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TOPICAL REVIEW

Recent advances in the comparison of matter– and antimatter–atom collisions

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Abstract. The relatively recent advent of low energy antimatter projectiles has spurred a rapid advance in the comparison of matter- and antimatter-atom collisions. These experimental studies have in turn stimulated a great deal of theoretical effort to explain their results, and together both theory and experiment have shed new light on the dynamics of ion–atom collisions. Here we review these developments with particular emphasis on the processes of ionization and charge transfer.

1. Introduction

It is our purpose in this topical review to outline the recent advances which have been made in the comparison of atomic collisions utilizing both matter and antimatter projectiles. That such comparisons are possible experimentally is a relatively recent development. On the other hand, access to antimatter has always been available in theory, simply by varying the sign of the charge in the calculation. However, theory too, has of late undergone a significant advance which has been in large part attributable to the strenuous new tests presented by the experimental measurements and represents an expanded view of the details of fundamental atomic collisions.

Indeed, one finds that not only are antimatter-atom collision studies interesting in and of themselves, but they also contribute to the better understanding of matter–atom collisions. This additional insight derives from the fact that antimatter–atom studies focus our attention on the underlying differences in the dynamics of the collision as well as on the partitioning of the overall scattering. Here we will concentrate on the singly charged family of projectiles 'electrons, positrons, protons and antiprotons' ($e, \bar{e}, p, \bar{p}$), which we note differ from one another in only mass and charge sign. Furthermore, our attention will also be focused on studies of ionization and charge transfer, since their recent experimental measurement has spurred a great amount of theoretical activity. We also refer the reader to a number of recent brief reviews of some of the aspects of matter-, antimatter-atom collisions provided by Inokuti (1989), Knudsen (1989), Charlton and Laricchia (1990), Schultz *et al* (1989b) and Kauppila and Stein (1989).

The discussion which follows, after a brief survey of the experimental advances which mark the advent of antimatter-atom collision studies (section 2), will be organized along the lines of the various possible reaction channels. To this end we begin, in section 3, with consideration of the total scattering cross section, and then in the next sections, 4–6, we survey ionization, charge transfer, excitation and elastic scattering. Particular emphasis is placed on interpreting the differences in these processes for matter and antimatter impact in terms of the varying collision dynamics. Finally,

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the last section is devoted to the discussion of various exotic collisions involving antimatter.

2. Antimatter projectiles for atomic physics

Prediction and observation of antimatter is a product only of the present century. In fact, the key with which the 'antiparticle' universe has been opened is Einstein's (1905, 1907) famous energy-momentum equation,

$$E^2=(pc)^2+(mc^2)^2 \tag{1}$$

which has solutions

$$E=\pm[(pc)^2+(mc^2)^2]^{1/2}. \tag{2}$$

The meaning of the negative energy states is, of course, not immediately clear, since classically such particles would represent ordinary matter which had undergone a transition to a negative energy state and emitted radiation; thus, in the classical view, if such states existed, all matter would disappear! Dirac (1930) postulated that there were actually particles which were 'holes in a negative energy sea' and corresponded to 'antiparticles'. Later, Stueckelberg (1941) and Feynman (1948) put forth the more formal proposal that antimatter consisted of particles moving backwards in time. That is, this view implies that a particle of charge q moving backwards in time behaves like a particle of charge $-q$ moving forwards in time.

The first antiparticle to be predicted, the antielectron or positron (Dirac 1928), was observed by Anderson in 1933 (Anderson 1933), but, speculations about the existence of an antiproton were not experimentally confirmed until 1955 with the initial operation of the Bevatron at Berkeley (Chamberlain *et al* 1955). Subsequently, the counterparts to almost all known subatomic particles have been identified. However, experiments involving most forms of antimatter remained the province of nuclear and elementary particles physics for many years. At present, due to the rapid technological developments of the past two decades, positron beams (section 2.1) of high intensity and low, well defined energy have become readily obtainable. In addition, low energy antiprotons (section 2.2) have been produced quite recently so that high quality beams of electrons, positrons, protons and antiprotons are currently available for atomic collision experiments. Perhaps quite soon, low energy muon beams (section 2.3) which are similarly well defined in angular and energy widths will be available as well.

2.1. Positron beam sources

Development of positron-atom collision investigations has been somewhat different in that positron sources do not require the use of large, expensive particle accelerators and can be made on a smaller scale by collecting the positrons which result from the beta decay of nuclei. Indeed, quite early Massey and Mohr (1954) noted the potential utility in using positrons in atomic collision studies, but, as Bransden (1969) pointed out, the points of contact between theory and experiment regarding positron scattering were greatly impeded by the lack of a suitable positron low energy beam source. Since that time developments in high quality positron sources have occurred and have made possible a host of experiments. These advances have been reviewed in detail by Griffith and Heyland (1978) and Charlton (1985).

In particular, what these advances entailed were ways to lower the beam energy and to make it more well defined. Groce *et al* (1968) made an important discovery that when positrons emerge from a moderator, they displayed a much lower energy and smaller energy spread than was expected. Subsequent investigations by Coleman *et al* (1973) and Canter *et al* (1974), using backscattering gold and MgO covered moderators yielded substantial fluxes of low energy monoenergetic positrons. Other relatively efficient sources were developed, for example, by Costello *et al* (1972) who produced a well defined beam by moderating positrons produced by pair production and by Stein *et al* (1974) who took advantage of the positron emitting nuclear reaction $^{11}\mathrm{B}(\mathrm{p,n})^{11}\mathrm{C}$. In the latter case, a source is created by the bombardment of a boron target by a energetic proton beam, producing $^{11}\mathrm{C}$ which then decays to $^{11}\mathrm{B}$, with a half-life of about 20 min, accompanied by the emission of a 0.97 MeV positron. The positron energy is then degraded as it escapes the outer layer of the target.

Presently, typical moderators exist which allow the production of beams of 10^4 to 10^5 positrons/s with mean energies of a few eV and energy widths of only one or two eV. The most common type of system consists, for example, of a $^{22}\mathrm{Na}$ source with a moderator of polycrystalline annealed tungsten in the form of a thin foil or series of meshes. Larger fluxes (e.g. 10^7 to 10^9 positrons/s) can be obtained either at reactor facilities or electron accelerators, but thus far no atomic scattering experiments have been reported utilizing these sources. To date, experiments using positrons for atomic collision studies have been performed to measure cross sections for total scattering (section 3), ionization (section 4), positronium formation (section 5), excitation and elastic scattering (section 6) and have been proposed for use in the formation of exotic species such as antihydrogen (section 7). In addition, outside the scope of this brief survey, positrons have been used in studies concerning the annihilation in targets of all different phases of matter. Particularly in this aspect, they have been used in condensed matter physics as a sensitive probe of electronic structure (e.g. Hautojarvi 1979, Hasiguti and Fujiwara 1979, Coleman *et al* 1982b, Jain *et al* 1985, Dorikens-Vanpraet *et al* 1989).

2.2. Antiproton beam sources

The production of large fluxes of slow antiprotons suitable for atomic collision experiments is a very recent development. The most notable source of such particles is the Low Energy Antiproton Ring (LEAR) facility at the European Organization for Nuclear Research (CERN) which has been in operation since 1983 (see Chanel *et al* 1984). The use of the facility with regard to the recent atomic scattering experiments has been described by Elsener (1989), Hvelplund (1988) and Knudsen (1989). These novel experiments require the production, accumulation, cooling and delivery of antiprotons by the complex chain of accelerators and storage rings at CERN and as such, are indebted to the advances made in particle physics technology over the past half century.

In brief, antiprotons are produced by the bombardment of a thick target by a high energy (26 GeV) proton beam from the CERN proton synchrotron. The protons collide with nuclei in the target and proton/antiproton pairs are produced, along with other particles such as nuclear fragments and mesons. The antiprotons, of kinetic energy on the order of a few GeV, emerge from the target with a wide spread of momenta and emission angles and must therefore be cooled in a series of storage rings. From the stored, cooled beam, bunches of antiprotons are peeled off into the LEAR in which they may be further decelerated and from which they may be extracted as a monoenergetic DC beam at a rate of about $10^5\ \mathrm{s}^{-1}$, with energies as low as 5.3 MeV. Subsequent experiments further moderate the beam using foil degraders, however, with the disadvantageous increase of beam divergence and energy spread.

Since 1986, a number of significant atomic collision experiments have been performed utilizing the LEAR facility and are described in some detail in subsequent sections. For example, a striking difference in the double ionization cross section for antiprotons compared with that for protons has been found (section 4.2). Also, studies comparing proton and antiproton impact regarding the single ionization process and Barkas effect (section 4.5) have been made there, and, in addition, antiprotons from LEAR may be used in the future to produce antihydrogen (section 7).

2.3. Sources of other singly charged particles

Though not within the scope of this review, some mention should be made of the progress being made in the production of slow, monoenergetic muon beams. A number of facilities which produce large fluxes of mesons (e.g. TRIUMF (Vancouver, Canada), LAMPF (Los Alamos, New Mexico), SIN (Villigen, Switzerland) and others), are actively pursuing the development of such sources for use in atomic physics. Since muons do not interact through the strong nuclear force, there is no method to produce large numbers of muons directly, but they are a prominent decay product of charged pions, which can be produced in great quantities. For example, the positive pion may decay into a positive muon and a neutrino.

Efforts to develop moderators, similar to the developments that has taken place in positron moderators, have recently been reported by Harshman and co-workers (Harshman *et al* 1987, Harshman 1988). They have observed the thermalization of hot (4.2 MeV) positive muons down to energies on the order of 10 eV or less, with energy distributions of width on the order of 5 or 10 eV at the TRIUMF facility. Great interest exists in muon collisions since they provide another particle in the discrete mass range to explore the three-body problem and because the spectroscopy of muon-substituted systems represents a fundamental test of theory. Further, the possibility of muon catalyzed fusion has continued to attract attention as a possible future energy resource.

3. Total scattering cross sections

The cross section summed over elastic and all inelastic channels is referred to as the total scattering cross section (TSCS) and consideration of this quantity allows several significant features of matter–, antimatter–atom comparisons to be illustrated. Furthermore, experiments to determine the TSCS by both electron- and positron-impact represent the most extensive experimental program of atomic scattering which exists using both matter and antimatter projectiles. The state of the art of such measurements has progressed rapidly over the past two decades and TSCS measurements have been made at a number of laboratories. These experiments and their results have been reviewed in detail by Griffith and Heyland (1978), Stein and Kauppila (1982, 1986), Charlton (1985) and Kauppila and Stein (1989).

In particular, electron and positron impact comparisons allow the separation of the effects of varying the sign of the projectile charge while keeping other collisions parameters, such as the projectile mass, constant. This change in charge sign affects not only the dynamics of the collision (i.e. repulsive interactions become attractive interactions and vice versa) but also the reaction channels which are open. For example, for positron impact, the elastic, ionization, excitation and charge transfer channels are open (annihilation is significant below about 0.5 eV). On the other hand, for the electron the possible channels are elastic, ionization and excitation, which in addition, include exchange components. At sufficiently high energies, when the probability of charge transfer and of exchange become small, the TSCSs become equal for the two particles. However, at lower velocities, the differences in the TSCSs are quite prominent due to the changing role of the open scattering channels and the different dynamics of the collision.

