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ANTIPROTON DRIVEN MICROFISSION-FUSION ON CLOSER INSPECTION

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ABSTRACT

A closer look at the energetics of antiproton annihilation in real systems, coupled to hydrodynamics, materials strength, particle transport, equations of state, and related interactions is necessary to assess ultimate viability. The systematics of antiproton microfission-fusion are the subject of this analysis, as well as technology constraints.

INTRODUCTION

Potential schemes for employing antiproton-proton annihilation as a driver for space propulsion, power generation, condensed matter physics experiments, biomedical treatment, and others become more interesting and viable with the advent of portable storage traps (Penning) and related proof-of-principle storage experiments at LEAR recently. In the fission arena, micropellet experiments at the Phillips Laboratory SHIVA facility (imploding solid liner) are planned to study antiproton annihilation on uranium, by injecting some 10^7 antiprotons from a portable Penning trap over approximately 10 *nsec*. The design and construction of this trap have been undertaken by Los Alamos National Laboratory. Correspondingly, numerous calculations supporting the application of antiproton driven energetics have thus been proposed and reported. A closer look at the energetics of antiproton annihilation in real systems, coupled to hydrodynamics, materials strength, particle transport, equations of state, and related interactions is necessary to assess ultimate viability. The systematics[1-11] of antiproton microfission-fusion are the subject of the presentation, as well as technology constraints. In reviewing literature, it appears that estimates of antiproton energetics are optimistic, apparently rooted in material equations-of-state, neutronics, and burn treatments employed in analyses.

Antiproton annihilation in matter is one of the most energetic reactions observed routinely in high energy physics, some 1.87 *GeV* per annihilation. In actinide fuels, such as plutonium and uranium, antiproton annihilation at the nuclear surface also induces fission with very high probability and numbers of neutrons. The combination of the two effects might be expected to initiate and drive fission-fusion in hybrid or simple systems. In addition to the energetics of annihilation, the transport of antiprotons through matter, until they are stopped and captured on the nuclear surface, must be considered. The kinetics of neutrons in highly compressed material has been studied before,[7,8,11] and the conclusions have timely bearing on antiproton driven systems, namely that virtually impossible compressed states of matter are required for burn. Similarly, the nature of annihilation also requires transporting antiprotons in timely fashion through matter, so as to distribute the annihilation neutrons uniformly in the fissile region.

ANTIPROTON FISSION

Taking the pion-triggered CERN data of Angelopoulos[1] shown in Figure 1, we have constructed a fission neutron multigroup cross section table[2] for antiprotons, to be used in calculations of fission, fusion, and fission-fusion energetics. The spectrum[6] includes two component Maxwell-Boltzmann distributions, accounting for direct and evaporation processes, plus a Watt distribution, accounting for fission. Seven fit parameters, ($a_{e,d,f}$, $T_{e,d,f}$, E_f), take the form.

$$\frac{\partial n}{\partial E} = Y(E) = \sum_{i=d,e} a_i \left[\frac{4E}{\pi T_i^3} \right]^{1/2} \exp(-E/T_i) + a_f \left[\frac{\exp[-(E_f+E)/T_f]}{(\pi E_f T_f)^{1/2}} \right] \sinh(2E_f^{1/2} E^{1/2} / T_f) \ , \tag{1}$$

with i denoting direct, evaporation processes, and f fission. The T are characteristic temperatures, while the a are numbers of neutrons normalized to,

$$\sum_{i=d,e,f} a_i = \bar{\nu} \ , \tag{2}$$

and E_f is a fission barrier energy. Specifically, we have fitted,

$$\bar{\nu} = 13.6 \ ,$$

$$a_d = 4.39 \ , \ T_d = 112.8 \ MeV \ ,$$

$$a_e = 1.53 \ , \ T_e = 10.3 \ MeV \ ,$$

$$a_f = 7.68 \ , \ T_f = 2.3 \ MeV \ , \ E_f = .727 \ MeV \ , \tag{3}$$

using a Levenberg-Marquardt non-linear least squares algorithm.

Multigroup (g) fission fractions, χ, used in S_n and Monte Carlo neutron transport codes, can be estimated,

$$\chi_g = \int_{E_g}^{E_g} Y(E) \, dE \ . \tag{4}$$

Figure 1 contrasts the fission spectra (conveniently normalized) for neutrons and antiprotons incident on U_{238}. Clearly the antiproton spectrum is more peaked at higher energies than the neutron spectrum.

