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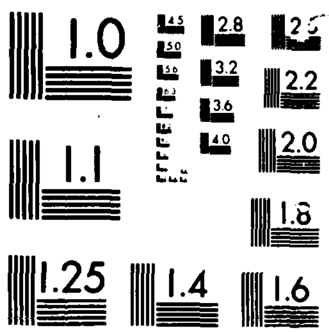

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December 1985

Annihilation of Antiprotons in Heavy Nuclei

April 1986

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NOTICE

FOREWORD

This report was prepared for the Air Force Rocket Propulsion Laboratory (AFRPL) under MIPR RPL-59004 by the Lawrence Livermore National Laboratory (LLNL) under the auspices of the U. S. Department of Energy. The work was performed at the LLNL during the period 1 April 1985 to 31 December 1985. Principal investigator for the LLNL was Mr David L. Morgan, Jr. Project Manager for the AFRPL was Dr Franklin B. Mead, Jr.

This technical report has been reviewed and is approved for publication and distribution in accordance with the distribution statement on the cover and on the DD Form 1473.

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A literature survey was conducted to find information relevant to the annihilation of a low-energy (sub-MeV) antiproton in a heavy nucleus. Such information is important to the use of nuclear fragments from the annihilation to heat a working fluid for space propulsion. The particular piece of information desired was the fraction of annihilation energy that becomes the kinetic energy of charged nuclear fragments emitted after the annihilation. The experimental and theoretical information located was sufficient to allow calculation of that energy fraction. Its value is about 10% for nuclei as heavy as silicon or greater and 20% for very heavy nuclei when the energy of fission fragments is included. Both values are less than the fraction of annihilation energy (38%) that becomes the kinetic energy of charged pions from the annihilation of an antiproton with a proton (hydrogen nucleus). These values are relevant to the choice of a working fluid that absorbs a portion of the annihilation energy and forms the exhaust for a rocket powered by antiproton annihilation. Although it is easier to couple the energy of charged nuclear fragments to the working fluid,

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the higher energy fraction for the charged pions makes hydrogen more attractive as the working fluid. It is therefore important to investigate possible means for efficient transfer of the pion energy to the working fluid.

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1. INTRODUCTION

Antiprotons colliding with a heavy nucleus annihilate with a proton or neutron in the nucleus. The numbers and energies of the particles emitted from the nucleus following annihilation are significant to the use of antiproton annihilation as a source of energy for spacecraft propulsion. An important quantity to consider is the fraction of the annihilation energy that goes into the kinetic energy of heavy charged particles emitted from the nucleus, such as protons and deuterons. A large value of this energy fraction facilitates transferral of the annihilation energy to a working fluid or plasma that forms the rocket exhaust. It has been the purpose of the work reported here to determine the energy fraction from relevant literature and to assess the significance of its value to annihilation propulsion. This purpose is important to the question of what form of matter should be employed in annihilation with antiprotons to achieve maximum efficiency in converting annihilation energy into propulsion energy.

1.1 Choice of Annihilating Materials

Consideration of matter-antimatter annihilation as an energy source for space propulsion has been taking place over the last several years. For details of the research, the reader is referred to the journal articles and reports by Forward, Morgan, Vulpetti, and Massier listed in the bibliography. Comprehensive research results are found in Air Force Rocket Propulsion Laboratory document, AFRPL-TR-85-034 (Forward) and in Volume 35 (1982) of the Journal of the British Interplanetary Society.

Matter-antimatter annihilation produces the greatest amount of energy per unit mass of propellant of any known possible means of propulsion. The form of antimatter most often considered for annihilation consists of antiprotons, which are the antiparticles to ordinary protons. The antiprotons might be contained in solid antihydrogen, each atom (or antiatom) of which is composed of an antiproton and a positron (an antielectron). Antiprotons are the preferred form of antimatter because each antiproton annihilation produces about 2000 times as much energy per particle as positron annihilation with electrons, and antiprotons are much easier to produce than antinuclei (composed of antiprotons and antineutrons). Antimatter of any other form involves antiparticles that are not stable; they would decay in storage before being used. In contrast, the form of matter to employ for annihilation with the antiprotons is less certain. Antiprotons annihilate with the protons and neutrons in the nuclei of matter atoms, but whether the nucleus should be a proton (nucleus of ordinary hydrogen), a heavy nucleus (e.g. of uranium), or something in between is not clear. The choice depends on how the annihilation energy manifests itself and on how it can be used to provide propulsion.

When protons or other light nuclei are employed, energetic pions (mesons with a mass of about 1/7 of the proton mass) are the principal product produced by the annihilation. Most of the pions are charged, and they can be directed by a magnetic field to produce thrust. However, their exhaust velocity is about 90% of the speed of light. Thus, for nearly all envisioned missions (not including interstellar flight) where the space craft velocity is much less than the speed of light, only a small fraction of the annihilation energy is transferred to the spacecraft; nearly all remains in the exhaust. To achieve a higher efficiency, it is therefore necessary to transfer the annihilation energy to a working fluid, of much higher mass than the antimatter, that has a much lower exhaust velocity but much greater thrust than the pions. The efficiency of energy transferral is affected by the form of matter chosen as the annihilation medium.

