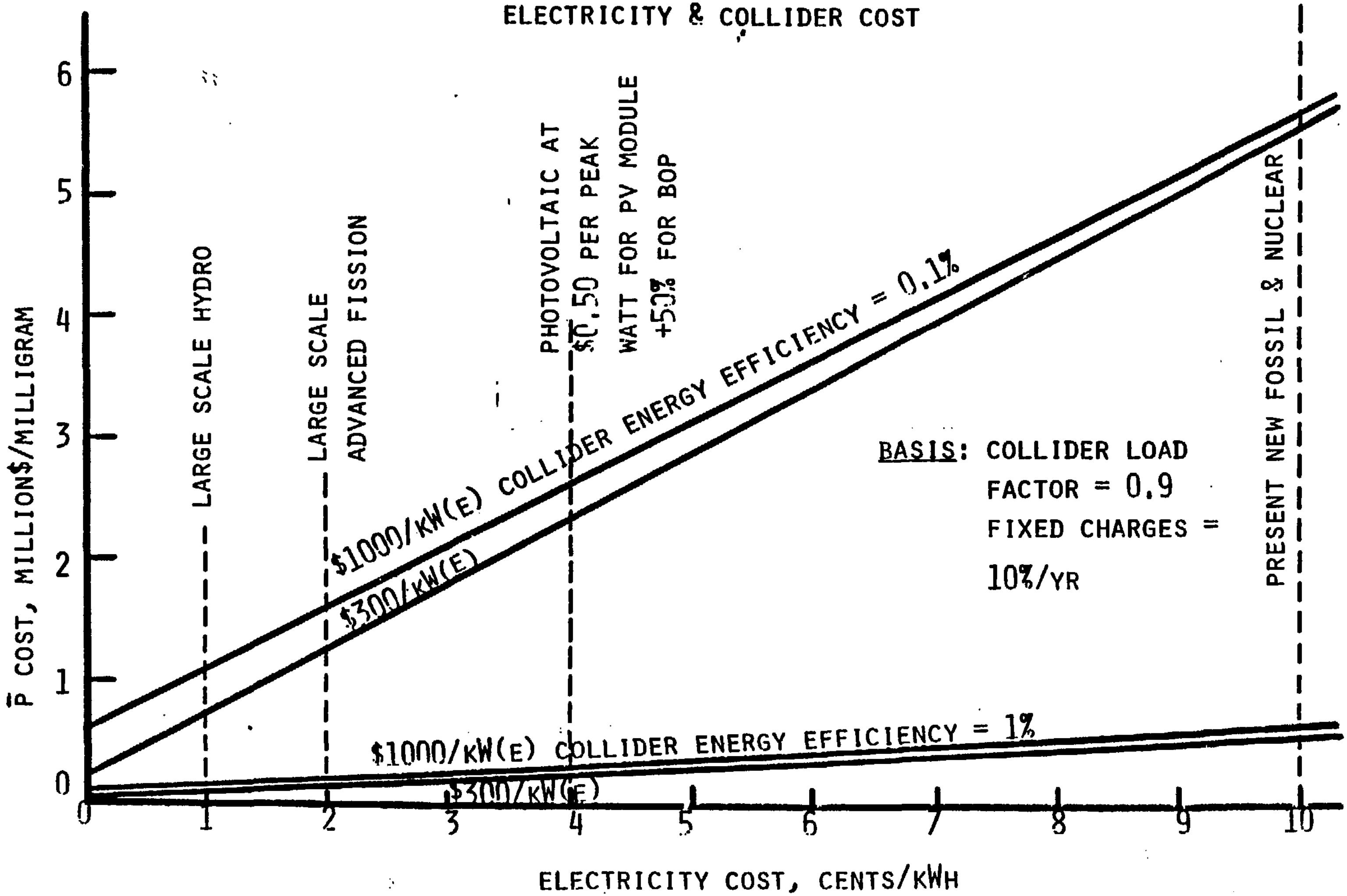


THE PARTICIPANT – SPECTATOR GEOMETRY

ROUTES TO LARGE SCALE, LOW COST ANTI-MATTER

- INCREASED PRODUCTION EFFICIENCY
  - COLLIDING HEAVY ION BEAMS
- LOWER COST ELECTRICITY
  - LARGE SCALE HYDRO
  - HIGH POWER DENSITY FISSION REACTORS
  - LARGE SCALE PHOTOVOLTAIC
  - ADVANCED FUEL FUSION REACTORS
    - MAGNETIC FUSION
    - ICF
  - MOON BASED POWER (PACER, ETC.)
- CO-PRODUCTION SYSTEMS
  - NUCLEAR FUEL (ACCELERATOR-BREEDER)
  - DE-SALINIZATION
  - PROCESS HEAT (CHEMICAL HEAT PIPE)
  - PEAKING POWER