TSCSs have been measured for a wide variety of targets including the noble gases (He, Ne, Ar, Kr and Xe), both atomic and molecular hydrogen, non-room-temperature gases such as the alkali metals (Na and K) and a number of molecules (N_2, CO, O_2, H_2O, CO_2, N_2O, NH_3, CH_4, SiH_4, CF_4, SF_6 and various hydrocarbons). Primary references to these works may be found in the review by Kauppila and Stein (1989). Experiments have utilized a method in which the electron or positron beam attenuation is measured after its passage through a target gas region. The TSCS may then be extracted from the relation

$$I = I_0 \exp(-nQ_{\mathrm{T}}L) \tag{3}$$

where I is the detected intensity, I_0 is the incident intensity, n is the target gas number density, L is the target gas path length and Q_{T} the TSCS. To illustrate the results of these measurements we display the TSCS for He in figure 1. Apparent in this figure is the huge difference between the positron and electron impact TSCS at low energies as well as the convergence of the cross sections at higher energies. The dominance of the electron TSCS at low energies is usually explained in terms of the differences in the interactions of the two projectiles with the target atom. That is, both positrons and electrons produce a dielectric polarization of the target which results in an attractive

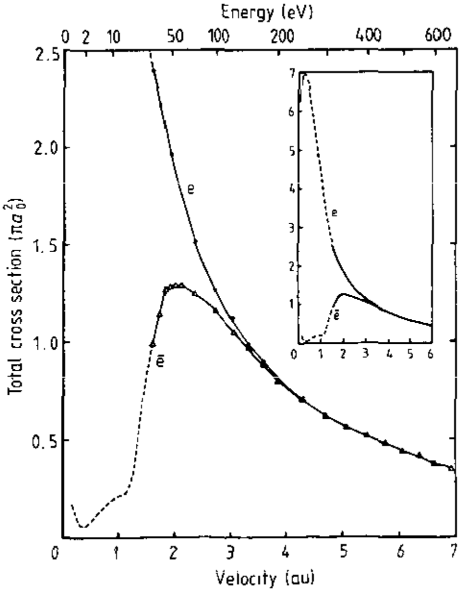

Figure 1. The total scattering cross section for electron and positron impact of helium measured by Kauppila *et al* (1981). The curves smoothly connect these experimental measurements, with those of Stein *et al* (1978), Kauppila *et al* (1977) and Milloy and Crompton (1977).

net interaction. However, the static interaction of the positron with the target is repulsive while for the electron it is attractive. Thus, these effects add for the electron but tend to cancel for the positron, lowering its relative cross section.

Also evident from the figure is the fact that for helium, the positron and electron cross sections converge near an impact energy of about 200 eV. However, the elastic cross sections are expected to differ substantially (see e.g. Dewangan and Walters 1977) to much larger energies, converging to within about 5% at 2000 eV. In fact, Campeanu *et al* (1987a) have considered in detail the partitioning of the TSCS among the various open reaction channels by studying a number of theoretical and experimental evaluations of partial cross sections. They found that the convergence of the TSCS at such a low energy results from the rather remarkable exact compensation of the partial cross sections.

The convergence of the cross sections occurs at larger energies and displays more complex behaviour for other targets, such as in the case of molecular hydrogen or xenon in which the positron TSCS rises above the electron TSCS before merging from above. In addition, for the alkalis (cf Kauppila and Stein 1989), targets of particular interest because of their pseudo-one-electron structure and the fact that due to their low ionization potentials positronium formation may occur down to arbitrarily low collision energies, the positron TSCSs exceed those of their antiparticle at low energies. These features observed experimentally present a challenge to theory in that their detailed explanation requires accurate calculation of elastic and inelastic cross sections over a wide energy range. The extant theoretical studies are described in the experimental surveys cited above and are discussed, as well, in the reviews of positron–atom and positron–molecule scattering by Ghosh *et al* (1982) and Armour (1988).

Thus, simply owing to their different charge sign, positrons and electrons manifest substantial differences in the TSCS due to the changing roles of the partial cross sections and interactions. In subsequent sections we will consider how these differences arise in the various individual open channels for positrons and electrons, as well as for protons and antiprotons.

4. Ionization

At very large impact velocities, electrons, positrons, protons and antiprotons should all be equally effective in ionizing a target atom. For example, in accordance with the Bethe–Born picture (Bethe 1930, Inokuti 1971, Inokuti *et al* 1978), the single ionization cross section should depend only on the collision velocity, v, and the square of the projectile charge, Z_p, i.e.

$$\sigma_{\text{ion}} \underset{v\to\infty}{\sim} Z_p^2 \ln(v)/v^2. \tag{4}$$

However, at lower velocities large differences exist in the ionization cross section arising from the differences in the sign of the projectile charge and projectile mass. These variations arise from changes in the collision dynamics and ionization mechanisms as well as from differences in the open reaction channels. Therefore, theoretical treatments which can account for and describe these effects must go beyond simple first-order theories such as the Born approximation. Critical tests of these ideas have recently been realized experimentally by adding to the existing proton and electron impact ionization data, corresponding measurements for positron and antiproton impact. We describe these experiments and the theoretical works which have been used to explain and predict their result by discussing the behaviour of the total cross sections for single, double and inner-shell ionization, the ejected electron spectra and, finally, the Barkas effect.

4.1. Single ionization

With the advent of the beam sources discussed above, considerable progress has been made during the 1980s in determining cross sections for some of the individual scattering channels. In particular, the single ionization of helium by positrons has been measured by Sueoka (1982), Diana *et al* (1985a) and Fromme *et al* (1986) (see figure 2). The group at the Universitat Bielefeld has also performed similar measurements for molecular hydrogen (Fromme *et al* 1988) and quite recently for atomic hydrogen (Spicher *et al* 1990). These works provide an important point of comparison with theoretical calculations of the positron impact cross section as well as with equivelocity electron impact measurements.

Figure 2(*a*) shows a comparison of the Bielefeld (Fromme *et al* 1986) measurements of single ionization for the positron impact of helium with earlier experiments and

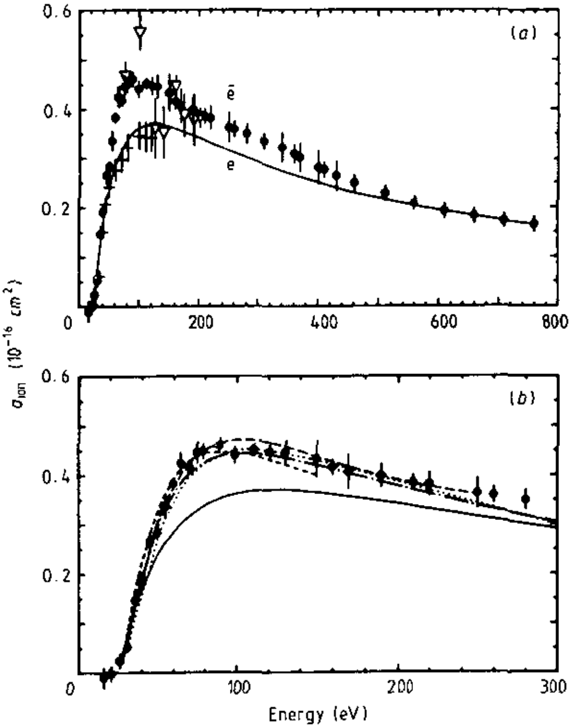

Figure 2. The total cross section for single ionization of helium by positrons and electrons. (*a*) Experimental data for positrons: Fromme *et al* (1986) (circles), Diana *et al* (1985a, b) (triangles) and Sueoka (1982) (crosses), and for electrons: Montague *et al* (1984) (full curve). (*b*) Theoretical results for positron impact: Campeanu *et al* (1987b) (long broken curve), Peach and McDowell (1986) (broken curve), Basu *et al* (1985) (short broken curve) and McGuire (1986) (dotted curve).

with a curve representing the corresponding measurements for electron impact. The Bielefeld results clearly indicate that the ionization cross section for positrons is larger than that for electrons at energies between 20 and 500 eV. Above this energy range the cross sections for these two oppositely charged particles converge, consistent with the prediction of the Born model. In contradiction to these results, the early experiment of Sueoka (1982) indicated that the cross section was slightly smaller for positron impact than for electron impact. The result of Diana *et al* (1985a), on the other hand, qualitatively agrees with the Bielefeld result, but has much larger experimental uncertainties and scatter.

In figure 2(*b*), the Bielefeld measurements are compared with the results of a number of theoretical treatments: distorted-wave Born approximations (Campeanu *et al* 1987b, Basu *et al* 1985), first Born approximation (Peach and McDowell 1986), and Glauber approximation (McGuire 1986). It should be noted that the first Born and Glauber approximations yield ionization cross sections which are identical for positrons and electrons and that the apparent agreement with experiment comes from the fact that exchange was not included. That is, the enhancement of the positron impact cross section in these models results from considering 'electron scattering without exchange.' The distorted-wave treatments, which depend on the sign of the projectile charge through the distorting potential, also agree well with the experiment and should be considered more complete models.

The enhancement of the positron impact cross section has also been found by the Bielefeld group (Fromme *et al* 1988, Spicher *et al* 1990) for molecular hydrogen in the intermediate collision velocity regime. To our knowledge, no published theoretical result exists for this system. In addition, the Bielefeld group has reported the first measurement of the positron impact ionization of atomic hydrogen (Spicher *et al* 1990). The result of this recent experiment indicates an enhancement of the positron cross section over that for equivelocity electrons, but comparison with theoretical results shows substantial disagreement. The theoretical treatments include the distorted-wave approximations of Ghosh *et al* (1985) and Mukherjee *et al* (1989) and classical trajectory Monte Carlo (CTMC) approximation (Ohsaki *et al* 1985, Wetmore and Olson 1986). The model of Mukherjee *et al* (1989) is very similar to the treatment of Campeanu *et al* (1987b) which agreed well with the positron–helium experiment. At present no explanation of the discrepancy between theory and experiment for this case has been put forth.

Measurements comparing proton and antiproton single ionization cross sections have been obtained by a group from the University of Aarhus, Denmark, with their collaborators at CERN (Andersen *et al* 1987, see also Knudsen 1989). Their measurements, in the energy range of 0.5 to 5.0 MeV, corresponding to velocities in the range of 4.5 to 14 au, indicated that the proton and antiproton impact ionization cross sections are equal within the experimental uncertainties. Thus, experiment indicates that the single ionization cross sections for all four singly charged particles (e, ē, p, p̄) converge for collision velocities greater than about 4 or 5 au.