If the annihilation medium consists of an element of high atomic number, some of the pions produced by annihilation (of antiprotons with the protons and neutrons of the heavy nuclei of that element) will transfer their energy to the nucleus, and nuclear fragments (protons, neutrons, deuterons, and other light nuclei) will be emitted. The masses of the fragments are much greater than the pion mass, so it is much easier to transfer the energy of the charged fragments to a working fluid than to transfer the energy of the charged pions. (Transfer of energy of neutral particles of either kind is still more difficult.) Ease of transfer means less distance that a particle or fragment must travel through the working fluid to transfer its energy. Large transfer distances might require rocket motors (where the transferral would occur) that are much larger than those used for chemical propellants.

If the fraction of annihilation energy going into the kinetic energy of charged nuclear fragments for heavy nuclei is about the same or greater than the fraction of energy going into the kinetic energy of charged pions for light nuclei, then chosing a heavy element for the matter will be advantageous as opposed to hydrogen or another light element where essentially no fragments are produced. Therefore, it is important to determine the fraction of antiproton annihilation energy that goes into the kinetic energy of charged nuclear fragments when antiprotons annihilate in heavy nuclei. To that end, a literature survey was conducted to locate information from which the energy fraction could be determined.

2. THE LITERATURE SEARCH

The literature search was conducted to obtain information on the annihilation of antiprotons in nuclei with a mass equal to, or greater than, carbon. Occasionally the search area was broadened to include lighter nuclei. Of greatest interest was the annihilation of antiprotons in uranium-238 nuclei, the most massive nuclei of any naturally occurring isotope. It appeared likely that this annihilation would have the largest fraction of pion energy transferred to charged nuclear fragments, because the large size of the nucleus leads to a large distance of travel for the pions within the nucleus. Carbon was chosen as the "lower limit" on heavy nuclei for two reasons. First, on a logarithmic scale the carbon nuclear radius is about midway between the nuclear radii of uranium and a proton. Second, carbon is a fairly common target in antiproton experiments, so it appeared likely that some relevant experimental information would exist. Information was sought on annihilation in the hydrogen and helium isotopes because it is relevant to the basic antiproton-proton and antiproton-neutron annihilations.

2.1 Procedures and Results

The search was conducted by consulting reference documents, by using computer data bases, and by communicating with individuals in the field of high energy physics. The Physics Briefs, INSPEC, American Institute of Physics, NTIS, and DTIC data bases were searched for publications over the last five to eight years. This yielded about two hundred citations for examination. Approximately fifty of the cited publications were obtained, because they were relevant to determining the energy fraction. Many of these had references to relevant publications of twenty to thirty years ago which were also obtained. The relevant publications are included in the Bibliography.

The personal contacts produced much useful information, including the results of a calculation of antiproton - uranium-238 annihilation,[1] and experimental results for antiproton annihilation in uranium-238 and silicon.[2] These results, when combined with earlier work, allow determination of both theoretical and experimental values for the energy fraction.

2.2 Antiproton - Heavy Nucleus Research

Experimental research on antiproton - heavy nucleus annihilation is concentrated in two time periods. The first period began shortly after the discovery of the antiproton in 1955[3] and continued into the early 1960's. The second period began about four years ago and includes the present. That period followed a time of heightened theoretical interest in the consequences of the large energy deposited in nuclear matter by annihilation.[4] This energy can lead to interesting physical circumstances (described in terms of quarks and gluons) that can improve the understanding of strong forces. The initial experimental work involved the study of charged particle tracks in photographic emulsions[5] and bubble chambers[6] exposed to antiproton beams at Lawrence Berkeley National Laboratory and subsequently at Brookhaven National Laboratory. At the present time most experimental work is being conducted at the LEAR (Low Energy Antiproton Ring) facility in the Antiproton Complex at CERN (Centre Européenne pour la Recherche Nucléaire, now named

European Organization for Nuclear Research) near Geneva, Switzerland (e.g., Ref. 2).

Some values for the energy fraction were determined during the first period of experimental work[5,6] However, these values are based on observation of a small number of annihilations (compared to modern capabilities) and either do not apply to specific nuclei or do not include heavy charged particles and fragments of all significant energies and types. The literature search yielded no published values of the energy fraction from the second period of experimental work, but many of the results from recent experiments at LEAR on antiproton annihilation in heavy nuclei are not fully published.[7] Hence the possibility of modern published values of energy fractions in the near future. The various pieces of experimental and theoretical information that currently exist, however, may be used to calculate the fraction of annihilation energy transferred to the kinetic energy of heavy, charged particles (or nuclear fragments) in antiproton annihilation with uraniums-238 and silicon nuclei.

3. ANNIHILATION PHYSICS

When an antiproton ($\bar{p}$, single negative charge) annihilates with a proton (p, single positive charge) or neutron (n, neutral) in a heavy nucleus, a number of lighter particles are produced. The number and types of particles vary from annihilation to annihilation. In nearly all annihilations, however, the particles are types of mesons, with pi-mesons (pions) being most likely. Most of the other mesons are "resonances," so called because they are short-lived excited states of more stable mesons, which decay into other particles (pions, to a large degree, in roughly 10^{-23} to 10^{-19} s) by way of strong forces. A small number of K-mesons (kaons) are produced directly or by decays of the short-lived mesons. The pions and kaons decay via weak and electromagnetic forces so they have much longer lifetimes (about 10^{-16} to 10^{-8} sec). The kaons constitute only about 2% of the decay products.

The three above "forces" plus gravity are the four fundamental forces of nature. In decreasing order of strength: strong forces are the nuclear forces that bind protons and neutrons in nuclei and give rise to fission and fusion energy; electromagnetic forces bind electrons to nuclei and are responsible for most physical, chemical, and biological phenomena; weak forces cause the radioactive decay of nuclei and the decay of some fundamental particles; and gravitational forces are responsible for weight and the motion of celestial bodies.

