1988

INTERACTIONS OF ANTIPROTONS WITH ATOMS AND MOLECULES

Mitio Inokuti
Argonne National Laboratory

Nucl. Tracks Radiat. Meas., Vol. 16, No. 2/3, pp. 115–123, 1989
Int. J. Radiat. Appl. Instrum., Part D
Printed in Great Britain

0735-245X/89 $3.00 + 0.00
Pergamon Press plc

INTERACTIONS OF ANTIPROTONS WITH ATOMS AND MOLECULES*

MITIO INOKUTI
Argonne National Laboratory, Argonne, Illinois 60439, U.S.A.

(*Received* 14 *November* 1988)

Abstract—Antiproton beams of relatively low energies (below hundreds of MeV) have recently become available. The present article discusses the significance of those beams in the contexts of radiation physics and of atomic and molecular physics. Studies on individual collisions of antiprotons with atoms and molecules are valuable for a better understanding of collisions of protons or electrons, a subject with many applications. An antiproton is unique as a stable, negative heavy particle without electronic structure, and it provides an excellent opportunity to study atomic collision theory. Comparison of the stopping powers of a material for an antiproton and a proton at the same speed will be the most clearcut approach to the Barkas effect. The moderation of an antiproton in matter is roughly similar to that of negative pions and muons, but some differences remain to be elucidated. Full discussion of the interactions of a low-energy antiproton with an atom or molecule must consider the adiabatic potential determined by the electronic motion in the field of the antiproton and nucleus at rest. When an antiproton approaches an atom or molecule sufficiently closely, then some of the atomic or molecular electrons no longer remain bound and ooze out with extremely low kinetic energies; thus, the atom or molecule becomes ionized, often multiply ionized. This mechanism of ionization is absent for a proton. Upon complete moderation, an antiproton is eventually captured by the Coulomb field of a nucleus and thus an antiprotonic atom is formed. The present article also touches upon some problems related to condensed matter. For instance, the possibility of channeling of antiproton beams in a crystal is considered.

1. INTRODUCTION

IT IS well known that an antiproton is the antiparticle of a proton and that it was discovered in 1955. What is now attracting much attention is that beams of antiprotons are available for experiments. At present, antiproton beams are produced only at CERN, Fermilab, and a few other laboratories, and the beam intensities achieved are quite low. For instance, the number of antiprotons that are stored in the LEAR (Low-Energy Antiproton Ring) at CERN is about 2×10^9. This leads to 10^5–10^6 antiprotons/s extracted for a period of typically 45 min. However, the antiproton beam intensity will be increased greatly in the years ahead.

In principle, the antiproton beam can be much higher in intensity and much better collimated in momentum than presently available beams, because the antiproton is virtually stable in a vacuum. (According to the current theory, the antiproton, like the proton, is supposed to decay, but this decay process is extremely slow. According to the current estimate, the proton lifetime is of the order of 10^{32} yr. In other words a total of a few protons may decay within the bodies of 100 persons while they live a full lifetime of about 80 years.) The beam of antiprotons will have much better quality than a beam of $\pi^{\pm}$ or $\mu^{\pm}$, which are unstable particles. In this sense, antiproton beams are similar to positron beams, which are used in many experiments (Humbertson and Armour, 1988) and in synchrotron radiation sources in many institutions around the world.

The motivation for producing antiproton beams is mainly for the study of elementary particles, as is seen in Bloch *et al.* (1987). The purpose of the present article is to consider antiprotons from the point of view of radiation physics as well as atomic, molecular, chemical, or solid-state physics.

2. ANTIPROTONIC ATOMS

In any discussion of the structure of matter we start with an atom. Among all atoms the most fundamental is the hydrogen atom. It is composed of a proton and an electron in a bound sate. Similarly, we consider a bound state of an antiproton and a positron, i.e. an antihydrogen atom. Do a hydrogen atom and an antihydrogen atom have the same energy levels and spectra? They should have exactly the same properties when they are isolated in a vacuum, according to the CPT (charge conjugation, parity, and time reversal) invariance. However, if we observe an antihydrogen atom in our laboratory, the antihydrogen spectrum may not necessarily be identical with the hydrogen spectrum. This is because our universe

*Work supported by the U.S. Department of Energy, Office of Health and Environmental Research, under Contract W-31-109-Eng-38.

is overwhelmingly composed of ordinary matter made from nucleons and electrons. Therefore an antihydrogen atom may be influenced by the whole universe, including our laboratory, and this influence may differ from that affecting a hydrogen atom.

How does one produce antihydrogen atoms in the laboratory? This task is very difficult indeed. In the first place, antiprotons and positrons are obtained most frequently as beams, and it is very difficult to combine them into a bound state (Poth, 1986; Neumann, 1987; Humbertson and Armour, 1988). The difficulty arises because the system must somehow lose excess energy. One way to do this would be radiative recombination, in which the excess energy is emitted in the form of a photon or many photons. However, the cross-section for that process is extremely small, according to theory. It will be much more efficient to have a third body to carry off the excess energy, as is well known from the recombination between an electron and a positive ion, which is often studied in the laboratory. If we are to produce an antihydrogen atom, an ideal third body should include neither an electron nor a proton, which must be kept away from a positron or an antiproton for a period sufficient to prevent annihilation. Obviously, there is no such third body. As another candidate, one could use the process in which an antiproton collides with a positronium and an antihydrogen atom is produced, viz.,

$$\bar{p} + (e^- e^+) \rightarrow (\bar{p} e^+) + e^-. \qquad (1)$$

This process is certainly exothermic and should have an appreciable cross-section at low energies, according to theory (Humbertson *et al.*, 1987; Darewych, 1987; Nahar and Wadehra, 1988; Ermolaev *et al.*, 1988; Ermolaev, 1989). Within the CPT invariance, the cross-section for process (1) should be the same as for

$$p + (e^- e^+) \rightarrow (p e^-) + e^+, \qquad (2)$$

a process that is much easier to study in experiment. A beam of positronium atoms may be produced at an appreciable intensity by injecting low-energy positrons into helium or other gases (Humbertson and Armour, 1988).