This convergence, as well as the variations in the cross section at lower velocities, is illustrated in figure 3 where the CTMC calculations of Schultz (1989) are displayed for equivelocity protons, antiprotons, positrons and electrons colliding with helium. As this figure indicates, the detailed behaviour of the single ionization cross section is determined by an interplay of projectile mass and sign of charge effects. At the highest velocities displayed, the cross sections do indeed converge, but, upon close inspection it is seen at low velocities ($v < 3$ au), the proton and antiproton cross sections are larger than those for positron and electron impact. This effect of projectile mass

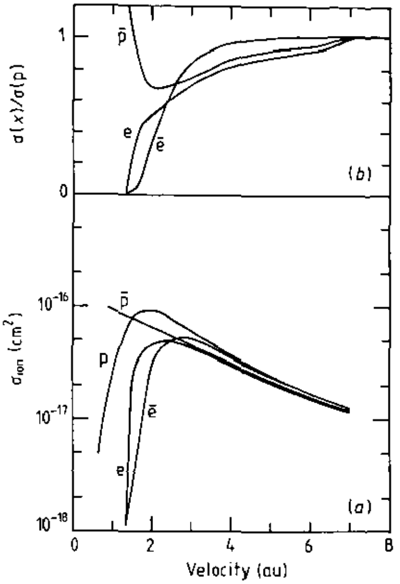

Figure 3. (*a*) The total cross section for single ionization of helium by electron, positron, proton and antiproton impact. (*b*) The cross sections relative to the proton impact cross section.

occurs because the heavier particles possess much greater energy above the ionization threshold than their lighter counterparts.

At high intermediate velocities (3 to 5 au), however, the positively charged particles are seen to have slightly larger cross sections than the negatively charged particles. This behaviour was also found by Olson (1987) utilizing a different model of the target atom within the CTMC framework and was noted, as well, by Fainstein *et al* (1987), using the continuum distorted-wave approximation to compare proton and antiproton impact of helium, and in a very recent experiment by the group working at CERN (Andersen *et al* 1990). In this case, the positively charged particles present an attractive potential which produces a region of reduced binding of the atomic electron resulting in a greater number of ionized electrons. Electrons ejected by this mechanism of force cancellation originate with velocities approximately one half of the incident velocity and have come to be called '$v/2$' or 'saddle-point' electrons (Olson 1983, 1986, 1987, Olson *et al* 1987).

At lower velocities, the effects of varying charge sign and mass produce a more complicated situation. For example, for the positively charged particles, charge transfer competes with the ionization process. Also, in slow collisions, the positively charged particle leads to intermediate over-bound states whereas the negatively charged particle produces intermediate antibound states. This molecular effect enhances the ionization probability at low velocities for the negatively charged projectiles. This has been discussed, for example, by Mehler *et al* (1987) who considered inner-shell ionization by proton- and antiproton-impact and by Kimura and Inokuti (1988) who considered protons and antiprotons interacting with atomic hydrogen and helium.

Near threshold, the theory of Wannier (1953), later extended by Vinkalns and Gailitis (1967), based on a classical picture, predicts that the ionization cross section for electron impact should behave as

$$\sigma_{\mathrm{ion}} \sim (E - E_{\mathrm{ion}})^n \qquad (5)$$

where E is the impact energy, E_{ion} the ionization threshold, and n an exponent dependent on the final state charge of the target. For the single ionization of neutral atoms this exponent takes on the value $n = 1.127$. In this three-body break-up process, since the available energy will be shared among the two electrons and since the electron–electron interaction is repulsive, they should emerge at an angle near 180° to one another, equidistant from the ionized atomic core. Quantum mechanical treatments developed by Peterkop (1971), Rau (1971), Klar (1981a) and Feagin (1984) have obtained essentially the same results. In addition, Klar (1981b) and Grujić (1982) have considered positron impact and predict that in this case $n = 2.651$. Since the positron–electron interaction is attractive rather than repulsive, the two particles should emerge with a relative angle near zero rather than 180°. The applicability and validity of the Wannier model for electron impact has been demonstrated experimentally by a number of investigators and in particular for the ionization of hydrogen (McGowan and Clarke 1968) and helium (e.g. Cvejanović and Read 1974), the K-shell ionization of Ne (Hink *et al* 1981), the K- and L-shell ionization of Ar and Xe (Hippler *et al* 1983) and even for the ejection of two electrons by photoionization of H^- (Donahue *et al* 1982) and He (Kossman *et al* 1988).

Quite recently, Knudsen *et al* (1990) have made the first experimental determination of the threshold behaviour for positron impact, measuring the ionization cross section in H_2, He and Ne from about 1 eV to 80 eV above threshold. A fit of their data indicates an exponent of approximately $n = 1.3$, much closer to the value predicted for electron impact than for positrons, implying that either the Wannier model is not applicable for positron impact, or that its range of validity does not extend to as high an energy as expected. However, it should be noted that there is not a general consensus as to what energy the threshold law should extend. That is, many of the electron impact experiments indicate that the Wannier behaviour only continues up to one or two eV above threshold. Nevertheless, there is also evidence that its range might extend to much larger energies (i.e. 10–20 eV, cf Wetmore and Olson 1986, Feagin 1984). Further, a suggestion by Grujić (1982) indicates that the region of validity for positrons should be much larger than for electrons due to the larger polarization force present when the residual core experiences the asymmetric positron–electron final state. Therefore, the result of Knudsen *et al* (1990) presents a significant challenge. Independent verification of their result is not available from the previous measurements of ionization by the Bielefeld group since the energy resolution in those experiments at low collision energy was insufficient to make a quantitative estimate of the exponent.

Thus, it has come to be recognized that a rather subtle interplay of sign of the projectile charge and mass effects leads to the relative magnitudes of the total cross sections for single ionization. These effects occur for collision velocities corresponding to the ionization threshold up to around four or five times the orbital velocities of the target electrons, after which the cross sections merge and behave in accordance with the Born approximation. However, another level of complexity arises if we consider the removal of two electrons from the target, in which case differences caused by the variation of charge sign and mass persist to even larger velocities and manifest dependence on the correlated nature of the two electrons removed.

4.2. *Double ionization*

The removal of two electrons from a target atom could proceed in a number of different ways. For example, the first to be ionized may be impulsively removed, leaving a remaining electron with some probability to be 'shaken off' since it is not in an eigenstate of the residual ion. Or perhaps the first electron may be driven into the other by the projectile, ionizing them both. Clearly, models which ignore the interaction of the electrons in the target will be unable to accurately account for double ionization and, in fact, Byron and Joachain (1966, 1967) quite early demonstrated that multiple ionization cannot be represented well by an independent electron model. Thus, double ionization by proton, antiproton, positron and electron impact poses a strenuous test of theory, requiring treatments which account for sign of the charge and mass differences and which also explicitly treat electron–electron interaction.

That a dependence on the sign of the projectile charge exists was found through the observation by Puckett and Martin (1970) of a surprising difference between the proton and electron impact double ionization of helium. They found that at collision energies greater than about 2 MeV u^{-1}, the double ionization cross section was greater by a factor of two for electrons than that for protons. This effect was later explained in terms of the interference of two scattering amplitudes which have different projectile charge dependences (McGuire 1982, 1984, 1987, McGuire and Burgdorfer 1987). In the first of these processes, called a 'two-step' mechanism, the projectile interacts once with each of the two target electrons (TS-2), with an amplitude proportional to Z_p^2. The second, having an amplitude proportional to Z_p, occurs when one electron is rapidly removed by the projectile and the second is ionized through shake off (SO). The squared sum of the two amplitudes leads to a term proportional to Z_p^3 and, consequently, the positively and negatively charged projectiles will have different cross sections.

Comparison of proton and antiproton impact double ionization allows a superior discrimination of the charge sign effect since the mass of these two projectiles is the same. In fact, observation of the electron/proton difference by the Aarhus group (Haugen *et al* 1982) was followed by their collaboration at CERN comparing proton- and antiproton–helium collisions. The result (Andersen *et al* 1986), expressed as a ratio of the double and single ionization cross sections, R, for proton and antiproton impact is displayed in figure 4. As this figure illustrates, the ratio is larger for antiprotons throughout the energy range covered by the experiment (0.5 to 5.0 MeV). Since the single ionization cross sections for protons and antiprotons in this energy range were shown to be the same to within the experimental uncertainties, the enhancement of the ratio is therefore due to an enhancement of double ionization cross section for antiproton impact. Several theoretical explanations of this result have been proposed. For example, the model explaining the electron/proton difference on the basis of the interference of SO and TS-2 amplitudes was extended (Andersen *et al* 1987) to include the TS-1 amplitude, where the first electron is driven into the second by the projectile causing double ionization.

The first full calculation to explain the enhancement was made by Reading and Ford (1987a, b) using the forced impulse model (FIM), a treatment based on the solution in the semiclassical limit of the time-dependent Schrödinger equation using the coupled-channels approach (see figure 4). They utilized a two-electron basis set constructed of s and p one-electron orbitals and have estimated, and provided confirmation (Ford and Reading 1988), that the inclusion of d orbitals accounts for about a 35% increase in the absolute magnitude of their results. This model is particularly significant in that it includes an approximate treatment of the electron–electron interaction. The FIM divides the collision into time segments short enough that the electron–electron interaction may be neglected, then, at the end of each segment, the system is allowed to settle back into a two-electron eigenstate by turning on this interaction.

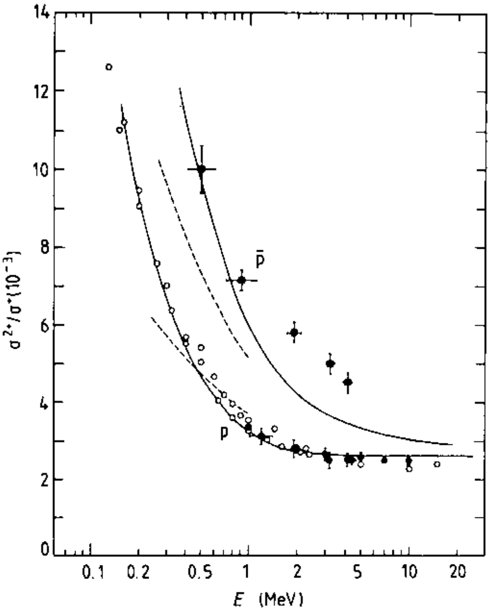

Figure 4. The ratio of the total cross sections for double and single ionization of helium by proton and antiproton impact. Experimental data for antiprotons: Andersen *et al* (1987) (squares) and protons: Andersen *et al* (1987) (full circles), Puckett and Martin (1970), Knudsen *et al* (1984) and Shah and Gilbody (1985) (open circles). Theoretical results: Reading and Ford (1987a) multiplied by a factor of 1.35 (full curve) and Olson (1987) (broken curve).

In another treatment which emphasizes the importance of the electron–electron interaction, Olson (1987) utilized the classical trajectory Monte Carlo (CTMC) technique, incorporating a Bohr model of the helium atom. In this case, the two electrons are initialized opposite each other in the target atom and the collision is simulated by the solution of the classical equations of motion. The CTMC Bohr model results (see figure 4) qualitatively reproduce the antiproton impact enhancement but do not provide as good a quantitative prediction as the FIM. They do, however, provide important insight into the dynamics of the double ionization process and indicate that the enhancement arises due to two dynamical effects.