For many purposes including antiproton-annihilation propulsion, the antiproton annihilation products may be taken to be entirely pions, including charged pions (π^+ and π^-) and neutral pions (π^0). Characteristics of the pions from the annihilation of an antiproton at rest with a proton (i.e., when the relative velocity is nearly zero) are given in Table 1. The energy spectrum of the charged pions is shown in Fig. 1.

The pions eventually decay. The π^+ and π^- decay via weak forces into muons and neutrinos (the muons then decay into electrons, positrons, and neutrinos) while the π^0's decay via electromagnetic forces into photons (γ-rays).

The cross section for the annihilation of an antiproton with a proton is about 1.3 times the cross section for annihilation with a neutron for equal, low-incident energies.[8] This ratio was determined from observing annihilations of protons and neutrons in nuclei, but it also applies to free protons and neutrons. In annihilation with a neutron, the number of negative

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Table 1. Characteristics of pions from $p + \bar{p}$ annihilation at rest (information derived from Ref. 12 and other sources in the Bibliography). Total annihilation energy = mass energy of $p + \bar{p}$ = 1876.5[illegible] MeV. About 4% of the annihilation energy goes into other particles (mainly kaons).

particle	mean number of particles of each type per annihilation	mean kinetic energy per particle [MeV]	mass energy of particle [MeV]	mean life-time [s]
π^+	1.50	235	139.58	2.60×10^{-8}
π^0	2.0	203	134.98	$9.\ \times10^{-17}$
π^-	[illegible]	[illegible]	139.58	[illegible]

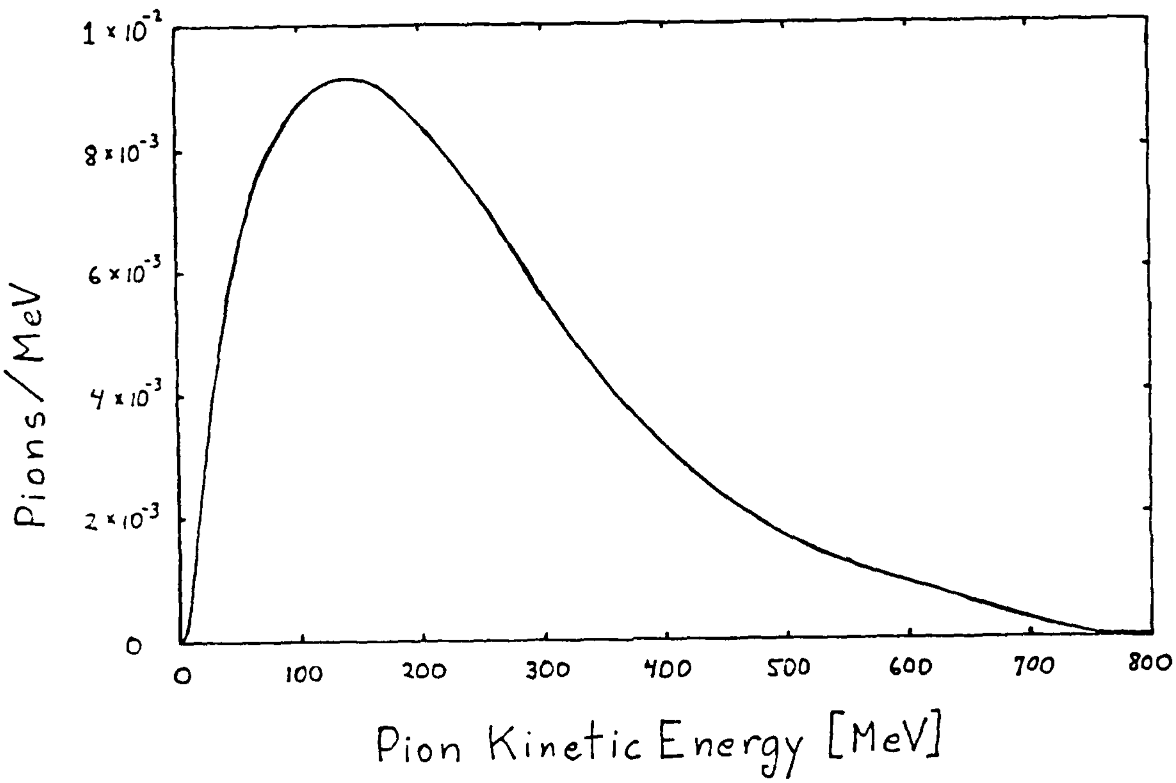

Fig. 1. Kinetic energy spectrum of charged pions from antiproton-proton annihilation at rest. Adapted from Ref. 17 for 0-600 MeV, from Ref. 18 for 600-700 MeV, and extrapolated to calculated cut-off for annihilation into $\pi^+ + \pi^- + \pi^0$ for greater than 700 MeV. The spectrum is normalized to a single annihilation, thus the area under the curve is 3.00, the mean number of charged pions per annihilation.

pions produced is always one more than the number of positive pions since charge must be conserved. The mean relative proportion of charged pions is somewhat greater than for annihilation with a proton, but the mean energies of the pions are about the same.