ANTIPROTON TRANSPORT

A multigroup technique[3,4] for transporting charged particles has been developed, and amounts to defining a downscattered cross section, σ', over many energy groups, G, in terms of the experimental (or theoretical) stopping power, $\partial E / \partial s$, for E the energy and s the path length. It has been employed in applications (ion beams, ICF, α and proton energy deposition in fuels, etc) with success. It is appropriate for transporting antiprotons in materials, when energy deposition and range are necessary in calculations for injected antiprotons, usually with kinetic energies in the *keV* range.

A multigroup cross section, σ_g', is defined in the continuous-slowing-down approximation (CSDA) in terms of stopping power, $\partial E / \partial s$,

$$\sigma_g' = \int_{E_g}^{E_g} \left[\frac{\partial E}{\partial s} \right]^{-1} dE = \left[\frac{\partial s}{\partial E} \right]_g \Delta E_g \ . \tag{5}$$

with groups selected in constant lethargy, ζ,

$$\zeta = \ln(E_{g+1} / E_g) \ , \tag{6}$$

numbering some 50, or more, for particles in the *keV* range. Integrals over energies can be carried out mid-point to mid-point across groups, g. The group energy deposited in a cell, ε_g, is the difference of particle current inflow minus outflow, J_g^{net}, times group energy, E_g,

$$\varepsilon_g = E_g \, J_g^{net} \ ,$$

$$J_g^{net} = \int_{in} \mu \, \phi_g \, d\mu - \int_{out} \mu \, \phi_g \, d\mu \ , \tag{7}$$

with μ the appropriate direction cosine, and ϕ the antiproton group angular flux. Total energy deposition, ε''', is then the sum over all group energy deposition terms, G,

Figure 1. Comparative Fission Spectra in U_{238}.