In the first, it was found that antiprotons preferentially scatter one electron into the other from larger impact parameters than protons, therefore contributing a larger cross section. This occurs since the antiproton and electron have the same charge sign and cause the impinging antiproton to push one electron in towards the other, spatially correlated, electron. In contrast, for similar proton impact events, the positively charged proton must attract the electron in such a way that it is deflected first towards the proton and then back towards the other electron, a process with a much lower probability. The second effect, which dominates at relatively low collision velocities, involves screening of the nuclear charge. In small impact parameter collisions of an antiproton with the target, the negatively charged projectile partially screens the nucleus and, due to the reduced binding, the electron–electron repulsion causes the two electrons to escape. For similar proton impact events, the apparent nuclear charge is increased in the collision, increasing rather than decreasing the binding of the electrons. Significantly, this screening/antiscreening effect contributes a larger amount to the predicted proton/antiproton double ionization difference than do the relatively infrequent electron–electron collisions. Other theoretical studies have emphasized particular aspects of the role of these effects. For example, the screening effects have been illustrated at very low collision velocities by Kimura and Inokuti (1988) through their calculation of the potential energy curves for the proton–helium and antiproton–helium systems. Also, in a treatment in which an attempt is made to build the correlation effect into the independent electron model (Vegh 1988) the antiproton enhancement derives from the linked, or correlated, motion of the two electrons.

The Aarhus–CERN group has also repeated the measurement of the ratio for other target gases (He, Ne and Ar) (Andersen *et al* 1987) and over a larger energy range (65 keV to 20 MeV) (Andersen *et al* 1989a), obtaining results supporting the original data. In addition, they have extended their study to include positron and electron impact (Charlton *et al* 1988, 1989). Figure 5 summarizes these extensions, showing the ratio, *R*, for all four equivelocity projectiles colliding with helium. We note from the figure that, as in the case of proton/antiproton comparisons, the negatively charged light particle shows an enhancement over its positively charged counterpart. In addition, these measurements indicate that at relatively low velocities, the ratio is quite small for both electrons and positrons. This occurs since the double ionization threshold is greater than the single ionization threshold.

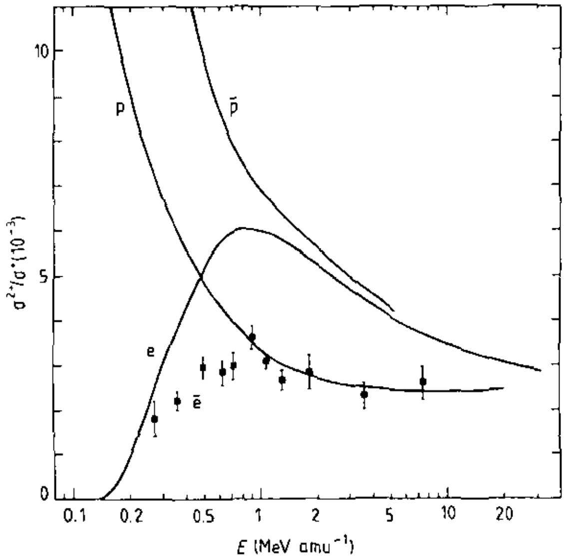

Figure 5. The ratio of the total cross sections for double and single ionization of helium by proton, antiproton, electron and positron impact. A smooth line has been drawn through the experimental data except for positrons (Charlton *et al* 1988).

At asymptotically large energies, it has been argued that the ratio should reach a common value and, indeed, the p, p̄, e, ē experiments show that above 10 MeV u^{-1} the ratios all tend to a value of about 0.0022. In addition, a measurement for relativistic electron impact of helium at 40 MeV (Müller *et al* 1983) has given practically the same result (i.e. 0.0026). However, the behaviour is not the same for all projectiles. For example, in high energy photoionization, where the limit is governed by shake-off, the ratio is about one order of magnitude larger (Carlson 1967). For charged-particle impact the ejected electron emerges with a much lower velocity, thus perturbing the residual ion and the shake-off limit is not strictly applicable (see, for example, McGuire 1984 and references therein). Further, recent measurements of the ratio for N^{7+} impact of helium (Heber *et al* 1990) at energies up to about 30 MeV u^{-1} yield a value about 4.5 times larger than for the singly-charged particles. Therefore, either the asymptotic value for highly charged particles is different or the velocity at which the ratio becomes the same is significantly larger than expected.

Other experiments, not involving antimatter projectiles, have also recently been carried out to investigate double ionization. For example, measurements by Edwards *et al* (1988) concerning the ionization of H_2 by electron and proton impact have experimentally confirmed that the ratio is a function of the differences in both the single and double ionization cross sections. Also, Giese and Horsdal (1988) and Kamber *et al* (1988) have measured the differential cross section in both singly and doubly ionizing collisions of protons with He. Interestingly, the ratio of the double to single plus double ionization differential cross section measured by Giese and Horsdal displayed a distinct peak near 0.9 mrad. This peak was quite unexpected since energy and momentum conservation indicate that the maximum deflection of a proton from an electron at rest is 0.545 mrad. Giese and Horsdal suggested that this peak might be due to an interference between two or more of the mechanisms for double ionization. A number of alternative explanations for the peak have been put forward. For example, Reading *et al* (1989) postulated that two incoherent mechanisms operate to create coinciding deflections, Vegh (1989) proposed that triple collision events caused the effect, and Olson *et al* (1989) showed that the result could be obtained from two uncorrelated scattering events between the proton and the two helium electrons in the double ionization.

Clearly, the study of double ionization is an active and ongoing endeavour and, furthermore, the utilization of matter/antimatter comparisons in the experimental and theoretical investigation of this reaction, specifically to probe the role of electron correlation, has furthered the understanding of such fundamental collision processes.

4.3. Inner-shell ionization

The removal of an electron from the inner shell of an atom, producing a vacancy, will result in an electronic configuration which will relax with the associated emission of either photons or electrons. Understanding of such processes is important since they are significant energy loss mechanisms in the interaction of high energy particles with matter and, further, the yield of photons and electrons from such events allows the study of the electronic structure of the inner shells of atoms. In particular, interest in matter, antimatter impact comparisons stems from the fact that the sign of the projectile charge greatly influences the magnitude of the cross section. For example, proton- and antiproton-induced inner-shell ionization has been considered by a number of authors (Amundsen 1977, Martir *et al* 1982, Brandt and Basbas 1983a, b, Trautmann *et al* 1983, Mehler *et al* 1987) who have concluded that at low impact velocities relative to the inner-shell electron orbital velocities, the antiproton impact cross section will be enhanced relative to that for its positively charged antiparticle, due to a few relatively simple effects.

In the first place, the antiproton penetrates the atom more deeply than does the proton, since the projectile-nucleus interaction is attractive rather than repulsive.

Therefore, the negatively charged particle is pulled toward the inner shells enhancing the ionization probability. Also, since the proton–nucleus interaction is repulsive, the proton is slowed down and this dissipation of energy decreases slightly the ionization probability, whereas the antiproton is accelerated by the nucleus and the probability is increased. In addition, the proton increases the binding experienced by the inner-shell electrons since its charge adds to the nuclear charge while the antiproton decreases this interaction. This effect, which changes the net transient nuclear charge by plus or minus one, is significant even for large nuclear charges since in the low collision velocity regime the inner-shell ionization probability is inversely proportional to the ninth power of the binding energy, which is in turn proportional to the square of the nuclear charge.

These Coulomb deflection and binding energy effects are predicted to produce large enhancements of the inner-shell ionization probability for antiproton impact at low to intermediate energies, the effects becoming negligible for very large velocities when the collision time becomes very short and the electrons are removed in a much more sudden, impulsive manner. The theoretical works have therefore largely been motivated by the anticipated availability of relatively low energy antiprotons from facilities such as the LEAR at CERN. However, experimental comparisons have already been made between positron and electron impact by a number of groups. The earliest measurements showed that at very high energies, as expected, the inner-shell ionization cross sections for electron and positron impact are the same (cf Hansen *et al* 1964, Hansen and Flammersfeld 1966, Seif el Nasr *et al* 1974, Schiebel *et al* 1976). In fact, the electron/positron difference should be greatest when the collision time is longest, that is, when the collision energy (E) is on the order of the binding energy (U) of the inner-shell electrons, $E/U \lesssim 1$, or put another way, when the collision velocity is comparable with or lower than the electron's orbital velocity.

Indeed, more recent experiments at lower energies for the K-shell ionization of silver (Ito *et al* 1980, $3.8 < E/U < 15.4$) and copper (Schultz and Campbell 1985, $2.8 < E/U < 4.4$) have indicated that the electron impact cross section is larger than that for positron impact. Also, of interest is the observation of the quantum electrodynamic difference between electron–electron (Møller 1932) and positron–electron (Bhabha 1936) scattering. It was suggested (e.g. Schiebel *et al* 1976, Tawara 1977), based on a model developed by Kolbenstvedt (1967, 1975) for K-shell ionization by electron impact, that the Møller/Bhabha difference would cause the positron impact cross section to be larger than the electron impact cross section. In order to isolate this difference from the strong Coulomb deflection effect in K-shell ionization, Lennard *et al* (1988) measured the L-shell ionization cross sections for electron and positron impact of gold in the scaled energy range of $2 < E/U < 4$. Their results indicate that at the lowest energies observed, the positron cross section is indeed larger than the electron cross section.

4.4. *Ejected electron spectra*

The variations which occur in the ionization process due to the changes in the projectile mass and sign of charge are manifested in large differences in the distribution of electron ejection angles and energies. In particular, the study of the electronic spectra illuminates in detail the underlying mechanisms which differentiate ionization by electron, positron, proton and antiproton impact and provides a deeper insight than does comparison of total cross sections alone. Thus far, differential cross sections have been calculated by a number of authors comparing matter and antimatter projectiles, but have been experimentally determined only for the case of electron and proton impact. Since the required flux to measure differential cross sections is much larger than that required for total cross sections, analogous experiments for positrons await the required enhancement of their sources and for antiprotons, the greater allotment of beam time.

The object of much of the recent study of the electronic spectra produced in intermediate velocity collisions has been to explore the departures from the scaling of the results with the square of the projectile charge predicted by the first Born approximation (see Reinhold *et al* 1987, Stolterfoht *et al* 1987). It has been shown that the conventional division of the electronic spectra used in one-centre treatments which consider the ionized electron as moving in either the continuum of the target or of the projectile does not provide an adequate description. Recent works have demonstrated that two-centre techniques which treat the ejected electron as being influenced by the combined Coulomb fields of projectile and residual target ion determine the shape and magnitude of the electronic spectra (Olson *et al* 1987, Fainstein *et al* 1988a, b, Reinhold and Olson 1989, Brauner *et al* 1989, Reinhold *et al* 1990).