3.1 In Heavy Nuclei

When an antiproton with an energy of a few hundred MeV or less strikes a heavy nucleus, the probability for annihilation with either a proton or neutron is so high that annihilation occurs on the surface of the nucleus. The annihilation pions are emitted isotropically in the center of mass system of the annihilating particles, so about one-half of the pions will enter large nuclei. The cross section (or probability) for interaction of these pions with the nucleons (neutrons and protons) is sufficiently large that they will interact with one or more nucleons before exiting the nucleus, if they indeed get out. A pion may scatter from a nucleon or may be absorbed by a nucleon. When absorbtion occurs, the excited nucleon will usually re-emit a pion. In both cases, some of the kinetic energy of the pion is transferred to the nucleon. The energy transferred is usually well above the 5 - 10 MeV mean binding energy with which each nucleon is bound within the nucleus. Thus, a number of nuclear fragments, which are individual nucleons or combinations of nucleons, will be emitted from the nucleus. In addition, the nucleus will be left in an excited state. If the residual nucleus is sufficiently heavy to be unstable to fission, then it is likely that fission will follow the cascade of the pions through the nucleus.[(9)] The fission energy transferred to the kinetic energy of the two roughly equal nuclei that result is about 175 MeV.[(10)]

3.2 Nuclear Fragment Energies

Most of the fragments emitted will be individual protons and neutrons.[5,6] A few will be deuterons (designated d, one p and one n), tritons (designated t, one p and two n's), helium-3 nuclei (designated ^{3}He, two p's and one n), and alphas (designated α, two p's and two n's). The total kinetic energy transferred to these fragments depends on the dynamics of the pion-nucleon interactions and on the size of the nucleus. Some possible energies that might be available to the fragments are given in the first two columns of

Table 2. The first column considers the kinetic energy of one-half of the pions, and in the second column the mass energy of these pions is also included. The last row of both columns additionally includes the kinetic energy of the fission fragments that may be present from fission of the residual nucleus. Table 2 also gives the kinetic energy of the charged pions produced by annihilation with a proton (about the same as for annihilation in other light nuclei consisting of only a few nucleons).

It is apparent from the figures in Table 2 that if a high fraction of the available energy is transferred to charged nuclear fragments when annihilation occurs in a heavy nucleus, then the kinetic energy of these fragments is comparable to the kinetic energy of the charged pions from annihilation with a proton (hydrogen nucleus). It is this possible fact that makes heavy elements potentially attractive as an annihilation medium and working fluid for antiproton annihilation (and led to this study), since transferral of energy to the working fluid with the relatively heavy charged nuclear fragments is easier to accomplish than with the relatively lighter pions.[11] It will be seen in the following two sections, however, that only a fairly small fraction of the available energy goes into the kinetic energy of charged fragments. Much goes into reemitted pions and a significant amount into the kinetic energy of neutrons.

Table 2. Possible energies that may be available to nuclear fragments following annihilation of an antiproton at rest in a heavy nucleus compared to the kinetic energy of charged pions produced by proton-antiproton annihilation. Small contribution from kaons not included.

	Annihilation in heavy nucleus		Annihilation with a proton
	Half of pion kinetic energy	Same with mass energy	Kinetic energy of charged pions
Energy [MeV]	556	900	705
Fraction of annihilation energy	0.30	0.48	0.38
Fraction with kinetic energy of fission fragments included	0.39	0.57	-----

4. THEORETICAL RESULTS FOR URANIUM

Michael R. Clover of Los Alamos National Laboratory provided the output of a computer run that gives the details in the Intra-nuclear Cascade Model of $\bar{p}$ scattering by a uranium-238 nucleus.[1] These results are similar to, but more detailed than, those reported by Clover et al. for the same problem.[12]

The code performed a monte carlo simulation of encounters between a 175 MeV (lab energy) antiproton and a ^{238}U nucleus (at rest in the Lab frame). The number of encounters was 7029 of which 4950 were inelastic (the $\bar{p}$ changes form or loses energy in the center-of-mass frame). The $\bar{p}$ did not pass close enough to the nucleus for inelastic processes to occur in the other encounters. Nearly all of the inelastic encounters involved $\bar{p}$ annihilation, however in 244 inelastic cases the $\bar{p}$ remained intact but lost energy to individual nucleons, and in 17 cases charge exchange occurred. In these latter cases the antiproton struck a proton and an anti-neutron plus a neutron were produced, with the anti-neutron then leaving the nucleus without annihilating. In charge exchange, the antiproton gives its negative charge to a proton and becomes an antineutron ($\bar{n}$), while the negative charge neutralizes the positive charge of the proton making it a neutron.

The code output contains the number and energy spectra of the nuclear fragments, pions, kaons, and other particles produced in the inelastic collisions. From the spectra, the mean energy for each particle or fragment may be calculated. The numbers and mean energies are give in Table 3. A correction was applied to these quantities to obtain similar quantities for the case of interest here in which only annihilations occur. Table 3 also contains those results, along with the mean total kinetic energy given to each particle or fragment type for a single annihilation. The particle and fragment numbers allow calculation of the mass energy of the created particles (pions and kaons) and the nuclear binding energy lost (potential energy gained) when the nucleons and fragments leave the nucleus. These are also in Table 3. The code gives information on the distribution of nuclear states following annihilation from which the mean excitation energy of the residual nucleus was determined. That value is shown in Table 3 where it is added with

Table 3. Theoretical characteristics of nuclear fragments, particles, and the residual nucleus resulting from the encounter of a 175-MeV antiproton with a ^{238}U nucleus based on Ref. 1. Statistical errors are not shown.