A potentially effective method is to use a trap, by arranging a suitable electric and magnetic field (the trap), in which a low-energy particle can be caught. A great deal of work has been done on traps for electrons and ions, and one for antiprotons has been realized by Gabrielse *et al.* (1986). One might also put a positron in the same trap and let it combine with the antiproton to form an antihydrogen atom (Gabrielse *et al.*, 1988).

3. COLLISIONS OF ANTIPROTONS WITH ATOMS AT HIGH ENERGIES

Antiproton beams are initally obained at high kinetic energies because most of the antiproton formation reactions are efficient at energies above a few tens of GeV. In the LEAR, the antiprotons are decelerated to much lower energies and then stored. Thus, antiproton beams of MeV kinetic energies or even lower have been obtained. Let us consider how antiprotons of these energies slow down in matter.

It is appropriate to treat most of the collisions at high energies by using the first-order Born approximation, in which we regard the interactions between the incident particle and an atom or molecule as a weak perturbation and apply the first-order perturbation theory (Bethe, 1930). Indeed, work has been done for many years on collisions of protons with atoms and molecules. As a result, we have learned that the first-order Born approximation provides a generally correct picture for most high-energy collisions (Inokuti, 1971). More precisely, for those collisions that occur at large impact parameters, much larger than the size of the target atom or a molecule, the first-order Born approximation is adequate.

In the language of quantum mechanics, for collisions that result in small-angle scattering, we can describe the motion of the incident particle by a plane wave and obtain reasonable results. Indeed, collisions that satisfy such a condition are predominant at high energies, and therefore the total cross-section for a collision at high energy can be approximated by the first-order Born approximation. In this approximation the scattering amplitude for every process is proportional to z, where z is the charge of the incident particle. As a result, every cross-section is proportional to z^2. This is one of the important results of the theory of Bethe (1930). As a consequence, the cross-sections for a given target are the same for a proton and an antiproton at the same energy. Further, any material will have the same stopping power for a proton and an antiproton at the same energy.

For collisions that involve small impact parameters (and often result in large scattering angles), the first-order Born approximation may not be adequate. When these collisions make appreciable contributions, cross-sections for antiprotons and those for protons may be different at the same energy. This difference should be observable even at high energies in specially selected processes. Exactly this kind of observation was made in the experiment by Andersen *et al.* (1987). They used antiprotons and protons from LEAR and studied the ionization of helium, neon, and argon atoms. Ionization is a process in which one or more electrons are ejected from an atom. For one-electron ionization, no significant difference between antiprotons and protons was found at energies between 0.5 and 4.2 MeV. With smaller probability, two-electron ionization occurs. The probability of this process is very much different for antiprotons and protons. For instance, when the target is helium, antiprotons cause double ionization (two-electron

ejection) at about twice the probability for protons of the same energy.

One way to consider departures from the first-order Born approximation is to consider the interactions between the incident particle and the target atom up to the second-order perturbation. The resulting scattering amplitude is of the form $zA_1 + z^2A_2$. Here A_1 is the first-order Born contribution, and A_2 is the second-order Born contribution. The cross-section, then, is of the form $z^2|A_1|^2 + z^3(A_1^*A_2 + A_2^*A_1) + \cdots$ Consequently, the expression for the stopping power will have a term proportional to z^2 (the Bethe term) plus a new term proportional to z^3. We call this term the Barkas term. Work on this subject was pioneered by Barkas *et al.* (1963), who found that π^+ and π^- have slightly different ranges in matter at the same kinetic energy. More precisely, the negative particle had a range in a nuclear emulsion about 4% greater than did the positive particle at $\beta = 0.1$–0.2. (See Heckman, 1970 for a historical account.) This implies that the stopping power of the nuclear emulsion is smaller by about 1% for the negative particle. Usually this is interpreted in the following way. Both negative particles and positive particles traversing matter cause electric polarization of electrons, but in opposite directions. Negative particles repel electrons, and therefore shift the mean position of the electrons away, thus reducing the mean energy transfer to the electrons, compared to that in the absence of the polarization. Positive particles attract electrons, and therefore shift the mean position of the electrons closer, thus increasing the mean energy transfer to the electrons, compared to that in the absence of the polarization. For a survey of recent studies on the Barkas term, see Lindhard (1976) concerning theory and Andersen (1985) concerning experiment. It will be illuminating to measure the stopping power of the same material for antiprotons and protons over a wide range of energies. The resulting data will be crucial to the study of the Barkas term.

More generally, comparisons between antiprotons and protons in their collisions with atoms and molecules will provide excellent guidance for collision theory. This is similar to the great advantage of comparing electrons and positrons in their collisions with atoms and molecules (Humbertson and Armour, 1988). A summary of current and planned experiments at CERN is given by Elsener (1989).

Some special effects in antiproton collisions will be found in the energy distribution and angular distribution of secondary electrons. So far, protons and other positive ions have been used for the study of secondary-electron distributions. Although there have been studies on the incidence of electrons, there have been very few measurements on secondary electrons resulting from negative heavy particles. It is not easy to use π^- or μ^- for measurements because they are unstable. Negative atomic ions such as H^- have been used, but their collisions are more complicated because of their loose electronic structure. By contrast, antiprotons will provide an important example of negative heavy ions without electronic structure.

Recall the phenomenon called *capture into continuum* that is related to ionization by protons and other positive ions (Salin, 1969; Macek, 1970). The term *capture into continuum* refers to the process in which secondary electrons are generated with about the same velocity vector as the incident positive particle. In other words, the incident positive particle drags some of the electrons along by its Coulomb attractive forces. The same phenomenon also occurs in the traversal of positive particles in solids. Electrons thus generated in solids at velocities comparable to that of the incident charged particle are called *convoy electrons.*

Now, the incidence of a negative particle such as an antiproton results in Coulomb repulsion between the negative particle and the electrons. Therefore, the number of electrons that have velocity vectors comparable to that of the incident negative particle should be depressed. We may call this effect the *exclusion of electrons in the forward direction.* This will be seen as dips in the energy distribution and angular distribution of secondary electrons. Briggs (1986) and Brauner and Briggs (1986) carried out calculations and discussed the shape and the magnitude of the dips that arise in this way for electrons. Studying these dips will be more straightforward with antiprotons rather than electrons, because antiprotons are heavy and generally have smaller deflection angles. Fainstein *et al.* (1988) present a prediction about the dip for antiproton collisions with helium.