In this light, the behaviour of the electronic spectra may be seen as the interplay of the electron removal process with the subsequent dynamic evolution in the two-centre field. For example, an electron removed in proton impact experiences during the collision the combination of two attractive potentials, one due to the proton and the other due to the partially screened target core. In contrast, the electron is subject to the effects of one repulsive and one attractive potential in antiproton impact. The effects of such differences on the singly differential cross sections as a function of ejection energy and angle have been calculated for matter and antimatter impact with helium at intermediate energies by Garibotti and Miraglia (1980), Fainstein *et al* (1989), Olson and Gay (1988) and Reinhold and Olson (1989). In figures 6 and 7 we display the results of the calculation of Fainstein *et al* (1989) using the continuum distorted

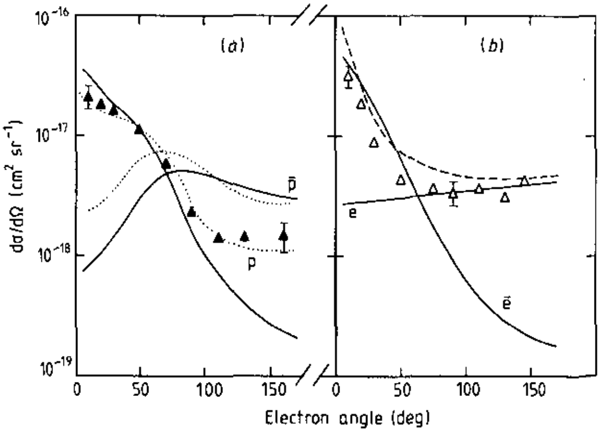

Figure 6. The singly differential ionization cross section as a function of ejection angle for electron, positron, proton and antiproton impact of helium at a velocity of 2.83 au. Experimental data for protons: Rudd and DuBois (1977) (full triangles) and electrons: Rudd *et al* (1976) (open triangles). Theoretical results: Olson and Gay (1988) (full curves) and Fainstein *et al* (1989) (dotted curves). For electrons, the theoretical cross section for the sum of the indistinguishable target and projectile electrons is shown (broken curve).

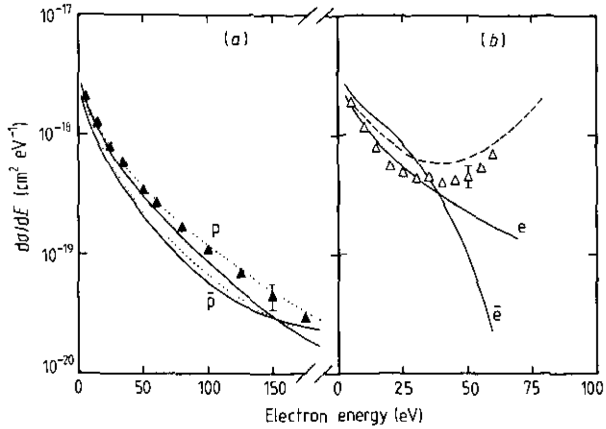

Figure 7. The singly differential ionization cross section as a function of ejection energy for electron, positron, proton and antiproton impact of helium at a velocity of 2.83 au. Symbols the same as in figure 6.

wave-eikonal initial state (CDW-EIS) model for protons and antiprotons and the calculations of Olson and Gay (1988) using the CTMC method for electrons, positrons, protons and antiprotons.

As figure 6 illustrates, the positively charged projectiles produce ejection primarily to the forward direction whereas the negatively charged projectiles produce much less forward emission. This behaviour arises quite simply because protons and positrons, due to their positive charge, pull the ejected electrons in the direction of their velocity while antiprotons and electrons repel them. The ejected electron energy distribution, displayed in figure 7, shows that, owing to their greater kinetic energy when compared with electrons and positrons of equal velocity, the heavy particles have a much larger cross section at high ejection energy. This figure also indicates that for relatively low ejection energies, the positively charged particles have a larger cross section than their negatively charged antiparticles. This difference has been explained as being due to the sign of the charge-dependent difference in ionization known as the 'saddle point' mechanism.

Conventionally, it has been thought that most of the electrons removed in ionizing collisions would be associated with either the target or the projectile. That is, either the electron would be impulsively knocked into the target continuum or would be transferred to the continuum of the projectile. Olson (1983), in studying the distribution of electron velocities in proton impact of atomic hydrogen, found that at intermediate collision velocities a significant number of electrons were found with velocities of about $v_p/2$, where v_p is the velocity of the projectile, strictly associated with neither the target or projectile. The production of these electrons was attributed to the stranding of ejected electrons in the saddle, or equiforce, region between the proton projectile and the target core. The subsequent experimental and theoretical study of these electrons is discussed by Olson *et al* (1987).

With particular regard to the positive/negative particle difference in the production of soft electrons, the saddle-point picture provides a simple explanation. Ejected electrons of low energy originate primarily in relatively weak, distant collisions of the projectile with the target electron. In this case, since the positively charged projectile produces a region of reduced binding centred about the equiforce point, the probability of the escape of the electron is enhanced. For the negatively charged particle the midpoint region is one where the electron experiences a repulsion and no net decrease of binding. Thus, positively charged projectiles are more efficient in producing slow ejected electrons due to the effect of force cancellation of the target nucleus and projectile fields. Furthermore, electrons ejected at relatively large energies arise primarily from very close collisions of the projectile with the electron and the negatively charged particles produce more electrons of high energy since they repel the ejected electron while the ejected electron must expend kinetic energy to escape from the combined projectile+nucleus Coulomb field for positively charged projectiles.

On these bases, the angle or energy distributions of the ejected electrons are seen to be strongly dependent on the sign of the projectile charge. Analysis has shown that variations are also present in the doubly differential cross sections. For example, the study performed by Fainstein *et al* (1988b) comparing the proton and antiproton impact spectra at zero degrees (figure 8(*a*), (*b*)) has indicated quite different behaviour for the two projectiles. That is, at an ejected electron energy E_p corresponding to

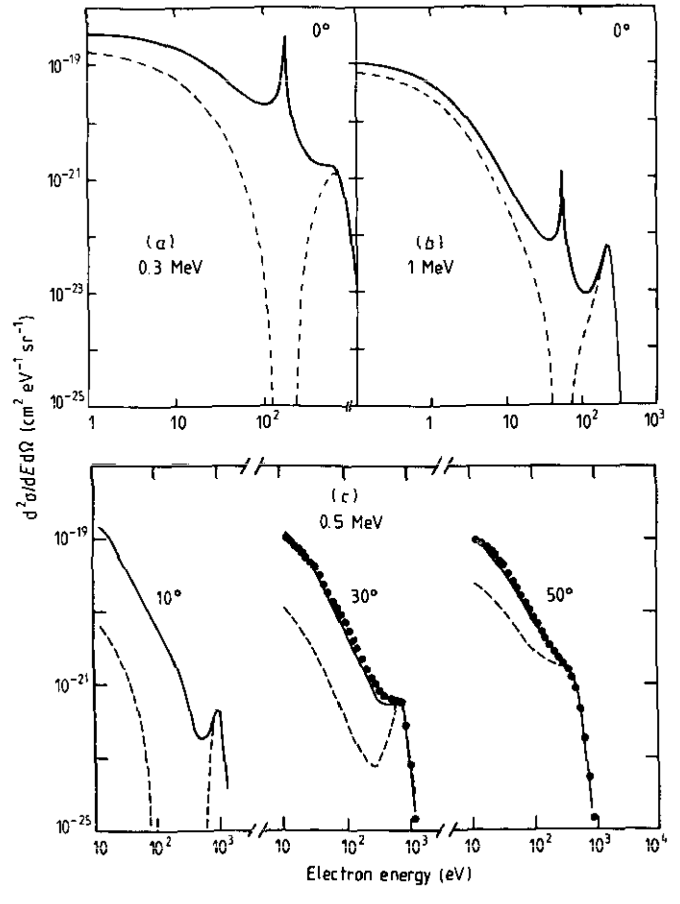

Figure 8. The doubly differential ionization cross section as a function of ejection energy for proton- (full curves) and antiproton- (broken curves) impact of helium. Theoretical results (*a*) and (*b*) at 0° ejection angle (Fainstein *et al* 1988b) and (*c*) larger ejection angles (Reinhold and Schultz 1989). Experimental data (full circles): Rudd *et al* (1976).

electrons travelling at velocities equal to the projectile velocity (i.e. $E_p = 0.5\ v_p^2$), the proton results display a very large rise in the cross section forming a cusp at E_p, whereas the antiprotons display a very broad dip or 'anticusp'.

The proton-induced cusp at E_p is known as the 'electron capture to the continuum' (ECC) peak and was first predicted by Salin (1969a, b) and Macek (1970) and found experimentally by Crooks and Rudd (1970) and Harrison and Lucas (1970). The existence of the ECC peak may be demonstrated by simple first-order theories, but more elaborate two-centre treatments are required to explain the details of the observed magnitudes and shapes. The cusp is usually attributed to the divergence of the Coulomb factor which determines the density of states of the continuum at threshold. It has also been proposed that the peak is formed by the Coulomb focusing of electrons emitted with velocities nearly equal to the projectile velocity at small angles in a post-collisional attractive interaction (Ovchinnikov and Khrebtukov 1987, Reinhold and Olson 1989). In the case of antiproton impact, the dip is predicted to occur since, in the post-collision regime, electrons which are emitted with velocities nearly equal to that of the antiproton, and emerge at small angles with respect to the nearly undeflected antiproton path, will be 'defocused' or repelled to higher energies and larger angles (Reinhold and Schultz 1989). Alternatively, Fainstein *et al* (1987) describe the dip as arising from the zero of the Coulomb factor describing the density of states for a repulsive potential.

In addition, the difference between the proton and antiproton impact doubly differential cross sections persists to larger emission angles (figure 8(*c*)). These differences due to the attractive/repulsive post-collisional interactions are very large for ejection energies less than E_b, the energy of the binary encounter peak, but it is predicted that protons and antiprotons should produce binary peaks of very nearly the same magnitude, thus implying that in extremely close collisions, the sign of the charge does not strongly influence the cross sections. However, small differences in the proton and antiproton impact cross sections for fast electrons (i.e. energies greater than that of the binary peak), have been predicted to exist on the basis of both the CDW-EIS and CTMC calculations.

Also, very recently, experimental evidence has been found by a collaboration at LEAR (Yamazaki *et al* 1990) for the existence of the anticusp. Yamazaki and co-workers have made preliminary measurements of the production of electrons in the forward direction for proton and antiproton bombardment of thin carbon foils in the collision energy range of 500 to 750 keV. The experiment is complicated by the fact that the target thickness results in a smearing of the effect due to the production of hot secondary electrons which are degraded into the anticusp region, and wake riding electrons which are brought forward into this region as well (Burgdörfer *et al* 1989, Burgdörfer 1990).

The ECC peak is a well studied feature of the electronic spectra for heavy-particle impact. In this case, the projectile is nearly undeflected in the collision and provides a clearly preferred direction towards which equivelocity ejected electrons may be focused. For light-particle impact, the projectile may be deflected to much wider angles (Schultz and Olson 1988) and consequently, there might be some question as to whether or not an ECC structure would exist in the doubly differential cross section. Using a three-body Fadeev formalism, Mandal *et al* (1986) have predicted that for positron impact of atomic hydrogen, a cusp should appear at zero degrees. Their results indicate a peak very similar in nature to the heavy-particle-induced peak. In contrast, Schultz and Reinhold (1990) have obtained a somewhat different result for the same system using the CTMC method. They found that due to the spread of deflected positrons and due to the fact that positrons may give up a relatively large portion of their incident kinetic energy in the collision, the ECC peak is spread to a greater extent in angle and energy relative to the shape expected for heavy-particle impact.