	Inelastic Scattering		Annihilations only		
particle or fragment	mean number per event	mean kinetic energy per particle or fragment [MeV]	mean number per annihilation	mean kinetic energy per particle or fragment [MeV]	total kinetic energy for each type per annihilation [MeV]
p	1.419	101.2	1.498	101.7	152.4
n	3.608	72.4	3.809	72.8	277.4
π^+	0.758	212.	0.801	213.	170.6
π^0	1.137	197.	1.201	198.	238.
π^-	1.206	193.	1.273	194.	247.
K^+	0.030	84.	0.032	85.	2.7
K^0	0.068	65.	0.071	66.	4.7
K^-	0.039	99.	0.041	99.	4.1
$\bar{p}$	0.049	146.	-	-	-
$\bar{n}$	0.003	134.	-	-	-
d	0.347	77.9	0.366	78.4	28.7
t	0.266	62.3	0.280	62.6	17.6
^3He	0.163	65.6	0.172	66.0	11.4
α	0.044	54.3	0.047	54.6	2.6

Total kinetic energy to particles/fragments	1156. MeV
Total mass energy of π's & K's	523.
Nuclear recoil kinetic energy	1.
Nuclear binding energy lost (approx.)	59.
Mean excitation energy of residual nucleus (approx.)	296.
Total Discrepency	17.
$p + \bar{p}$ mass energy + $\bar{p}$ kinetic energy	2052. MeV

the other energies in an attempt to reproduce the total input energy, the sum of the annihilation energy and the incident kinetic energy of the antiproton. This sum falls 17 MeV short of the input energy. One possible explanation involves the assumption employed that the mean binding energy per nucleon is the same in the possible residual nuclei as in ^{238}U, whereas it is likely somewhat less. Another possible explanation is a small systematic error in the numerical integration of the energy spectra to obtain the mean energies of the particles and fragments. In any case, the discrepency is less than one percent of the total energy, and hence negligible for our purposes.

The residual nucleus, after annihilation, is in a highly excited state from which more fragments (mainly nucleons) will be emitted by evaporation, along with the emission of gamma rays. The contribution of evaporation to the total energy in emitted fragments may be estimated by considering Fig. 4 of Ref. 13. Here it is shown that the energy deposited by evaporated protons following antiproton annihilation in a 1 mm thick slab of silicon is about the same as the energy deposited by the protons emitted during the initial intra-nuclear cascade. Using this fact and a formula for the rate of energy deposition for charged particles in matter(14), it can be determined that the total kinetic energy in the evaporated protons is less than one-tenth that of the initial cascade protons when the initial energy of the evaporated protons is 25 MeV. If that initial energy is 10 MeV, then the ratio of the energies is one-hundredth. The reason for the nearly equal deposition of energy is that the lower-energy, evaporated protons deposit their energy much more rapidly than the faster cascade protons. Since the mean energy of each evaporated proton is probably around 10 MeV and certainly less than 25 MeV,(15) the contribution of evaporated protons is insignificant. The same is very likely true for other fragments, so evaporated fragments may be neglected.

4.1 Fraction of Energy to Charged Fragments

The results of Table 3 give 213 MeV for the total kinetic energy of heavy charged fragments (p,d,t,^{3}He,α) following annihilation of a 175 MeV antiproton in a ^{238}U nucleus. In an antiproton annihilation rocket engine, the antiprotons will most likely be at much lower energy. They may be stored at temperatures near absolute zero(11) (10^{-5} to 10^{-4} eV, perhaps) and extracted and transported to the rocket engine at energies well under 1 MeV. As far as the intra-nuclear dynamics is concerned, the annihilation of such an antiproton amounts to annihilation "at rest". More energy is transferred from the pions to the fragments for a $\bar{p}$ energy of 175 MeV than a $\bar{p}$ energy of nearly zero. This is because center-of-mass motion at 175 MeV tilts the pion distribution forward resulting in more pions entering the nucleus and because the pions share the additional 175 MeV of energy.[5,6] Available experimental information allows determination of the ratio of kinetic energy tranferred to charged fragments for annihilation at rest to the same quantity for annihilation at 175 MeV.

From Ref. 6 the value of the above ratio, when comparing annihilations at 25 MeV and 120 MeV is 0.84 ± 0.08. Assuming an inverse linear dependence on energy, this gives 0.73 ± .12 for the ratio from 0 MeV to 175 MeV. From Ref. 5 the ratio is 0.57 ± 0.06 for zero to 166 MeV. When similarly extrapolated to the case of 0 MeV to 175 MeV, this latter ratio becomes 0.56 ± 0.06. Combining the two ratios for 0 MeV to 175 MeV with somewhat more weight for the latter, the value of 0.62 ± 0.10 is obtained as a single value for the ratio, where the large error reflects the discrepancy in the two ratios. Application of this single ratio yields 130 ± 20 MeV as the theoretical value for the kinetic energy of the heavy charged fragments (p,d,t,^{3}He,α) resulting from antiproton annihilation at rest in a ^{238}U nucleus. That value, along with related quantities is given in Table 4. It may be seen from Table 4 that annihilation of antiprotons in heavy nuclei is less attractive than indicated by earlier estimates of an energy fraction of about 0.5.[11] A similar conclusion occurs when experimental information on $\bar{p}$-heavy nucleus annihilation is considered in the following section. These results apply whether or not the ^{238}U nucleus or proton are free or in uranium and hydrogen atoms (or molecules) since they pertain to events per annihilation. The annihilation rate for antiprotons at energies around a few eV or less is much higher when the annihilating medium consists of atoms or molecules than free (bare) nuclei[11] (see also entries in Bibliography by Morgan and Hughes).