Upon incidence of positive particles, another phenomenon occurs even more frequently than capture to continuum. This phenomenon is referred to as the *production of saddle point electrons* (Meckbach *et al.*, 1986; Gay *et al.*, 1988; Irby *et al.*, 1988). In this phenomenon, an electron from either the target or the projectile may stay around a saddle point of the two-center attractive Coulomb potential arising from the incident positive particle and the target ion core. These electrons are observable in experiments at some angles (such as 10°) from the incident direction, with velociy v_e of the order of 0.2–0.5 of the incident particle velocity v. A simple expression for the ratio is $v_e/v = 1/[1 + (z/z_c)^{1/2}]$, where the particle charge is z and the ion core charge is z_c (Irby *et al.*, 1988). This phenomenon should be absent for negative incident particles (Olson and Gay, 1988). It will be desirable to verify this by using antiprotons.

What we have discussed above is only a small part of the rich physics expected to be found in the ejection of secondary electrons. It should be emphasized that our knowledge of secondary-electron production by negative particles is poor, apart from the case of incident electrons. So far we have discussed individual collisions. We could also discuss consequences of the many collisions accompanying the passage of

negative particles through matter. We expect that many ions and excited states would be produced around the track of negative particles, just as for positive particles. But, in what way would the yield of ions and excited states be different? In what way would the yield of secondary electrons depend on the particle sign? These questions are important for considering the effects of radiation. For instance, it would be interesting to learn how antiprotons and protons differ in biological actions and also in track formation in nuclear emulsions. In this context, there has been only one experimental report by Sullivan (1985), who determined the dose–depth curve for antiprotons in polyethylene. According to this report, an antiproton near the end of the range delivers to the material a considerably higher density of energy than a proton. The discussion of the following section will be pertinent to this result, and to other aspects of low-energy interactions.

Measurements on the stopping-power difference between protons and antiprotons of the same energy have been recently reported by Andersen *et al.* (1989) and by Gabrielse *et al.* (1989).

4. LOW-ENERGY COLLISIONS WITH ATOMS

Once an antiproton slows down in matter and attains a kinetic energy of tens of keV, it behaves differently from a proton. Towards the end of the track, protons and antiprotons will exhibit completely different phenomena. This is because at those kinetic energies the speed of an antiproton or a proton is comparable to the orbital-electron speed in an outer shell of an atom or molecule, or perhaps even lower. Here, we must first consider the incident particle and the ion core of an atom or molecule as fixed and discuss how the outer electrons move. As a first approximation, we determine electronic wave functions in the field of the particle and the ion core at rest, and then take into account how the electronic motion might or might not follow changes in the distance between the incident particle and the ion core. The basic concept here is the adiabatic potential that governs the relative motion of the particle and the ion core at near-zero speed. The correctness of this approach has been amply shown throughout the long history of the study on collisions between a positive particle and an atom or a molecule (Fano and Lichten, 1965; Barat, 1986; Harel and Salin, 1988).

For consideration of the behavior of antiprotons at low energies in matter, an excellent model exists in the classic paper by Fermi and Teller (1947), who discussed the behavior of slow pions and muons. Antiprotons and negative pions and negative muons are heavy particles, much heavier than electrons, and therefore similar in their behavior. Fermi and Teller presented extensive and imaginative considerations on π^- and μ^- in a variety of substances and determined the time required for π^- and μ^- to stop completely in matter. They concluded that the time will be about 10^{-13} s in solids and liquids, and about 10^{-9} s in air. These times are much shorter than the mean lifetime of π^- (2.8×10^{-8} s) and mean lifetime of μ^-(2.2×10^{-6} s). Therefore, in ordinary substances, π^- and μ^- first completely stop and then decay.

The mesons thus completely stopped will eventually be captured by one of the nuclei in matter. This bound state is generally referred to as a *mesic atom*. Its presence is detected by analyzing X-rays resulting from transitions between bound states.

An early paper by Wightman (1950) includes discussion not only of π^- and μ^- but also of antiprotons. While Fermi and Teller discussed various substances, Wightman discussed only hydrogen (both atomic and molecular) in great detail. He treated as particles π^- and μ^- and "hypothetical particles of 1000 m and 1837 m". Surprisingly, this paper was published five years before the experimental detection of antiprotons. He concluded that it takes about 2.4×10^{-10} s for an antiproton of intial energy 10 MeV to be stopped completely in liquid hydrogen. This time is shorter than the corresponding times for negative mesons.

A great deal can be learned from Fermi and Teller and also from Wightman. An important point is that when a negative particle approaches a hydrogen atom up to a particular distance, the electron that was originally in the hydrogen atom must move into a continuum state. This is best understood by looking at the adiabatic potential of the system consisting of the negative particle and a hydrogen atom (Fig. 1). Wightman indeed calculated the adiabatic potential for the ground state. Recently, Kimura and Inokuti (1988) have calculated the adiabatic potentials for the ground state as well as for low-lying excited states.

In the ground state, when the distance between a negative particle and the hydrogen nucleus (a proton) becomes 0.639 a.u., then the adiabatic potential becomes zero, as was first stated by Fermi and Teller. At internuclear distances greater than this value, the electron avoids the negative particle and goes behind the proton but still manages to form a bound state. When the distance is shorter than this value, the electron tries to stay behind the proton, but the localization requires a higher kinetic energy. As a result it is impossible to maintain a bound state. Thus, the electron must come out with approximately zero energy. In other words, the electron will ooze out, leaving behind the negative particle and the proton, which will eventually form a bound state. This is nothing but an antiprotonic atom. A detailed analysis of this process in hydrogen, which leads to the formation of protonium ($p\bar{p}$) is given by Cohen (1987).