In addition, Briggs (1985, 1986) and Brauner and Briggs (1986) have studied the triply differential cross section (TDCS) for both electron and positron impact, observing that cusp-like structures are present in these cases too. Also in recent years, it has been shown that in electron impact ionization a post-collisional interaction occurs pushing both electrons to larger angles (see for example the review by Ehrhardt *et al* (1986)). Quite recently Brauner *et al* (1989), by using a product of three Coulomb wavefunctions in the asymptotic regime, have provided an important treatment of the TDCS which models in a consistent way all post-collisional interactions. This technique has been shown to yield good agreement with experiment (figure 9). In fact, this method is related to, and is an extension of, treatments using products of two Coulomb wavefunctions to describe an electron in the continuum of two heavy particles developed in heavy-ion impact studies (Belkić 1978, Crothers and McCann 1983).

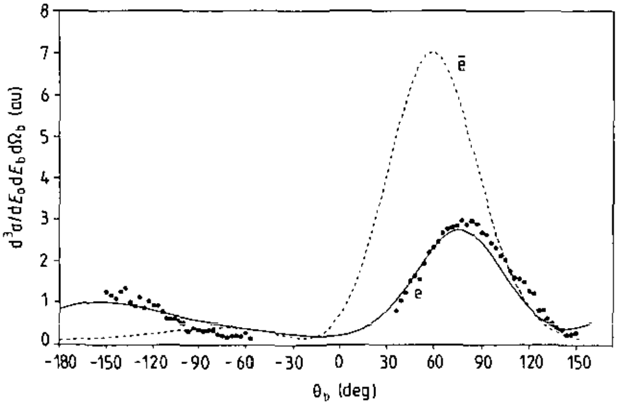

Figure 9. The triply differential ionization cross section for the electron (full curve) and positron (broken curve) impact of atomic hydrogen at 150 eV calculated by Brauner *et al* (1989). The scattering angle is fixed at 10° and the ejection energy at 3 eV. The experimental data for electron impact are from Ehrhardt *et al* (1988).

4.5. *The Barkas effect*

Matter-, antimatter-atom collision differences are manifested not only in single atom situations, but are present for aggregate matter as well. For example, since protons and antiprotons produce different ejected electron spectra, the energy lost by these charged particles as they pass through matter will be different and, consequently, so will their range and the stopping power of the medium. In addition, other effects caused by the varying projectile charge sign, such as the change in the open reaction channels, will contribute.

One such manifestation is known as the Barkas effect and is related to the difference in the range of particles in their penetration of a thick target when only the projectile charge sign is varied. Through the analysis of pion, muon and sigma hyperon emulsion tracks, Barkas *et al* (1956, 1963) were able to show that the range was greater for the negatively charged particle than its positively charged antiparticle. The greater range of the negatively charged particle was inferred to be due to its reduced stopping power.

That is, since the ionization cross section is larger for the positively charged particle, the energy that it loses, and consequently the stopping power of the material, is greater. It has been interpreted that this arises due to polarization of the target material which depends on the sign of the projectile charge (Jackson and McCarthy 1972, Ashley *et al* 1972, 1973, Lindhard 1976, Brandt and Basbas 1983a, b).

Recently, theoretical calculations for protons and antiprotons colliding with helium lead to the prediction of the Barkas effect for this system (Olson and Gay 1988, Olson 1987). These calculations showed an enhanced single ionization cross section for protons, relative to that for antiprotons, at energies when the electron capture channel was negligible. Calculated energy loss spectra confirmed that the stopping power of antiprotons was less than that of protons for energies less than 1 MeV. The preponderance of 'saddle point' electrons (Olson and Gay 1988) for the proton case was proposed as the major reason for the enhancement. This model was at first contradicted by the measurements made by the Aarhus group collaborating at LEAR (Andersen *et al* 1986, 1987) which did not show differences between the single ionization cross sections for protons and antiprotons and Andersen *et al* (1987) proposed the possibility of an opposite or 'anti-Barkas' effect contribution to the range of these particles from the double ionization contribution. Their more recent measurements (Andersen *et al* 1990) over a wider range of energies have, however, confirmed the theoretical consensus that the proton single ionization cross section is larger than the antiproton impact result at intermediate energies.

In fact, direct measurements of the Barkas effect have been completed at LEAR. Gabrielse *et al* (1989a) measured directly the range of protons and antiprotons in aluminium, observing a 6% enhancement of the range of antiprotons over that for protons at an incident energy of 5.9 MeV (figure 10). At the same time, Andersen *et al* (1989b) measured the stopping power for protons and antiprotons in silicon over the energy range from 0.538 to 3.01 MeV. These authors demonstrated that the stopping power of protons was enhanced over that for antiprotons by 3–19%, the largest

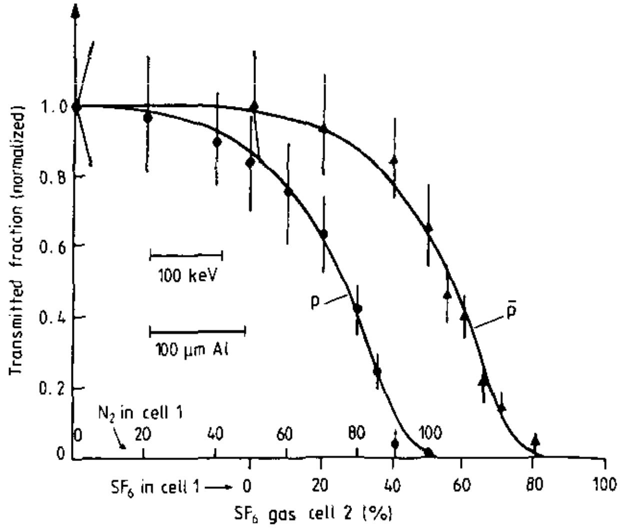

Figure 10. The normalized transmitted fraction of protons and antiprotons detected after passing through an aluminium degrader, illustrating the energy loss and range differences between these two oppositely charged particles, obtained by Gabrielse *et al* (1989a).

difference being at the lowest measured energies. Both of the measurements appear to confirm the existence of a Z_p^3 contribution to the ionization cross section. The source of this difference between proton and antiproton impact may lie in target polarization effects or the existence of 'saddle point' electrons. However, another possibility, which has not been explored, is that electron capture may have a dominant contribution to the observed Barkas effect for the Al and Si cases, since capture from the L shell by protons is quite probable in the energy range investigated.

5. Charge transfer

A second electron removal channel exists for the positively charged particles which dominates at low collision velocity; namely, charge transfer. Comparison of the charge transfer cross sections for proton and positron impact isolates the effect of changing projectile mass on the reaction and, as such, provides a fundamental testing ground for both theory and experiment.

In the case of proton impact, charge transfer results in the formation of a neutral hydrogen atom, whereas for positron impact, the product is positronium. Positronium, the bound state of an electron and a positron, is unstable, annihilating into either two or three photons, depending on the spin orientations. That is, orthopositronium ($S=0$) has a ground state lifetime of 1.3×10^{-10} s and decays to three photons and parapositronium ($S=1$) has a lifetime of 1.4×10^{-7} s and decays to two photons (an interesting review of the properties of positronium and its simple interactions is given by Rich (1981)). The ground state is bound by 6.8 eV and consequently, the capture threshold in positron impact collisions is 6.8 eV below the ionization threshold. Because the product positronium has a very short lifetime, unlike its counterpart in proton impact collisions, experimental determination of the positron impact charge transfer cross section is quite difficult. Charlton and Laricchia (1990) have recently reviewed the experiments which have been performed to measure the total cross section for positronium formation, as have Griffith (1984, 1986), Coleman (1985) and Charlton (1985) previously.

The total cross section for positronium formation has been measured for a number of gases by three independent groups. The first measurements were performed by Charlton *et al* (1980) at University College London (UCL) through the detection of the three photon coincidences which result from the annihilation of orthopositronium. This group has reported measurements for the inert gases (He, Ne, Ar, Kr, Xe) and some molecular gases (H_2, N_2, O_2, CO_2, CH_4) (Charlton *et al* 1983, Griffith 1984). As described by Charlton (1985) and Charlton and Laricchia (1990), these experiments have been shown to suffer from systematic errors such as the loss of orthopositronium at the walls of the scattering chamber.

A completely different method was used by Fornari *et al* (1983) at the University of Texas at Arlington (UTA) who inferred the positronium cross section by measuring the fraction of the incident positron beam that was lost during its transmission through an extended gas cell, the positron beam being confined to the forward direction by the application of an axial guiding field. The UTA measurements, originally performed in H_2, He and Ar, have been repeated and extended to higher energies for H_2 and He by Diana *et al* (1986a), and have been reported over this energy range for Ne, Ar, Kr and Xe by Diana *et al* (1985a, 1986b, 1987a, b, 1989).

The third group reporting positronium formation cross sections is that at the Universität Bielefeld (UB), and has made measurements in He (Fromme *et al* 1986) and H_2 (Fromme *et al* 1988). Their method is similar to that used at UTA in that the positron beam is passed through a long scattering cell and is confined by an axial magnetic field. However, rather than measuring simply the beam attenuation, they measure the total yield of ions in coincidence with the scattered positrons. The single ionization cross section may then be deduced from the coincidence counts while the sum of capture and ionization is found from the rate of ion production. The charge transfer cross section is obtained as the difference.