Table 4. Theoretical kinetic energy of heavy, charged fragments (protons and heavier) resulting from annihilation of an antiproton in a uranium-238 nucleus (based on Ref. 1) compared to the kinetic energy of charged pions in p + $\bar{p}$ annihilation at rest. Quantities for annihilation at rest are obtained by applying a factor to those at 175 MeV. The factor is obtained from experimentally based information in Refs. 5 and 6.

annihilating nucleus	^{238}U	^{238}U	p
$\bar{p}$ energy [MeV]	175	0 (at rest)	0 (at rest)
energy to charged fragments/pions [MeV]	210 (to fragments)	130 ± 20 (to fragments)	705 (to pions)
fraction of annihilation (plus any incident) energy	0.10	0.07 ± .01	0.38
fraction with kinetic energy of fission fragments included	0.19	0.16 ± .01	-----

5. EXPERIMENTAL RESULTS FOR URANIUM AND SILICON

Among the results of LEAR experiment PS187 reported in Ref. 2 are momentum-differential cross sections for proton production in 180 MeV antiproton annihilation with Si and ^{238}U nuclei (see Fig. 3 in Ref. 2, reproduced here as Fig. 2). By reading values from the graph, the cross sections may be integrated to obtain the total cross section for proton production as well as the mean energies of the protons. That was done under the assumption that there is no significant contribution to the total kinetic energy of the protons for momenta below 250 MeV/c (kinetic energy = 33 MeV) which is the low momentum cutoff on the graph. For ^{238}U, the cross section is 5800 mb (millibarn = 10^{-27} cm^2) and the mean kinetic energy is 100 MeV. For Si the cross section is 1350 mb and the mean kinetic energy is 110 MeV. To obtain the kinetic energy of the protons for each annihilation requires knowing the number of protons emitted per annihilation. That number is equal to the proton production cross section divided by the annihilation cross section, but the annihilation cross sections are not given in Ref. 2 (nor in Ref. 13 on the same experiment). They can, however, be obtained from other experimental information.

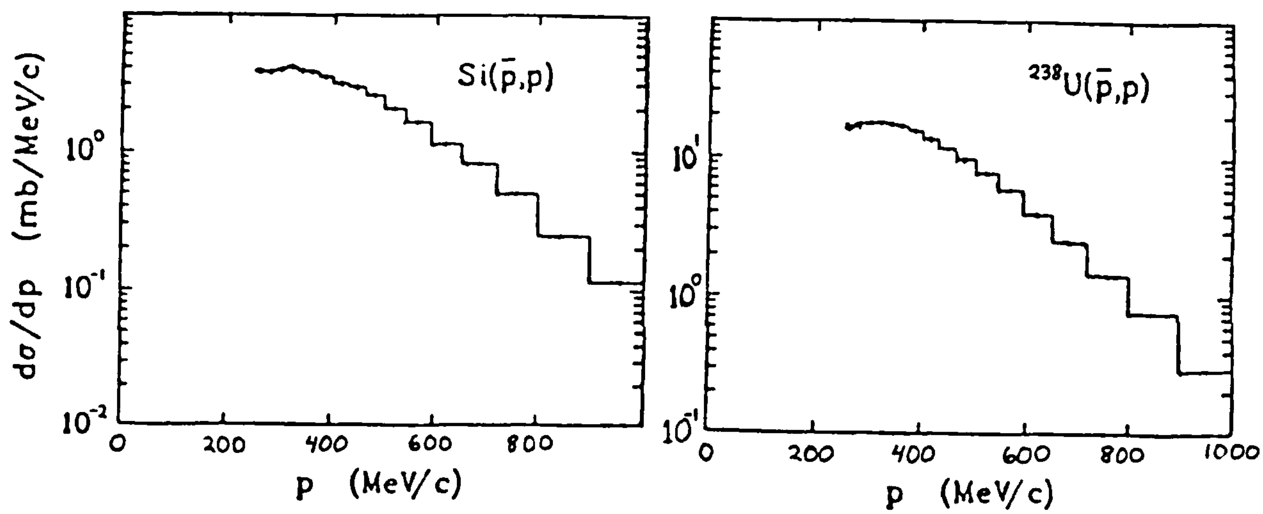

Fig. 2. Momentum-differential cross sections for proton production in the annihilation of 180 MeV antiprotons in silicon and uranium-238. Note, the symbol p is used both to designate a proton and for the momentum of a particle (here, a proton). Taken from Fig. 3 of Ref. 2.

5.1 Annihilation Cross Sections

Nakamura et al.[16] give measured values of $\bar{p}$ annihilation cross sections in carbon, aluminum, and copper for antiproton energies between 100 MeV and 350 MeV. At such energies, the cross sections are the same for free nuclei and ones in atoms. They call the cross sections "absorption cross sections", but it is evident that they are essentially equal to annihilation cross sections because the only other inelastic process included was charge exchange, which accounts for only about 0.3% of the absorption cross section. Besides their own values, Nakamura et al. also give annihilation cross sections in their Fig. 2 from other measurements for higher energies. That figure is reproduced here as Fig. 3. Because of the fairly simple dependence of annihilation cross section on atomic number of the nucleus and on the momentum or energy of the antiproton, the measurements of Nakamura et al., along with the other measurements in Fig. 3 can be used to determine the antiproton annihilation cross sections for silicon and uranium-238.