The same physics that we discussed (the disappearance of the electron bound state within a certain

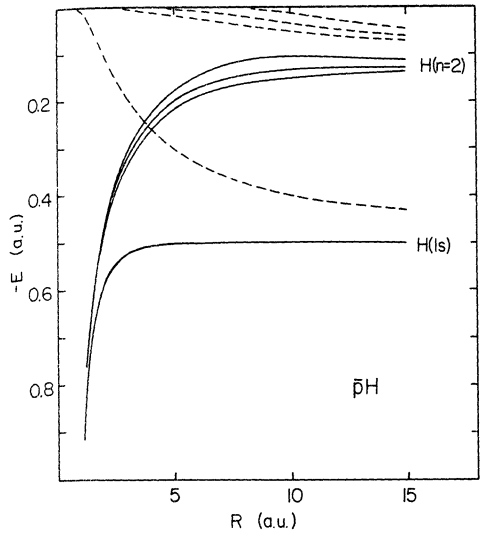

FIG. 1. Adiabatic potentials for an antiproton approaching a hydrogen atom. The horizontal axis represents the distance R between the antiproton and the hydrogen nucleus, measured in atomic units, $\hbar^2/m_e e^2 = 0.529 \times 10^{-8}$ cm. The vertical axis represents energy measured in atomic units, $m_e e^4/\hbar^2 = 27.2$ eV. The broken curve shows the pure electronic energy. The solid curve shows the adiabatic potential, the sum of the electronic energy and the attractive Coulomb potential between the antiproton and the hydrogen nucleus. Note that the adiabatic potential is attractive in general. For every state, the electronic energy reaches zero at a finite value of R. At shorter distances, a bound state cannot be maintained, and the electron goes to the continuum, i.e. it oozes out. This figure is reproduced, with the publisher's permission, from Kimura and Inokuti (1988).

distance) is also relevant in the context of the scattering of an electron with a polar molecule such as lithium fluoride or water. If the electric dipole moment is sufficiently large, there is a bound state. If the moment is smaller than a value called the *critical dipole moment*, there is no bound state. Turner (1977) discussed in detail the history of the study of this problem. According to Turner's account, Fermi and Teller gave this value as 0.639, which was obtained by Fermi after detailed analysis and numerical calculations repeated over a long period of time. However, the paper of Fermi and Teller contains no discussion of the derivation of this value.

The adiabatic potentials for the system consisting of an antiproton and a helium atom are given in Fig. 2. As the internuclear distance approaches zero, the electronic structure in the ground state converges to that of the negative hydrogen ion, H^-. Nevertheless, the pure electronic energy (shown by the broken curve) for the ground state crosses with the continuum $e + He^+$. The pure electronic energy for any excited state eventually reaches the zero value and emerges into the continuum at a particular value of the internuclear distance. This situation is qualitatively similar to the interaction of an antiproton with any atom.

In summary, when an antiproton approaches an atom, a polarization attraction occurs at very large distances, just as when a proton approaches. This polarization force is given by a potential of the form $-\alpha e^4/2R^4$, where α represents the dipole polarizability of the atom and R represents the distance. At shorter distances the adiabatic potential curves will show different behavior depending upon the symmetry of the electronic orbital. Eventually the Coulomb attraction between the antiproton and the nucleus will become dominant at short distances. Then electrons act to screen a part of the Coulomb interaction. At distances shorter than a critical value, at least one of the electrons will no longer remain bound. In higher excited states, electrons are even more prone to leave. Thus, the approach of an antiproton will probably induce one electron or more to ooze out from the atom. The probability is understandably large for two-electron ejection from helium by the antiproton, as was observed by Andersen *et al.* (1987). In their experiment, the antiproton had kinetic energies higher than 1 MeV and was therefore quite fast. Nevertheless, some of the antiprotons should have arrived with small impact parameters and thus should have approached the nucleus sufficiently closely. Then the mechanism of ionization as described above would have been operative. Of course, this is an effect specific to a negative incident particle that cannot happen with proton incidence.

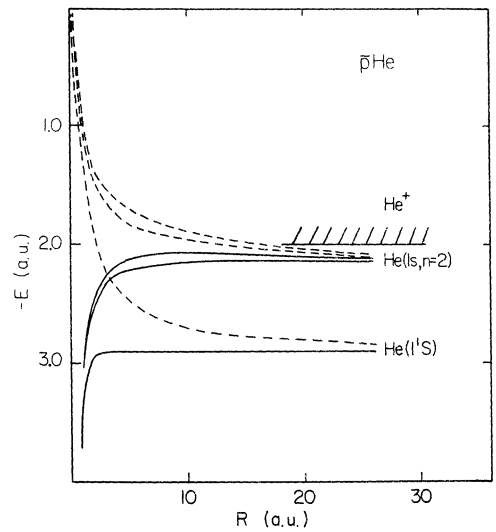

FIG. 2. Adiabatic potentials for an antiproton approaching a helium atom. The horizontal axis represents the distance between the antiproton and the helium atom, and the vertical axis the energy, both measured in atomic units as in Fig. 1. The broken curve shows the pure electronic energy, and the solid curve the adiabatic potential, the sum of the electronic energy and the attractive Coulomb potential between the antiproton and the helium nucleus. In the ground state, the electronic energy remains negative at all values of R. (At $R \to 0$, the electronic state approaches that of the hydrogen negative ion H^-, which is bound.) For any excited state, the electronic energy reaches zero at a finite value of R; this behavior is similar to that in the system of an antiproton plus a hydrogen atom shown in Fig. 1. This figure is reproduced, with the publisher's permission, from Kimura and Inokuti (1988).