The results of the positronium formation measurements of the three groups are displayed in figure 11 for H_2 and He. As one may easily see, the measured cross section rises very sharply at low energies, due to the presence of the threshold, peaks at energies

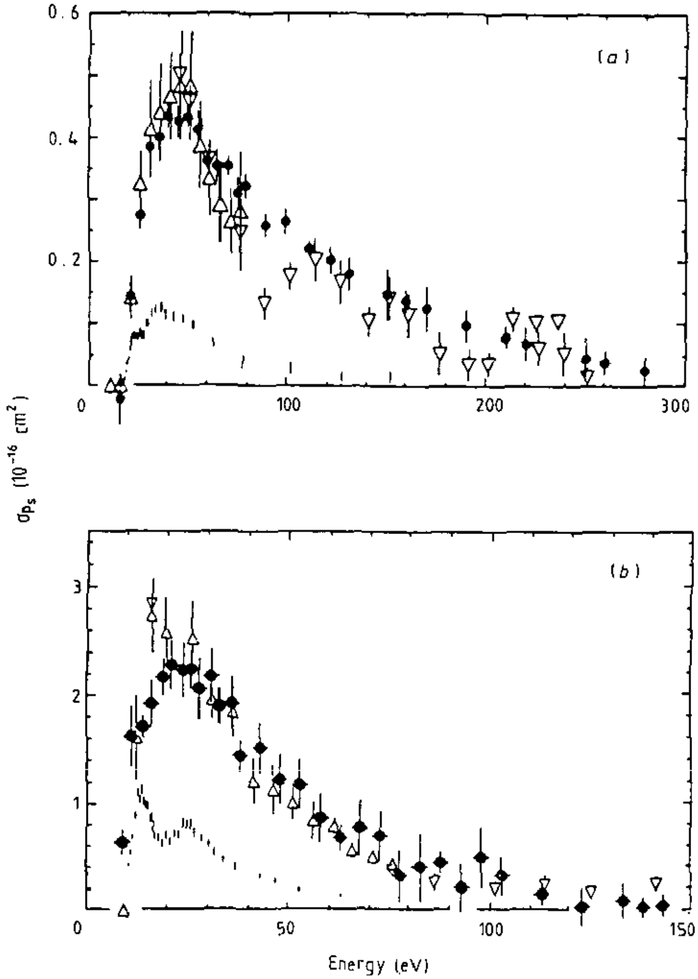

Figure 11. The experimentally measured total cross section for positronium formation in helium and molecular hydrogen. (*a*) Helium: Fromme *et al* (1986) (full circles), Diana *et al* (1986a) (inverted triangles), Fornari *et al* (1983) (triangles) and Charlton *et al* (1983) (bars). (*b*) Molecular hydrogen: Fromme *et al* (1988) (full circles), Diana *et al* (1986a) (inverted triangles), Fornari *et al* (1983) (triangles) and Griffith (1984) (bars).

corresponding to about twice the orbital velocity of the electron and drops off at higher energies. Qualitative agreement exists between the UTA and UB results, but the UCL data fall well below the other measurements. As mentioned above, the UCL experiment has been affected by systematic errors and consequently its disagreement with the other determinations should not be given too much weight. Indeed, the UCL group reports (Charlton and Laricchia 1990) that new measurements are in better agreement with the results of the other groups. Also this comparison of the experimental results indicates that for helium, the UTA data display secondary maxima, in disagreement with the UB data. No explanation has yet been put forth explaining the source of these oscillations in terms of either experimental artifacts or the physical mechanisms of capture.

Theoretical estimates of the positronium formation cross section for atomic targets have been made using a wide variety of approaches and for various energy regimes. The first calculation of positronium formation was, in fact, made using the Born approximation by Massey and Mohr (1954). Detailed reviews of many of these treatments have been made by Bransden (1969), Ghosh *et al* (1982), Humberston (1986) and Charlton and Laricchia (1990). In addition, Armour (1988) has reviewed the theory of positron-molecule scattering. Here we will confine our discussion to the results of treatments pertinent to comparison with the experiments at intermediate energies, and particularly in the case of helium which is of fundamental interest.

For example, in figure 12 we present a comparison of a number of different theoretical results with the experimental data of Fromme *et al* (1986) for positronium

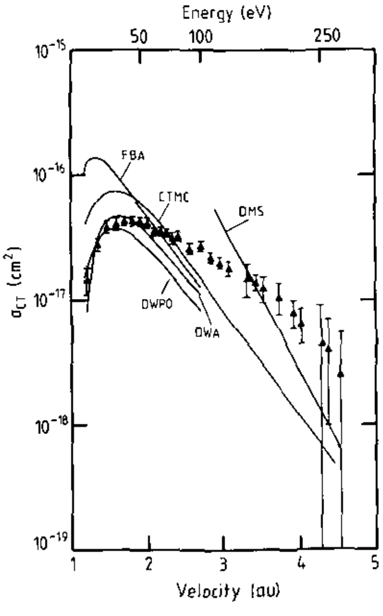

Figure 12. Comparison between theoretical calculations of the total cross section for positronium formation in helium: first Born approximation (FBA) and distorted-wave approximation (DWA) (Mandal *et al* 1979), distorted-wave polarized-orbital approximation (DWPO) (Khan and Ghosh 1983), classical trajectory Monte Carlo method (CTMC) (Schultz and Olson 1988) and second Born approximation (DMS) (Deb *et al* 1987a). Included are the experimental measurements of Fromme *et al* (1986).

formation in helium. Included in this figure are the first Born (FBA) and distorted wave (DWA) approximations of Mandal *et al* (1979), the distorted wave polarized orbital (DWPO) method of Khan and Ghosh (1983), the second Born approximation of Deb *et al* (DMS) (1987a) and the classical trajectory Monte Carlo (CTMC) treatment of Schultz and Olson (1988). At collision velocities from just above threshold to about the peak, the distorted wave treatments show reasonable agreement with experiment, but at higher velocity, all the methods underestimate the measurements. In fact, the UTA and UB data fall off as a function of impact energy as E^{-1} to $E^{-1.5}$ whereas the theories decay as E^{-3} to E^{-5}. The discrepancy between theory and experiment represents a considerable challenge.

A resolution of this disagreement has been proposed by Schultz and Olson (1988) based on an adjustment to the experiments due to the hypothesized incomplete confinement of scattered positrons. Specifically, since in both the UTA and UB experiments the positronium formation cross section is determined by the loss of flux from the beam and relies on axial magnetic confining fields, if flux is lost due to incomplete confinement of those positrons deflected to large angles in ionizing collisions, an overestimation of the positronium formation cross section will result. Schultz *et al* (1989a) have made a quantitative estimate of these proposed adjustments and showed that they could account for the difference between theory and experiment. Nevertheless, further investigation of the positronium formation cross section both theoretically and experimentally is clearly needed to fully resolve the issue.

Comparison between theoretical and experimental positronium formation cross sections may also be made for molecular hydrogen and the other rare gases. For H_2, Ray *et al* (1980) have used the Jackson–Schiff approximation and find reasonable agreement with the UTA and UB measurements above about 50 eV impact energy. In addition, Bussard *et al* (1979) estimated the cross section semiempirically at low energies and use the first Born approximation of Sural and Mukherjee (1970) above 50 eV, obtaining an overestimation of the cross section at low energy and an underestimation at high. In this case the UTA and UB measurements are in reasonable accord above 30 eV, the UTA data not showing the threshold behaviour. Gillespie and Thompson (1977) have calculated charge transfer cross sections for positron impact of the rare gases using a distorted wave approximation, but their results extend only up to about 8 eV above threshold, and underestimate the UTA measurements by more than an order of magnitude. Schultz *et al* (1989a) have studied the positron–Kr system, finding reasonable agreement with the data of Diana *et al* (1987b) near the peak of the cross section, but predicting values as much as two orders of magnitude below the measurements at higher energies. By considering the possibility of incomplete confinement of positron's scattered to large angles, Schultz *et al* (1989a) have proposed a resolution to the discrepancy by adapting and repeating their proposed adjustment for the helium experiments.

Many calculations of charge transfer in the fundamental system of positrons on atomic hydrogen have been performed (see the above referenced reviews, Mandal *et al* (1979) and references therein and Khan *et al* (1985)) but as of yet no experimental determination of this cross section has been made, due in large part to the difficulties associated with the production of atomic hydrogen targets. Taken as a whole, the agreement between theory and experiment on the positronium formation cross section is rather poor, with the greatest discrepancies occurring at high intermediate collision velocity. Further study should be made to resolve these differences by independent determinations of the total cross section over the energy range covered by the existing experiments, extension of these measurements to even higher energies and by the eventual consideration of the differential cross section.

Comparison of equivelocity positron and proton impact charge transfer cross sections reveals that at low velocity the proton capture cross section is greater than that for positrons of equal velocity due to its greater mass and, therefore, energy above threshold. At higher impact velocities a less obvious effect leads to a significant difference. In fact, McGuire *et al* (1986) suggested that the positronium formation cross section should be larger than the hydrogen formation cross section. They argued that since the positron must give up half its kinetic energy to the electron in the capture process, its capture cross section should be larger than that for equivelocity protons because the cross section drops off rapidly with energy. For atomic hydrogen, they used the Brinkman-Kramers approximation finding that at high velocities the positron capture cross section should be about 6.6 times as large as that for protons. Using the CTMC technique, Schultz (1989) has found that the ratio rises from a value less than one near threshold to a value of about 7 for velocities greater than 5 au.

This ratio of positron to proton impact cross sections is displayed in figure 13 for collisions with helium. Included is the ratio of the experimental data of Fromme *et al* (1986) to tabulated proton data and several theoretical curves. Specifically, Deb *et al* (1987a) have used a second Born treatment and find that the ratio decreases from a value as large as fifty for low velocities, to a high velocity value around fifteen, in accordance with the asymptotic value they obtain with the Brinkman-Kramers approximation. A result with similar behaviour has also been obtained by Roberts (1989) using a second-order Fadeev-Watson approach, which also drops from a ratio of about fifty at low velocity to an asymptotic value of about four. In contrast to these results, CTMC

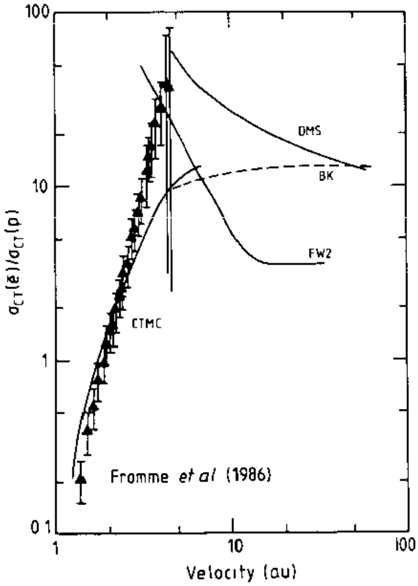

Figure 13. Ratio of the positron to proton impact charge transfer cross section in helium: classical trajectory Monte Carlo method (CTMC) (Schultz 1989), second-order Fadeev-Watson approximation (FW2) (Roberts 1989) and Brinkman-Kramers (BK) and second Born (DMS) approximations (Deb *et al* 1987a). Included is the ratio of the experimental measurements of Fromme *et al* (1986) to accepted proton impact data.

calculations (Schultz and Olson 1988, Schultz 1989) indicate that the ratio should initially rise from a value less than one near threshold to a large velocity value of about 13.

The experimental data have a behaviour most like the CTMC result at low velocity, but at slightly higher velocity go to a much larger ratio. At low velocities where the positrons have much less energy than do equivelocity protons one would expect the ratio to be less than one. As velocity increases this effect should diminish in importance and the ratio should reach one at sufficiently high velocity. At still higher velocities, theory and experiment agree that the ratio becomes larger than one, but it is not certain whether this ratio continues to rise or levels off. In fact, the high velocity behaviour of the ratio is also dependent upon the resolution of the discrepancy between theory and experiment as to rate of drop off of the positronium formation cross section noted above.

Nevertheless, experiment and theory indicate that the ratio exceeds a value of one. Schultz and Olson (1988) have suggested, based on a study of the differential scattering cross sections and a detailed analysis of the trajectories which lead to capture in their CTMC treatment, that this enhancement may be easily understood in terms of the mass difference between the light and heavy particles. That is, protons suffer very little deflection or energy loss in charge transfer collisions, whereas, positrons are much more likely to be deflected and braked into such a trajectory that readily vector momentum matches with an orbital electron, leading to capture.