For antiproton energies high enough that the DeBroglie wave length of the antiproton is small compared to the nuclear radius (true for the momenta in Fig. 3), the annihilation cross section is approximately proportional to the geometric cross section of the nucleus. In fact, this proportionality is a near-equality for antiproton energies of a few hundred MeV (momenta of several hundred MeV/c) since the proton has a near-unity probability of annihilating once it encounters the nucleus. At higher energies, the nucleus begins to become transparent to the antiproton. At much lower energies, the wavelength of the antiproton becomes large and the quantum-mechanical spreading of the antiproton destroys the simple geometric picture.

In this simple but fairly accurate view, the annihilation cross section has the form

$$\sigma_a = \pi C\ A^{2/3} p^{-\beta} \qquad (1)$$

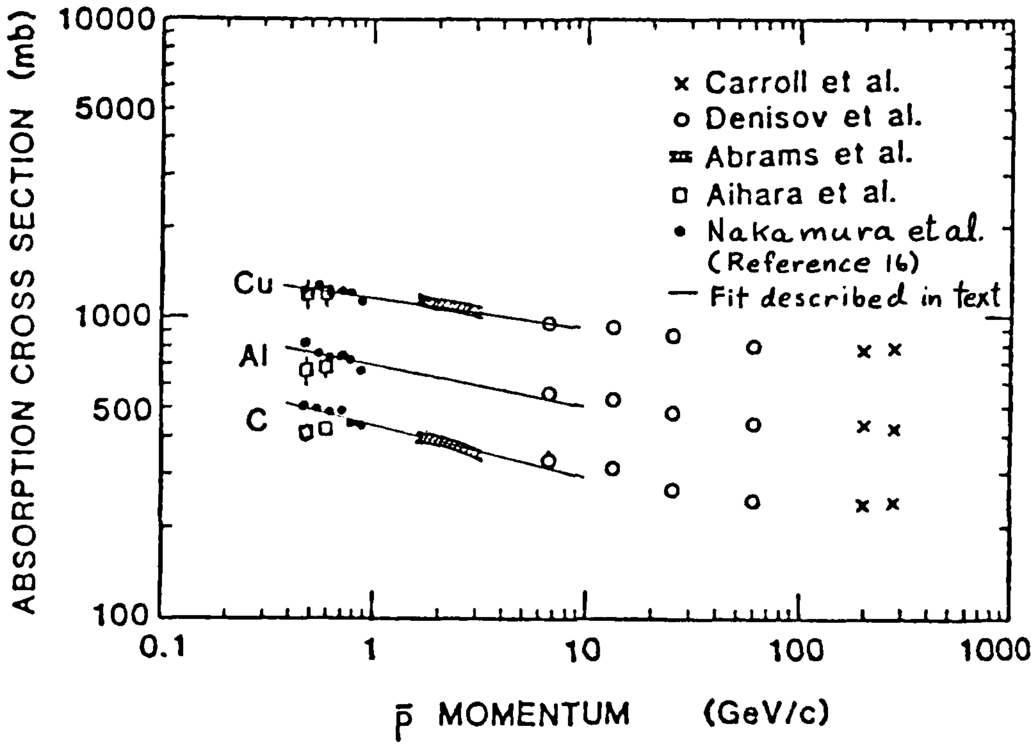

Fig. 3. Experimental antiproton absorption cross sections as functions of the antiproton momentum, from Fig. 2 of Ref. 16. The absorption cross section is essentially equal to the annihilation cross section. The solid curves are the fit described in the text. See Ref. 16 for full reference information on the experimental work.

where A is the atomic number of the nucleus (the area of the nucleus is proportional to $A^{2/3}$), p is the momentum of the antiproton (same symbol as used to designate a proton), and C and β are constants. The factor $p^{-\beta}$ can account, at least to a degree, for both the transparency of the nucleus as $p \to \infty$ and the spreading of the antiproton as $p \to 0$. A more accurate form for σ_a may be obtained by allowing β to depend somewhat on A, as appears must be the case from Fig. 3, and by replacing $C\ A^{2/3}$ with $(C^{1/2}A^{1/3} + d)^2$. The constant d accounts for the fact that annihilation may still take place out to some fixed distance beyond the mean radius of the nucleus. When such an altered form is used to fit the data of Fig. 3 for momenta less than 10 GeV/c, the results is

$$\sigma_a = \pi(1.35\ A^{1/3} + 0.83)^2 \left(\frac{p}{600\ \text{MeV/c}}\right)^{-0.5A^{-0.4}} \times 10^{-26}\ \text{cm}^2 \quad . \qquad (2)$$

Equation 2 gives the solid lines shown in Fig. 3 and gives a value of 2650 mb for ^{238}U with an antiproton energy of 175 MeV. This value is within 5% of the theoretical value of 2500 mb.(1) Equation 2 should not be employed for nuclei lighter than carbon. (For $\bar{p} + p$ it gives about twice the known value.)