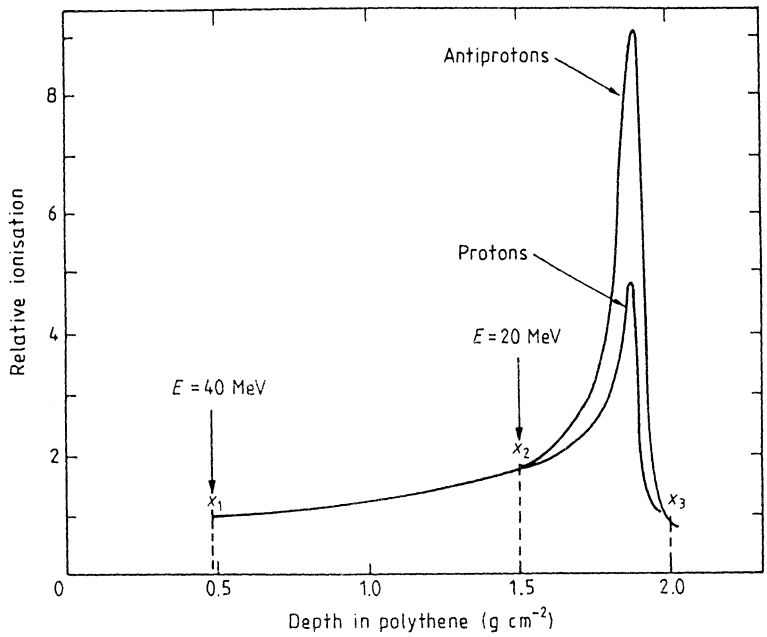

FIG. 3. The ionization by protons and antiprotons at different depths in polyethylene, reproduced with permission from Sullivan (1985).

This conclusion is consistent also with the results of Ermolaev (1988, 1989), who carried out calculations from points of view different from the adiabatic potential.

The multiple ionization upon the formation of antiprotonic atoms, at least at the outset, should happen equally in condensed phases. Evidence for this expectation is seen in the dose–depth curve reported by Sullivan (1985), and reproduced here as Fig. 3. Antiprotons of energies below 20 MeV cause far greater ionization in polyethylene than protons of the same energies. Eventually, some of the electrons will recombine with ions, releasing some excess energy. A part of the excess energy will be dissipated as heat, but a part of it is likely to cause a permanent change in the material structure. This process provides a novel mechanism of radiation effects.

Antiprotonic atoms (bound states of an antiproton around a nucleus) have been detected. Bacher *et al.* (1987a, b) have analyzed X-rays emitted near the end of an antiproton track in the gases neon, argon, and krypton (see also Bacher, 1987). The X-rays show a regular line structure like a Balmer series (Fig. 4). These lines represent transitions from a state with principal quantum number n to another with $n-1$, and are easily identifiable. Here the value of n is between 7 and 30. What is really remarkable in the spectra is that one or two lines at particular values of n are extremely weak or of almost vanishing intensity. These arise for the following reason. If an antiproton goes into an orbit of particular n, then its energy is comparable to the binding energy of an electron in a particular electron shell. As a result, interactions between the antiproton and electrons in the shell become particularly strong, and the electrons become ionized. In the beginning of this stage at least, the mechanism of ionization discovered by Fermi and Teller will operate. At later stages of electron ejection, the mechanism will be similar to the well-known Auger effect.

5. ANNIHILATION OF ANTIPROTONS AND CONSEQUENCES

A positron and an electron annihilate and give rise to two or more photons. When a proton and an antiproton annihilate, the probability of photoemission is quite small. A dominant process upon antiproton annihilation is the production of π^-, π^+, and π^0. This is easily understandable from the quark structure. In other words, a proton is a bound state uud, and an antiproton is a bound state $\bar{u}\bar{u}\bar{d}$, where u represents an up quark and d represents a down quark. The bar indicates an antiquark. When an antiproton and a proton combine to annihilate, a rearrangement of quarks occurs to give rise to $u\bar{d}$, $\bar{u}u$, and $\bar{d}u$, which will be observed as π^-, π^0, and π^+, respectively. Among the three pions, π^0, which is $\bar{u}u$, has a short lifetime of 0.8×10^{-16} s and decays predominantly into two photons. By contrast, π^+ and π^- have a much longer mean lifetime of 2.6×10^{-8} s. The number of pions actually produced has a distribution, according to experiment (Baltay *et al.*, 1966), and the mean number is about four. The reason can be understood from kinematics. The process leading to three pions is the most straightforward, but is subject to stringent kinematic restrictions on the motion of six quarks. Processes leading to the production of more than four pions certainly involve