PRODUCTION COST FOR ANTIMATTER
VS
ELECTRICITY & COLLIDER COST



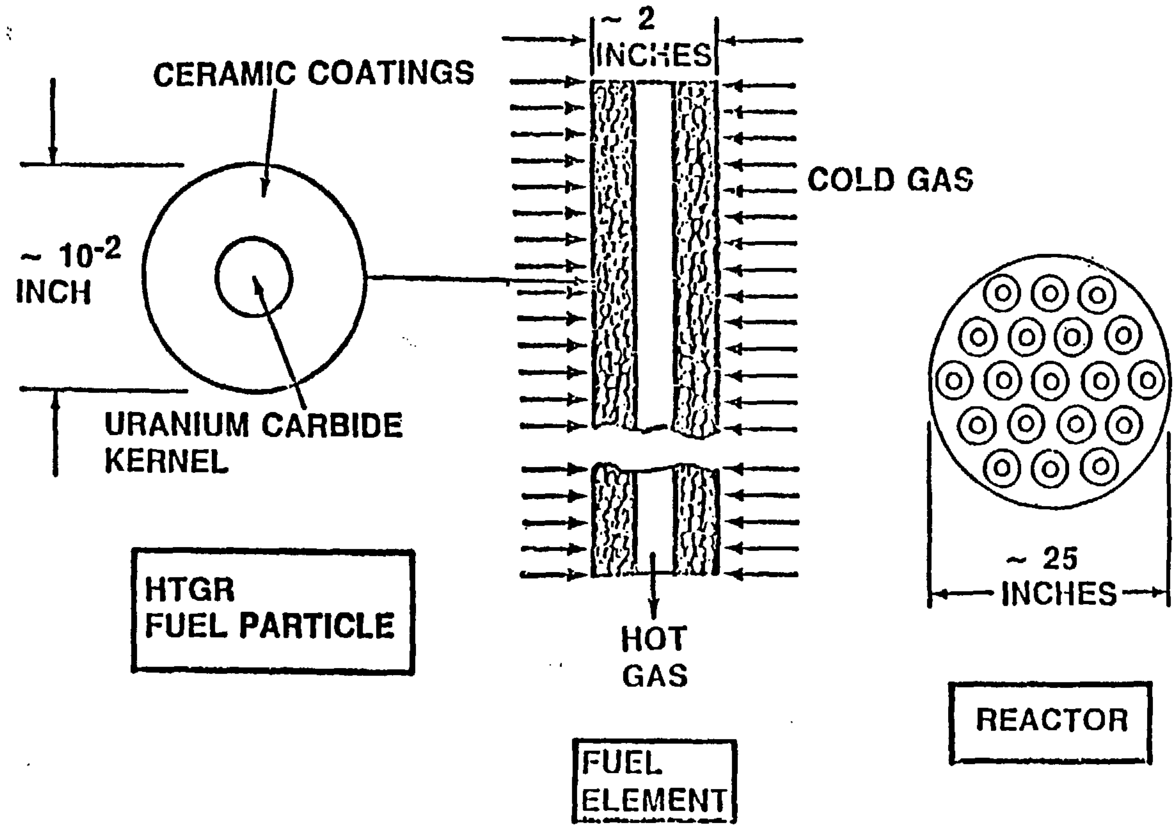
Large Scale Hydro

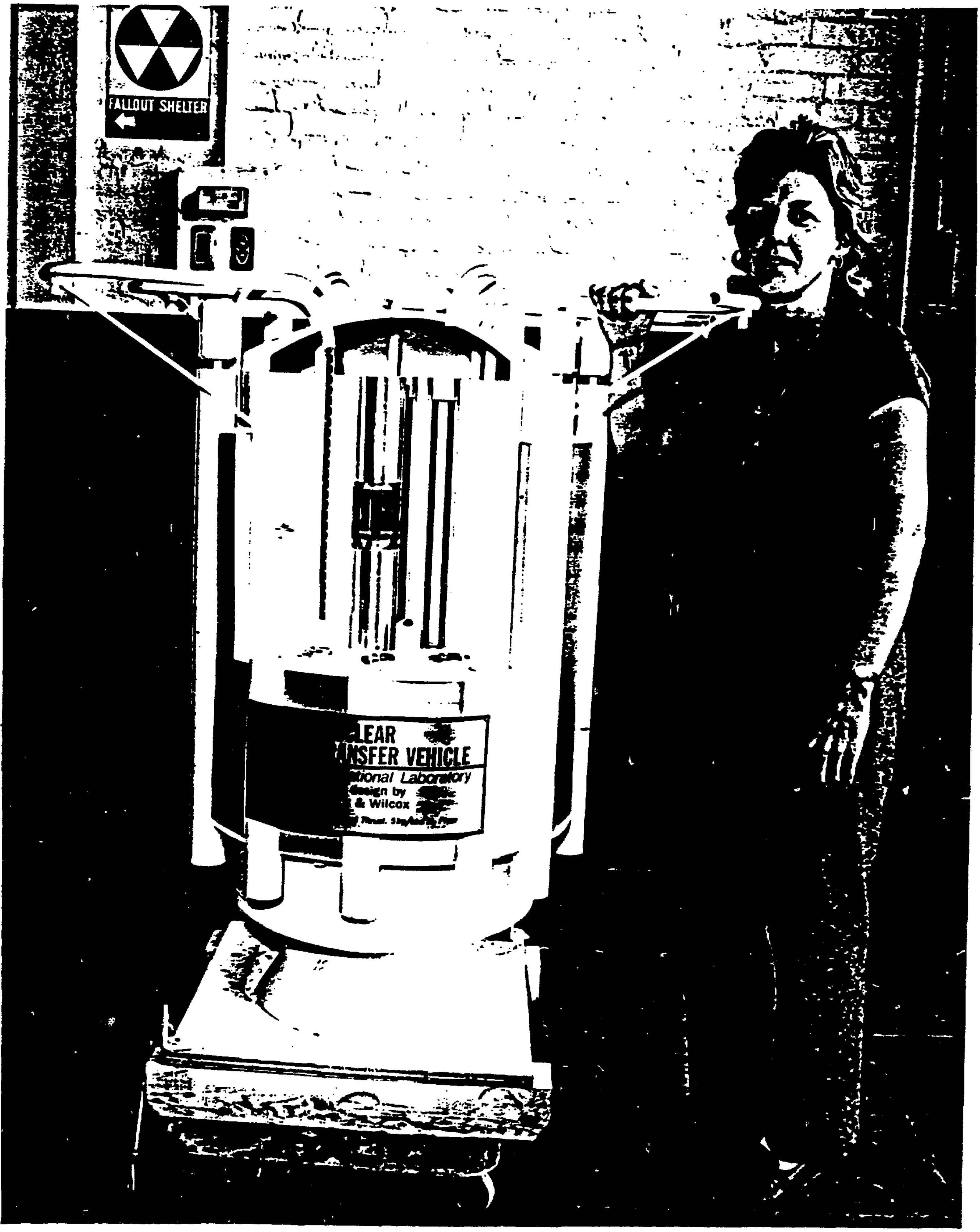
- Number of sites with large amounts of hydro available, but transmission costs/losses are prohibitive
- Most promising sites are in Alaska and Canada
  - politically secure
  - no major competing users for power likely
- Alaska site would
  - generate >100,000 MW(e) [>100 grams $\bar{P}$/year @ 1% efficiency]
  - have relatively low cost
    - ~B$ capital cost
    - ¢/kWh electric cost (10% f.c./year)
  - not result in major environmental damage

High Power Density Fission - Features

- Compact Particle Bed Reactor, HTGR type fuel particles
- D_2O moderated, helium cooled
- Pressure tube, calandria construction (CANDU type)
- 1000 MW(th), ~1m^3 core [3 MW/liter bed power density]
- Pneumatic loading/unloading of HTGR particles
- $^{233}U/ThO_2$ fuel cycle
- Short fuel residence time in reactor (~10 days total)
- Direct cycle turbine (~40% cycle efficiency)
- Small inventory of fission products in reactor (~1/100th of LWR)
- No transuranic waste (300 year burial time for Cs^{137} and Sr^{90})
- Mass production of standardized reactor/power conversion components