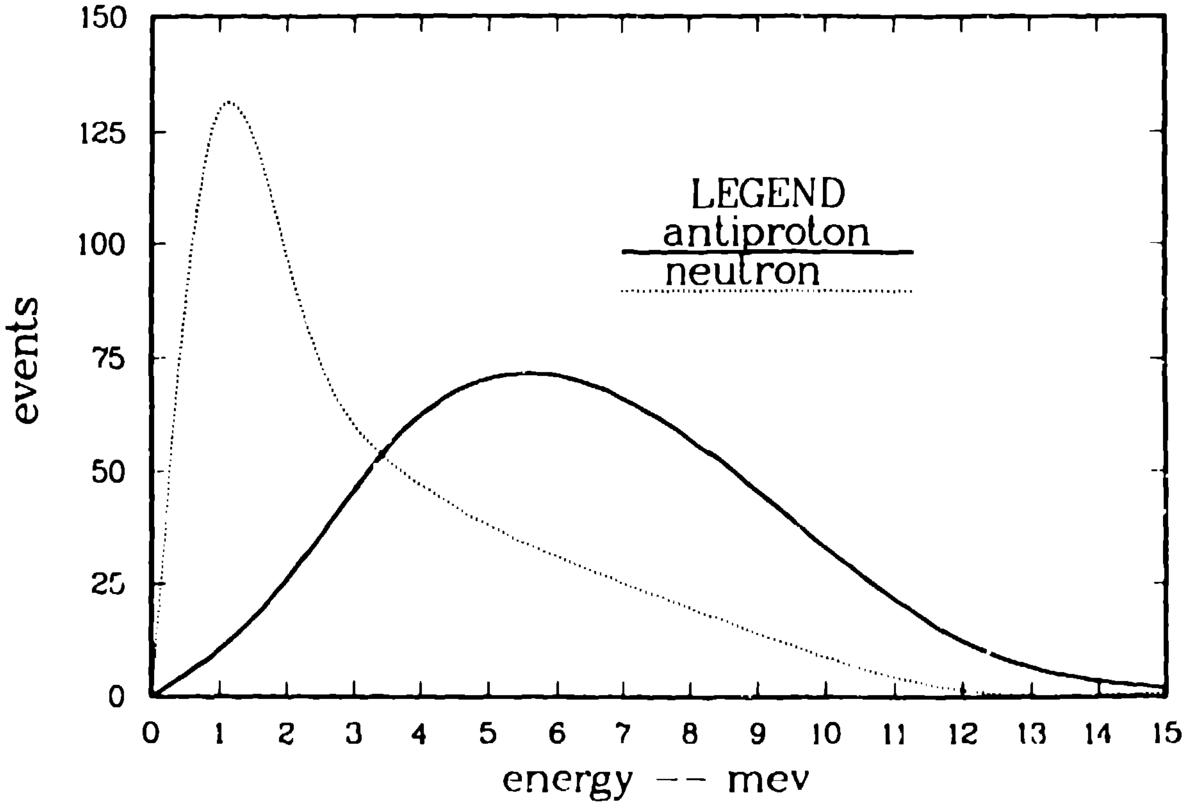
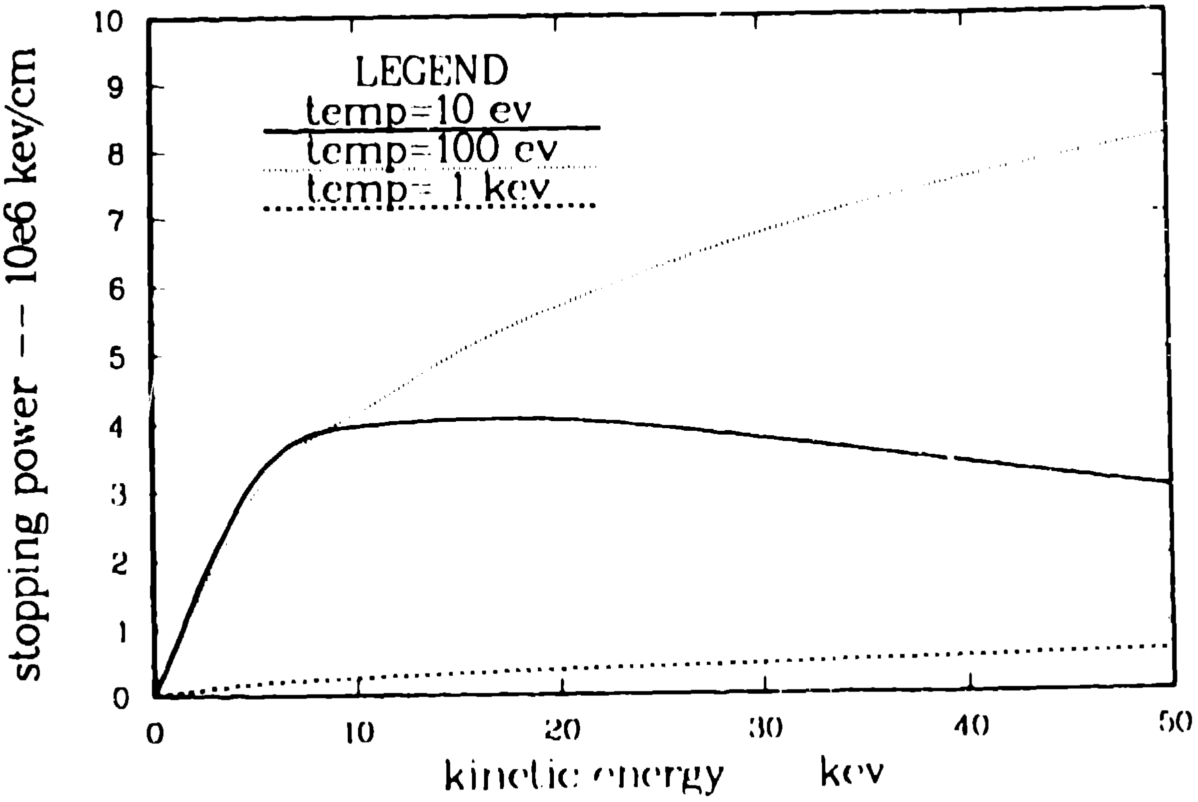


Figure 2. Antiproton Stopping Powers in U_{238}.



$$\varepsilon^{tot} = \sum_{g=1}^{G} \varepsilon_g \quad . \tag{8}$$

Groups are defined over a range of incident kinetic energy down to thermal energy, in decreasing group size according to Eq. (6).