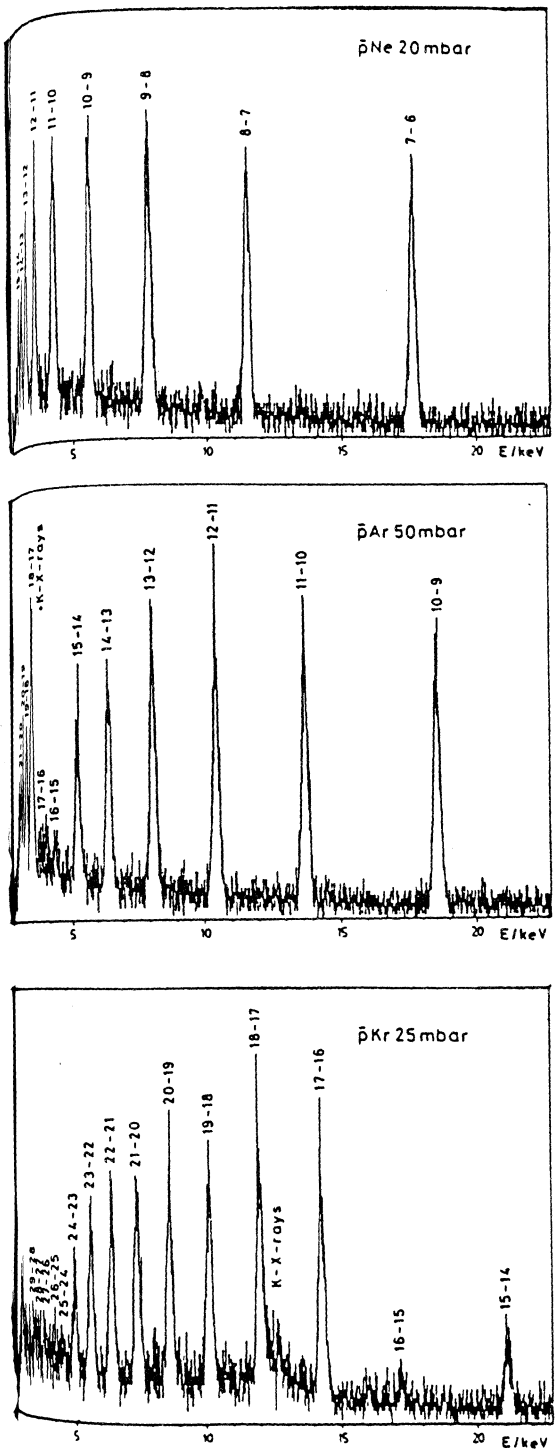

FIG. 4. X-ray emission spectra of antiprotonic atoms, reproduced with permission from Bacher *et al.* (1987a). The three panels show p̄Ne, p̄Ar, and p̄Kr, from top to bottom. The numeral above each line shows the principal quantum number n involved in the transition. According to Bacher *et al.* (1987a), the yields of all lines from $n = 15 \rightarrow 14$ to $n = 7 \rightarrow 6$ in p̄Ne are about the same after correction for the detection efficiency. In p̄Ar, the intensities for $n = 17 \rightarrow 16$ and $n = 16 \rightarrow 15$ are extremely weak. Energies of the states with $n = 15$–17 are very close to that of the electronic K line of Ar. In p̄Kr, the intensities for $n = 28 \rightarrow 27, \ldots,$ $n = 25 \rightarrow 24$ are weak. Energies of the states with $n = 25, \ldots, 28$ are close to those of electonic L lines of Kr.

production of quark–antiquark pairs, and this means increased degrees of freedom. In other words, the volume of the phase space appropriate for such processes is much greater.

When an antiproton and a proton annihilate at rest, energy is released of about $2M_p c^2 = 1.88$ GeV. If four pions were generated, there would be a total of $4M_\pi c^2 = 0.64$ GeV rest energy. This means that a total of 1.24 GeV kinetic energy is shared by the four pions. This corresponds to about 300 MeV per pion. Charged pions $\pi^\pm$ having this much energy will have ranges of many tens of centimeters in water or human tissue. Two γ-ray photons resulting from the decay of π^0 also propagate very far in water and other materials. The antiproton can also annihilate by combining with a neutron in a nucleus. Again, the decay products are mostly high-energy pions. Consequently, most of the energy obtained by the annihilation of antiprotons will be deposited in a very wide region.

This situation is different from the π^- absorption in the nucleus. When π^- is absorbed in the nucleus, the result is the production of many low-energy fragments, in which most of the pion rest mass is converted to kinetic energies. This is called a *star phenomenon*, in which the released energy is deposited in quite a small volume of the material. This is the rationale for using π^- for cancer therapy. When an antiproton annihilates with a proton or neutron in the nucleus, several nucleons may be ejected from the nucleus. However, the likelihood that the whole nucleus will be fragmented into small particles, each having very low energy, is remote, according to recent observations (Cugnon, 1988; Smith, 1988).

Proposals have been made for the potential use of antiprotons in medical therapy and imaging (Gray and Kalogeropoulos, 1982; Gray and Kalogeropoulos, 1984; Kalogeropoulos and Muratore, 1989). However, measurements by Sullivan (1985) show that only a small fraction (less than 30 MeV) of the energy is deposited in the vicinity of the end of the antiproton track in tissue-like materials. Consequently, antiprotons are unlikely to offer a great advantage in radiotherapeutic uses.

6. CONDENSED MATTER

We all know about channeling of protons and other positive particles. As many studies have shown, a positive particle incident at a particular angle with respect to a crystal plane of a metallic single crystal may travel through the neighborhood of a potential minimum of the lattice of positive ions, thus reducing encounters with electrons. A particle traveling in this way will lose much less energy to electrons and go much farther than the normal range. This phenomenon, *channeling*, has many applications, including the probing of the electronic structure of certain crystals.

Do antiprotons channel at all? The picture of channeling as sketched above will not apply to negative particles. There have been only a few reports on channeling of negative particles other than electrons. Electrons have small masses and therefore have notable wave mechanical effects, such as diffraction; therefore, the phenomenon of so-called *electron channeling* is more complicated than the picture presented above. One example of negative heavy particle channeling has been reported by Braid *et al.* (1979). According to them, π^- at energies 17.5 MeV and 255 MeV have been observed to channel through a silicon crystal. However, the situation is quite different for π^- and π^+ at comparable energies. According to the interpretation by the authors, π^- spiral around a linear arrangement of positive ions. Braid *et al.* (1979) call this *axial channeling*. Channeling of this kind might well happen with antiprotons. So far no experiment on this phenomenon has been reported.

Let us consider the behavior of antiprotons that have completely stopped in a crystal. They will eventually form an antiprotonic atom, as I discussed before in connection with experiments in gases. It is interesting to consider whether an antiproton could, under certain circumstances, avoid forming an antiprotonic atom and live a long time before annihilation. For this purpose an antiproton must stay out of any nucleus and must be located at a stable position somewhere in the lattice. One possibility might be the site at which a negative ion of valence one would ordinarily be present. If an antiproton somehow succeeds in substituting for a negative ion in the lattice at such a site, it might stay there for some time. (As a qualification of this idea, we should note a difference between a negative atomic ion and an antiproton in the lattice site. The stability of the negative atomic ion arises in part from the exchange repulsion between the ion and those ions forming the lattice. For the antiproton there is no corresponding effect.) If such a trap can be realized, and if a suitable detection method can be conceived, then we shall be in a position to study condensed matter physics from a new angle.