5.2 Fraction of Energy to Charged Fragments

Equation 2 may now be employed to obtain the annihilation cross sections for a 180 MeV antiproton (momentum = 608 MeV/c) on Si and ^{238}U (as in LEAR experiment PS187) and thence the numbers and energies of the protons produced by the annihilations. For ^{238}U, σ_a = 2650 mb so the number of protons per annihilation is 2.19 and their kinetic energy per annihilation is 219 MeV. To this must be added the energy of the other heavy charged particles which are not considered in Ref. 12 or 13. However, using the ratio, 0.39, of the combined kinetic energy of d,t,^3He, and α to the kinetic energy of the protons from the theoretical calculation of the previous section (since no experimental value is known), the total kinetic energy of the heavy charged fragments is found to be 305 MeV. If the procedure in the previous section is used to extrapolate the energy to annihilations at rest, the factor to be employed is 0.61 ± 0.10, and the result for the kinetic energy of the charged fragments per annihilation is 190 ± 30 MeV. For silicon, σ_a = 760 mb, the mean number of protons is 1.75, their kinetic energy per annihilation is 195 MeV, and the kinetic energy of the charged fragments is 270 MeV (for a $\bar{p}$ energy of 180 MeV). When extrapolated to annihilation at rest, the kinetic energy of charged fragments is 165 ± 25 MeV per annihilation. These results are summarized in Table 5.

The experimental values for fraction of annihilation energy in ^{238}U going into heavy charged fragments shown in Table 5 are somewhat higher than the theoretical results of Table 4, but the results are, nevertheless, in fair

Table 5. Experimental results for the kinetic energy of heavy charged fragments (p,d,t,^{3}He,α) from the annihilation of an antiproton in silicon and uranium-238 nuclei compared to the kinetic energy of the charged pions from $\bar{p}$ + p annihilation (energies in MeV). The relative contribution for charged fragments other than protons is based on the theoretical results of Ref. 1.

		$\bar{p}$ incident energy		
nucleus		180 MeV	at rest	
		w/o fission energy	w/o fission energy	w/fission energy
Si	kinetic energy of charged fragments	270	165 ± 25	-----
	fraction of annihilation (plus any incident) energy	0.13	0.09 ± 0.015	-----
^{238}U	kinetic energy of charged fragments	305	190 ± 30	365 ± 30
	fraction of annihilation (plus any incident) energy	0.15	0.10 ± 0.015	0.19 ± 0.015
p	kinetic energy of charged pions	-----	705	-----
	fraction of annihilation energy	-----	0.38	-----

agreement. The higher values are still not as high as previously supposed in Ref. 11. Thus, annihilation of an antiproton in a heavy nucleus is not as attractive as suggested in that report.

The values in Table 5 show only a small relative difference between the kinetic energies of charged fragments from silicon and uranium-238. Therefore, if it were desireable to employ antiproton-heavy nucleus annihilation, medium-weight nuclei would work about as well as the heaviest nuclei when fission energy is not considered.

6. DISCUSSION AND CONCLUSIONS

Prevous studies have indicated a possible difficulty in coupling the antiproton annihilation energy to a working fluid that forms the rocket exhaust in antiproton annihilation propulsion.[11] This difficulty is due to the large distance that the relatively light charged pions from antiproton-proton annihilation must travel to transfer their energy, compared to possible distances that can be travelled by the pions (or decay muons) while confined in a magnetically contained plasma of a few meters size. If annihilation were to occur in a heavy nucleus of a working fluid of high atomic number rather than in hydrogen, part of the annihilation energy would go into the kinetic energy of charged, heavy nuclear fragments emitted from the nucleus such as protons, deuterons, etc., whose energy could be more readily transferred to the working fluid. The purpose of this study was to determine the fraction of annihilation energy that goes into the kinetic energy of the charged, heavy nuclear fragments.

A literature survey yielded sufficient theoretical and experimental information from which the energy fraction could be determined. Its value is about 10% for nuclei as massive as silicon or greater. It is the same or less for lighter nuclei. If fission energy is included for very heavy nuclei, the value of the energy fraction is about 20%. Both of these figures are less than an earlier estimate of about 50%,[11] and they are significantly less than the fraction of the annihilation energy, 38%, that goes into the kinetic energy of charged pions in antiproton-proton annihilation. If the kinetic energy of the charged pions is included, the corresponding energy fractions are about 30% for nuclei as heavy as silicon or greater and 40% for very heavy nuclei when fission is considered. These figures are still less than, or not significantly greater than, 38%. Their low values are mainly a consequence of the fact that a significant amount of the annihilation energy goes into the kinetic energy of emitted neutrons. I assume that the amount of energy that can transfer from neutral particles to the working fluid is insignificant.

Thus, for plasma combustion chambers of a few meters size, annihilation of antiprotons in heavy nuclei does not offer an advantage over annihilation with protons if an effective means can be found to couple the kinetic energy of the charged pions from annihilation with protons to a working fluid. If such a means cannot be found, then annihilation in heavy nuclei will allow transferral of up to 10-20% of the annihilation energy to the working fluid.

Since annihilation with protons has the potential for giving two to four times as much energy to the working fluid as annihilation in heavy nuclei, it is important to investigate the transferral of energy from charged pions to a working fluid in more detail. One must determine the mechanisms that would allow efficient transferral of energy in a combustion chamber with dimensions of a few meters, inside a magnetic field (to contain the charged pions), and at attainable plasma densities. In the work for Ref. 11, estimates of energy transferral from the charged pions to nuclei and bound electrons were employed. These estimates must be replaced by accurate calculations, and transferral of energy to free electrons in the plasma (electron drag) must be added. In addition, it is important to determine the mean distance traveled by charged pions (or their decay muons) before they exit the chamber, as a function of the plasma density and the strength and configuration of the magnetic field.

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