Antiproton stopping powers[3,9] in actinides can be written in general form (keV/cm),

$$\frac{\partial E}{\partial s} = 1.303\times10^{-19} \left[\frac{n \Lambda Z^2}{AE} \right] \left[erf\,(\kappa) - (2\kappa/\pi^{1/2}) \exp(-\kappa^2) \right] \quad , \tag{9}$$

for Z and A the charge and atomic mass unit of stopping material, κ the antiproton energy E, scaled by temperature, T,

$$\kappa^2 = A \left[\frac{E}{T} \right] \quad , \tag{10}$$

Λ the Coulomb cutoff as a function of temperature and energy, erf the error function, and n the stopping particle number density (ions, electrons). Compared to protons, antiprotons are slightly longer-ranged. Obviously, any set of antiproton range-energy data could be fitted in similar functional form. Figure 2 depicts the electron stopping power for antiprotons in normal density U^{238}, at temperatures of 10 eV, 100 eV, and 1 keV. Such range of energies might be expected in portable trap applications.

SYSTEMATICS

Some calculations[5,7,8,11] of microfission-fusion in applications have been reported, and a discussion of systematics is illuminating. Results, exhibiting total fuel burn in 1 *gr* to 10 *gr* targets, are not realistic, considering drive pressure, compression, final density, numbers of initiating antiprotons, and fission and fusion neutron output. Related calculations underscore the effects of varying antiproton ignition levels for induced fission-fusion chains at high density, suggesting only some 10^7 initiating antiprotons. To enhance yield as a function of antiproton ignition level, we certainly can:

(1) increase compression;

(2) increase fissile mass;

(3) employ combinations;

but optimized design (minimum antiproton, drive pressure, fuel mass) must be pursued within constraints of present technology, particularly compressions and numbers of antiprotons necessary to drive a critical system. The high compressions cited are very difficult within existing technologies. Common reactor neutronics codes[10] suggest that some 10^{11} initiating antiprotons are requisite to drive such pellet configurations.

The combination of high fission probability and neutron multiplicity is still attractive to initiate and drive fission-fusion in simple or hybrid systems, possibly small systems because the initiation time is short (10 *nsec*), the resulting neutron intensity is high and focusible, and the first burst of annihilation neutrons starts the chain reaction at three generations. Systems employing antiprotons will witness higher local neutron intensities, compared to any neutron generators commonly available, considering factors such as antiproton beam size, flux out of the trap, and particle range. Shells lend themselves to antiproton initiation, recalling the short range of even *keV* antiprotons (about 50 *microns* at 50 *keV*).

Antiproton annihilation also lends itself to small (capsule) assemblies. The goal of any capsule device is to initiate self-propagating nuclear reactions in a small amount of material. The material is compressed to high density, and its inertia should maintain the high density while reactions occur. One challenge is to find practical methods of speeding up the nuclear reactions, so that fuel burn is more efficiently played off against disassembly. Rapid fission initiation is one such method, along with the additional leverage of fission heating of thermonuclear fuel, thereby reducing some of the gas compression requirements.

Over a wide range of target sizes, 1 *gr* to 100 *gr* approximately, two important factors, criticality and disassembly, affect fission (and ultimately fusion). Reactor code simulations and simple scaling arguments for multiplication rates suggest some lower limits relating antiproton intitiation number and rate, compression, and capsule radius, that is, a criticality condition,

$$\rho r > 120\, gr/cm^2 \ , \tag{11}$$

for ρ the average density, and r the radius at criticality, as well as a disassembly constraint,

$$r\alpha > 30\, cm/\mu sec \ , \tag{12}$$

with α the peak multiplication rate. The greater the numbers of initiating antiprotons, and the shorter the injection pulse length, the higher will be the multiplication rate. The higher the compressibility and the larger the capsule radius, the higher will also be the reaction rate.

The experiments planned at SHIVA STAR will provide important and requisite data points to benchmark calculations and models in such applications. In initial capsule (homogeneous *UDT*) simulations using reactor codes,[10] fairly compressed states ($150\, g/cm^3$) were necessary for ignition-burn. To get to final densities in the 150 g/cm^3 range, drive pressures in the 200 *Mb* range also appear requisite, using simple equations-of-state.[12] Somewhere near 10^8 initiating antiprotons are needed for densities at $150\, gm/cm^3$, less at higher densitities, more at lower densities.

Trap technology ports to many systems and experiments, and the mechanisms of antiproton annihilation possess interesting features not seen before. Los Alamos National Laboratory has been investigating applications of antiprotons, has performed related and scoping antiproton calculations, and hopes to perform some antiproton experiments, following proof of trapping technology (10^{10} portable antiprotons).

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