Falling short of that, we might still do some solid-state physics or structure determination by observing the mode of decay of antiprotons in solids. When an excess electron enters liquid water, with a high probability it forms a hydrated electron, a species that plays a crucial role in radiation chemistry (Hart and Anbar, 1970). Could an antiproton also hydrate? An antiproton in liquid water may quickly form an antiprotonic atom with one of the oxygen nuclei. In that case, there would be no time to form a hydrated antiproton. If a hydrated antiproton is possible, then there is a serious question about how to detect it. A hydrated electron has a strong absorption spectrum in the visible region and is easily observed. The corresponding spectrum of a hydrated antiproton will be in the microwave region and will be very hard to observe because of the strong absorption by water itself.

I have discussed a variety of problems concerning antiprotons and chemical and solid-state physics. Some of our cases are quite speculative because of the novelty of the subject. However, even within my limited imagination there are many interesting problems to consider and to study. I hope that some readers will share my interest and will find this area of study rewarding and promising.

Acknowledgements—I thank many friends who have generously given me valuable information and ideas while I conceived the content of the present article. They are K. Elsener, U. Fano, T. J. Gay, M. Kimura, K. Kowari, H. J. Lipkin, W. Raith, A. I. Sanda, and A. H. Sullivan. It is a great pleasure to dedicate this essay to Robert Katz. During our acquaintance of well over two decades, he has impressed me with persistent enthusiasm for better understanding of track structures and other topics in radiation biophysics, and with incisive remarks on those topics and on others such as haute cuisine. I sincerely hope that he will accept the present article as an expression of my appreciation of the great intellectual stimulus that he has given me.

REFERENCES

Andersen H. H. (1985) The Barkas effect and other higher-order Z_1-contributions to the stopping power. In *Semiclassical Descriptions of Atomic and Nuclear Collisions* (Edited by Bang J. and deBoer J.), pp. 409–430. Elsevier Science, Amsterdam.

Andersen L. H., Hvelplund P., Knudsen H., Møller S. P., Pedersen J. O. P., Uggerhøj E., Elsener K. and Morenzoni E. (1989) Measurement of the Z_1^3 contribution to the stopping power using MeV protons and antiprotons: The Barkas effect. *Phys. Rev. Lett.* **62**, 1731–1734.

Andersen L. H., Hvelplund P., Knudsen H., Møller S. P., Sørensen A. H., Elsener K., Rensfelt K.-G. and Uggerhøj E. (1987) Multiple ionization of He, Ne, and Ar by fast protons and antiprotons. *Phys. Rev. A* **36**, 3612–3629.

Bacher R. (1987) Der Ionisierungsgrad isolierter exotischer Atome. Ph.D. Dissertation, Universität Karlsruhe.

Bacher R., Blüm P., Elsener K., Gotta D., Heitlinger K., Schneider M. and Simons L. M. (1987a) On the production of highly ionized antiprotonic noble gas atoms at rest. In *Fundamental Symmetries* (Edited by Bloch P., Pavlopoulos P. and Klapisch R.), pp. 115–119. Plenum, New York.

Bacher R., Blüm P., Egger J., Elsener K., Gotta D., Heitlinger K., Kunold W., Rohman D., Schneider M. and Simons L. M. (1987b) Measurement of the antiprotonic Lyman and Balmer X-rays of $\bar{p}H$ and $\bar{p}D$ atoms at very low target pressures. In *Fundamental Symmetries* (Edited by Bloch P., Pavlopoulos P. and Klapisch R.), pp. 125–130. Plenum, New York.

Baltay C., Franzini P., Lütjens G., Severiens J. C., Tycko D. and Zanello D. (1966) Annihilations of antiprotons at rest in hydrogen. V. Multiple annihilations. *Phys. Rev.* **145**, 1103–1111.

Barat M. (1986) Electron capture in ion–atom and ion–ion collisions. In *Atomic Processes in Elecron–Ion and Ion–Ion Collisions* (Edited by Brouillard F.), pp. 271–311. Plenum, New York.

Barkas W. H., Dyer J. N. and Heckman H. H. (1963) Resolution of the Σ^--mass anomaly. *Phys. Rev. Lett.* **11**, 26–28.

Bethe H. (1930) Zur Durchgang geladener Teilchen durch Materie. *Ann. Phys.* **5**,325–400.

Bloch P., Pavlopoulos P. and Klapisch R. (eds) (1987) *Fundamental Symmetries*. Plenum, New York.

Braid T. H., Gemmell D. S., Holland R. E., Pietsch W. J., Ratkowski A. J., Schiffer J. P., Wanger T. P., Worthington J. N., Zeidman B., Morris C. L. and Thiessen H. A. (1979) Channeling of positive and negative pions in a silicon stack. *Phys. Rev. B* **19,** 130–134.

Brauner M. and Briggs J. S. (1986) Ionisation to the projectile continuum by positron and electron collisions with neutral atoms. *J. Phys. B* **19,** L325–L330.

Briggs J. S. (1986) Critical second-order scattering in three-body rearrangement and break-up processes. *J. Phys. B* **19,** 2703–2714.

Cohen J. C. (1987) Formation of protonium in collisions of antiprotons with H and H^-. *Phys. Rev. A* **36,** 2024–2030.

Jugnon J. (1988) Antiproton–nucleus annihilation. In *The Elementary Structure of Matter* (Edited by Richard J.-M., Aslanides E. and Boccara N.), pp. 211–218. Springer, Berlin.

Darewych J. W. (1987) Formation of antihydrogen in excited states in antiproton–positronium collisions. *J. Phys. B* **20,** 5917–5924.

Elsener K. (1989) Antiproton beams for atomic collision physics. *Comments At. Mol. Phys.* **22,** 263–280.

Ermolaev A. M. (1988) Interactions between $\bar{p}$ and H at intermediate antiproton energies. In *Atomic Physics with Positrons* (Edited by Humbertson J. W. and Armour E. A. G.), pp. 393–396. Plenum, New York.

Ermolaev A. M. (1989) Theoretical cross sections for keV antiprotons. *Hyperfine Interactions* **44,** 375–386.