PARTICLE BED REACTORS




FALLOUT SHELTER
VEHICLE
Laboratory
& Wilcox

Large Scale Fission - Economics

- Breeding ratio ~0.9
- Makeup ^{235}U or ^{233}U (accelerator breeder) @ \$50/gm
  - corresponds to 5×10^{-2} ¢/kWh
- ~1500 \$/kW(e) for reactor and power system
  - present LWR's ~\$3000 to 4000/kW(e) in U.S.
  - French costs much lower
  - small compact mass produced reactors permit
    - economics of large scale production
    - minimization of field construction costs
    - faster construction and lower interest costs
- 90% load factor
- 3B\$ fabrication and processing plant [20,000 MW(e)]
- ~2¢/kWh total electric cost

LARGE SCALE PHOTOVOLTAIC

- PV MODULES PROJECTED TO COST \$0.50 PER PEAK WATT BY MID-90'S (THIN FILM AMORPHOUS SILICON)

- TOTAL COST ~\$1.00/PEAK WATT (FACILITIES, POWER CONDITIONING, ETC.)

- AVERAGE CAPITAL COST ~\$4.00/WATT (AVERAGED OVER DIURNAL AND SEASONAL VARIATIONS)

- DELIVERED ENERGY COST IS 4.5 CENTS/kWH (10% FIXED CHARGES)

- POTENTIAL PROBLEMS WITH
  - LAND AREA REQUIREMENTS (~10 KM^2) - 40% FILL FACTOR
  - CELL LIFETIME (20 TO 30 YEARS?)

LARGE SCALE MAGNETIC FUSION

- Low cost favored by
  - Advanced fuel systems
    - no tritium breeding blanket
    - lower first wall neutron/heat load
    - direct energy conversion
  - Tandem mirror geometry
    - simpler coil/blanket construction
    - high beta operation
    - readily couples to direct converter
- Catalyzed DD fuel cycle favored
  - Shortage of He^3 for DHe^3 fuel cycle
  - Operating parameters for other cycles (p B^{11}, p Li^6, etc.) too difficult (e.g. temperature, Q value, etc.)

ACCELERATOR BREEDER - PRODUCTS

- ~100 NEUTRONS/GEV AVAILABLE FOR BREEDING
- CAN PRODUCE
  - COMMERCIAL NUCLEAR FUEL (Pu^{239} OR U^{233})
  - SPECIAL NUCLEAR MATERIALS
    - WEAPONS (Pu^{239}, H^{3})
    - FUEL FOR ULTRA SMALL REACTORS (AM OR CM)
  - TRANSMUTATION OF LONG-LIVED WASTES (ACTINIDES, Sr^{90}, Cs^{137})
  - COMMERCIAL ISOTOPES

ACCELERATOR BREEDER-SCALE & COSTS

BASIS: 1 GW BEAM (1 GM $\bar{P}$/YR AT 1%)
100 NEUTRONS/GEV
$1000/KW FOR BREEDER TARGET
90% LOAD FACTOR
10% FIXED CHARGES/YR

<u>NUCLEAR FUEL</u>

- ~7 METRIC TONS/YR OF U^{233} OR Pu^{239}

- ~15$/GM (TARGET COST)

- SUSTAINS

  20-1000 MW(E) [WR's]
  (CR = 0.6, 80% LF)

  45-1000 MW(E) HTGR's
  (CR = 0.8, 80% LF)

- 10 $\bar{P}$ FACILITIES COULD SUPPLY FUEL FOR ENTIRE U.S. ECONOMY

TRANSMUTATION OF WASTES

- TRANSMUTE ~7 TONS/YR OF ACTINIDES, OR
- ~3 TONS/YR OF H.L.F.P. (MIXED SR^{90}-CS^{137})
- 1 $\bar{P}$ FACILITY COULD TRANSMUTE WASTE FROM ~50-1000 MW ( ) REACTORS
- DIFFICULT TARGET DESIGN FOR HLFP ($\geq 10^{16}$ ~CM^2 SEC)

COMMERCIAL ISOTOPES

- GENERATES 2000 MEGACURIES/YR OF Co^{60}
- COST ~5¢/CURRIE (VS 1 $/CI)
- 1 $\bar{P}$ FACILITY COULD MEET ALL COMMERCIAL ISOTOPE REQUIREMENTS