Ermolaev A. M., Bransden B. H. and Mandal C. R. (1988) Formation of antihydrogen and destruction of positronium in $\bar{P} + Ps$ collisions in the antiproton energy range 2–100 keV. In *Atomic Physics with Positrons* (Edited by Humbertson J. W. and Armour E. A. G.), pp. 397–401. Plenum, New York.

Fano U. and Lichten W. (1965) Interpretation of Ar^+–Ar collisions at 50 keV. *Phys. Rev. Lett.* **14,** 627–629.

Fainstein P. D., Ponce V. H. and Rivarola R. D. (1988) Ionisation of helium by antiproton and proton impact. *J. Phys. B* **21,** 2989–2998.

Fermi E. and Teller E. (1947) The capture of negative mesotrons in matter. *Phys. Rev.* **72,** 399–408.

Gabrielse G., Fei X., Helmerson K., Rolston S. R., Tjoelker R. and Trainor T. A. (1986) First capture of antiprotons in a Penning trap: a kiloelectronvolt source. *Phys. Rev. Lett.* **57,** 2504–2507.

Gabrielse G., Fei X., Orozco L. A., Tjoelker R. L., Trainor T. A., Haas J., Kalinowsky H. and Kells W. (1989) Barkas effect observed with antiprotons and protons. *Phys. Rev. A* **40,** 481–484.

Gabrielse G., Rolston S. L., Haarsma L. and Kells W. (1988) Antihydrogen production using trapped plasmas. *Phys. Lett.* **129,** 38–42.

Gay T. J., Berry H. G., Hale E. B., Irby V. D. and Olson R. E. (1988) "Saddle-point" ionization. *Nucl. Instrum. Meth. B* **31,** 336–341.

Gray L. and Kalogeropoulos T. E. (1982) Possible biomedical applications of antiprotons. I. *In vivo* direct density measurements: radiography. *IEEE Trans. Nucl. Sci.* **NS-29,** 1051–1057.

Gray L. and Kalogeropoulos T. E. (1984) Possible biomedical applications of antiproton beams: focused radiation transfer. *Radiat. Res.* **97,** 246–252.

Harel C. and Salin A. (1988) Theory of low energy charge transfer by multiply charged ions. In *Electronic and Atomic Collisions* (Edited by Gilbody H. B., Newell W. R., Read F. H. and Smith A. C. H.), pp. 631–624. North-Holland, Amsterdam.

Hart E. J. and Anbar M. (1970) *The Hydrated Electron*. Wiley-Interscience, New York.

Heckman H. H. (1970) Stopping-powers differences between positive and negative particles at low velocities. In *Penetration of Charged Particles in Matter: a Symposium*, pp. 41–47. National Academy of Sciences, Washington, D.C.

Humbertson J. W. and Armour E. A. G. (eds) (1988) *Atomic Physics with Positrons*. Plenum, New York.

Humbertson J. W., Charlton M., Jacobsen F. M. and Deutch B. I. (1987) On antihydrogen formation in collisions of antiprotons with positronium. *J. Phys. B* **20,** L25–L29.

Inokuti M. (1971) Inelastic collisions of fast charged particles with atoms and molecules—the Bethe theory revisited. *Rev. Mod. Phys.* **43,** 297–347.

Irby V. D., Gay T. J., Edwards J. Wm., Hales E. B., McKenzie M. L. and Olson R. E. (1988) Projectile-charge dependence of ejected-electron spectra. *Phys. Rev. A* **37,** 3612–3614.

Kalogeropoulos T. E. and Muratore R. (1989) Antiprotons for imaging and therapy. *Nucl. Instrum. Meth. B* **40/41,** 1322–1325.

Kimura M. and Inokuti M. (1988) Characteristics of close collisions of an antiproton with atoms. *Phys. Rev. A* **38,** 3801–3803.

Lindhard J. (1976) The Barkas effect—or Z_1^3, Z_1^4-corrections to stopping of swift charged particles. *Nucl. Instrum. Meth.* **132,** 1–5.

Macek J. (1970) Theory of the forward peak in the angular distribution of electrons ejected by fast particles. *Phys. Rev. A* **1,** 235–241.

Meckbach W., Focke P. J., Goñi A. R., Suárez S., Macek J. and Menendez M. G. (1986) Effects of the Wannier ridge on secondary-electron spectra in proton–helium collisions. *Phys. Rev. Lett.* **57,** 1587–1590.

Nahar S. and Wadehra (1988) Formation of ground and excited states of antihydrogen. *Phys. Rev. A* **37,** 4118–4124.

Neumann R. (1987) Possible experiments with antihydrogen. In *Fundamental Symmetries* (Edited by Bloch P., Pavlopoulos P. and Klapisch R.), pp. 95–130. Plenum, New York.

Olson R. E. and Gay T. J. (1988) Dynamics of antimatter–atom collisions. *Phys. Rev. Lett.* **61,** 302–305.

Poth H. (1986) Antiprotonic, hyperonic, and antihydrogenic atoms. In *Proceedings of the First Workshop on Antimatter Physics at Low Energy*, Fermilab, 10–12 April, pp. 325–345. Fermi National Accelerator Laboratory, Batavia, Illinois.

Salin A. (1969) Ionization of atomic hydrogen by proton impact. *J. Phys. B* **2,** 631–639.

Smith G. A. (1988) Search for unusual behavior in $\bar{p}$-nucleus annihilation at rest. In *The Elementary Structure of Matter* (Edited by Richard J.-M., Aslanides E. and Boccara N.), pp. 219–224. Springer, Berlin.

Sullivan A. H. (1985) A measurement of the local energy deposition by centiprotons coming to rest in tissue-like material. *Phys. Med. Biol.* **30,** 1297–1303.

Turner, J. E. (1977) Minimum dipole moment required to bind an electron—molecular theorists discover phenomenon mentioned in Fermi–Teller paper 20 years earlier. *Am. J. Phys.* **45,** 758–766.

Wightman A. S. (1950) Moderation of negative mesons in hydrogen. I. Moderation from high-energies to capture by an H_2 molecule. *Phys. Rev.* **77,** 521–528