Another important point of comparison between positron and proton impact charge transfer collisions is the study of differential cross sections. Perhaps the most obvious difference is that the proton impact differential cross section will be very forwardly peaked, due to the proton's larger mass, whereas the positron cross section will extend significantly to large angles. Apart from this straightforward difference, great interest has developed in understanding the high velocity behaviour of the capture differential cross section, particularly for Thomas scattering. The prominent role played by this capture mechanism has been well established and has been described, for example, by Shakeshaft and Spruch (1979).

Thomas (1927) first argued that at high velocity the capture cross section should be dominated by a process in which two successive binary collisions occur since capture in a single binary collision is classically forbidden by conservation of energy and momentum. In the first binary collision the projectile interacts with the electron deflecting it into such a trajectory that in a second collision it is scattered from the target nucleus so that its exit velocity vector matches the projectile's. Energy and momentum conservation for this geometry yields the result that for proton impact, the proton is deflected to an angle of about 0.5 mrad, the so called Thomas angle. In actuality, the differential cross section displays a peak at this angle which has been recently experimentally observed for proton–helium and proton–hydrogen collisions by Horsdal-Pedersen *et al* (1983) and Vogt *et al* (1986), respectively.

Quantum mechanical perturbation treatments of this mechanism of capture must contain second-order terms since a double scattering occurs. Indeed, several such treatments (see for example Belkić *et al* 1979, Macek and Taulbjerg 1981, Miraglia *et al* 1981, Macek and Alston 1982, McGuire *et al* 1983, Taulbjerg and Briggs 1983) have been successfully applied. However, a further complication arises for capture by positrons. Since in this case the projectile has the same mass as the electron, two separate collision paths are possible. That is, the double scattering may occur as in the heavy particle case, or it may be the positron which is deflected in towards the nucleus and then scattered to match with the outgoing electron. Similar analysis on the basis of energy and momentum conservation yields a Thomas angle in this event of 45°.

As has been pointed out by Shakeshaft and Wadehra (1980), the amplitudes for these two paths cancel for ground-state to ground-state capture, but for transitions with odd parity, they interfere constructively and the Thomas peak is present. These effects have been illustrated for positron impact of hydrogen by McGuire *et al* (1986) at an energy of 50 keV showing how the inclusion of the various second order amplitudes add to produce the predicted Thomas peak. These authors have also made calculations for other impact energies and target atoms (atomic hydrogen (McGuire *et al* 1986, Deb *et al* 1987b) and He, Be, Ne, O and C (Deb *et al* 1987a)) and have obtained evidence of the Thomas peak in as low an energy range as several keV in helium.

The differential cross section for positronium formation at high energy has also been treated by Basu and Ghosh (1988) using a second Born approach, Tripathi *et al* (1989) in the Glauber approximation and Roberts (1989) with both the first- and second-order Fadeev–Watson methods. Roberts (1989) has compared the results of all of these different treatments and has observed that a great deal of disagreement as to (i) the structure of the differential cross section about the Thomas angle, (ii) the behaviour of the cross section for capture to states of positronium of different parity and (iii) the total cross sections that these theories predict.

Thus, the detailed behaviour of the capture cross section for positron impact clearly requires further study theoretically and, subject to the continued development of positron beam sources, experimentally.

6. Elastic scattering and impact excitation

Emphasized thus far has been the role of comparisons of matter- and antimatter–atom collisions in the study of ionization and charge transfer. However, differences are also manifested in scattering channels in which electrons are not removed from the target atom. Here we turn our attention to a brief description of the elastic scattering and impact excitation studies pertinent to such comparisons. Since the calculations for positron impact, which have been performed for many years in analogy to those made for electron impact as a probe of 'electron scattering without exchange', have lead to a very large body of theoretical work, no attempt is made to survey this vast literature here. We do note that a number of works exist containing surveys of various aspects of the electron/positron scattering problem (Ghosh *et al* 1982, Griffith and Heyland 1978, Walters 1984, Humberston 1979, Joachain 1987) and, in particular, Charlton and Laricchia (1990) have quite recently reviewed positron impact phenomena. We consider here several recent works which indicate the direction and scope of the current investigations concerning comparisons in these channels, since they are of great practical and fundamental interest and, in addition, electron impact studies pervade many practical concerns. For example, differential cross sections for the elastic scattering of positrons have been measured by both the Detroit (Wayne State University) and Bielefeld groups. The Detroit group's original experiment (Hyder *et al* 1986) was performed at intermediate energies (100, 300 eV) in argon and has been extended (Smith *et al* 1989, 1990) to lower energies (5 to 50 eV) and also performed (Smith *et al* 1989) for neon (13.6 eV). The Bielefeld group's measurements (Schwab *et al* 1987, Floeder *et al* 1988) have been made in argon at low energies just below (8.5 eV) and above (30 eV) the first inelastic threshold. The results of these measurements are displayed in figure 14 along with those obtained in an earlier, pioneering work by Coleman and McNutt (1979). In this figure the experimental results are compared to theory and analogous electron impact cross sections. Inspection of this figure indicates at once that the positron and electron impact cross sections have a very dissimilar angular behaviour. Differences in the form of the polarization interaction between the positron or electron and the target, opposite signs of the static interaction and the absence of exchange for the positron case, lead to very different overall interactions for the two projectiles and consequently quite different elastic differential cross sections.

However, perhaps the most significant implication of the experimental and theoretical results depicted is that the effects of other open scattering channels dramatically influence the elastic cross section. That is, above the positronium formation threshold, which in argon occurs at 9 eV, theoretical calculations must include the effects of the absorption or loss of flux to this channel, and at even higher energies, to other accessible channels. The importance of including absorption was pointed out in this context by Joachain *et al* (1977) and Khare *et al* (1982), and was taken into account in subsequent calculations by Joachain and Potvliege (1987) at intermediate energies and by Bartschat *et al* (1988) at lower energies, utilizing optical potential treatments.

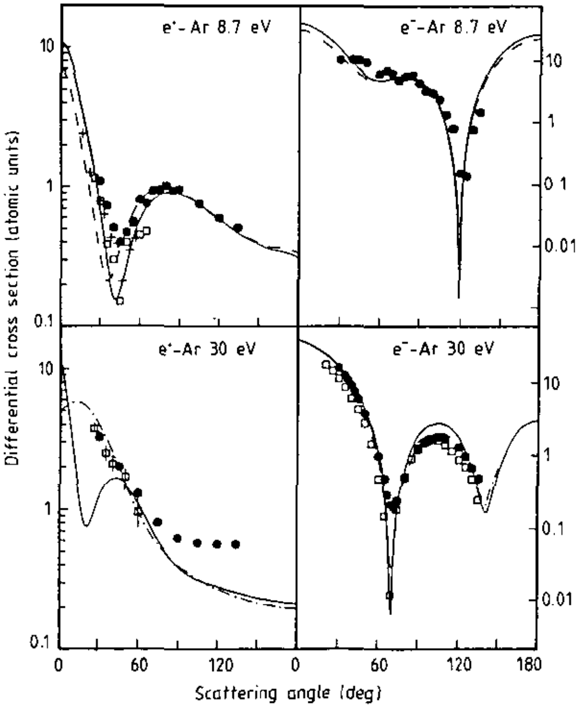

Figure 14. The differential cross section for elastic scattering of positrons and electrons from argon at 8.7 and 30 eV impact energy. Results for positron impact: experiments, Smith *et al* (1989) (circles), Coleman and McNutt (1979) (pluses) and Floeder *et al* (1988) (squares), and theories, McEachran *et al* (1979) (full curve), Montgomery and LaBahn (1970) (broken curve) and Bartschat *et al* (1988) (chain curve). Results for electron impact: experiments, Smith *et al* (1989) (circles) and Srivastava *et al* (1981) (squares), and theories, McEachran *et al* (1978) (full curve), Williams (1979) (broken curve) and Williams and Willis (1975) (chain curve).

Related to this absorption effect is the prediction (Brown and Humberston 1985, Campeanu *et al* 1987a) of a cusp in the total cross section appearing at the positronium formation threshold. That is, with increasing impact energy, the elastic cross section should exhibit an anomalous slope change when the new channel opens and competes strongly with it. That such behaviour should exist in the energy range near channel thresholds was originally proposed by Wigner (1948) in discussion relating to nuclear reactions. Evidence of this effect in electron-atom collisions has been proposed in studies of the elastic differential cross section near the first excitation threshold (e.g. Eyb and Hoffman 1975). However, no direct measurement of the total cross section for positron elastic scattering above the positronium formation threshold has yet been made. Campeanu *et al* (1987a) have estimated this cross section by subtracting the positronium formation cross section from the total scattering cross section. Their results do indicate a threshold anomaly, but, as they point out, the large uncertainties in the near-threshold positronium formation cross section suggest that caution should be used in conclusively stating that a cusp exists.

The measurements made thus far have been in target gases which have especially large elastic cross sections. However, with the advent of higher flux positron beams, more measurements of positron impact total and differential cross sections would be desirable in the theoretically more tractable gases like H, H_2 and He. Measurements concerning positron impact excitation have been made in He, as well as in Ne and Ar, but are also quite few in number. These experiments, based on the time-of-flight spectra method, have been performed by Coleman and Hutton (1980), Coleman *et al* (1982a), Sueoka (1982) and Mori and Sueoka (1984). They have been reviewed by Charlton and Laricchia (1990) who discuss the inherent limitations of the technique used which make comparison with theory difficult. Further, these reviewers note that corresponding theoretical results display a considerable number of variations from one another. In this regard, future extensions of the experimental measurements and the subsequent interplay with theory should be expected.

Indeed, one should expect new experiments, arising as larger positron fluxes become available, which complement the analogue electron impact experiments. Perhaps even strenuous tests of theory and detailed probes of the collision dynamics such as impact excitation alignment and orientation parameter measurements will occur. Already, a significant number of the theoretical works considering these parameters have included treatments for both electron and positron impact. In addition, antiproton impact studies also hold the possibility of leading to further insight into excitation phenomena in the future (see e.g. Lin *et al* 1989). We note that Pedersen and Hvelplund (1989) have observed a difference between electron and proton impact double excitation, emphasizing the correlated nature of the two-electron process required to produce double excitation. This study, comparing oppositely charged particle impact, has been motivated in large part by the proton/antiproton double ionization experiments.

7. Exotic collisions involving antimatter

As positron, antiproton and muon beam technology evolves and matures in its application to atomic collision studies, it should be expected that experiments will be performed to compare matter and antimatter interactions through a number of different reaction channels. Further, the future holds the promise of not only repeating the analogues of the traditional electron and proton experiments, but also novel measurements made possible by the advent of experimentally utilizable antimatter. Of current interest in atomic physics are investigation of (i) systems in which an exotic particle is substituted for its ordinary counterpart in an atom, (ii) bound states of matter and antimatter and (iii) bound states consisting exclusively of antimatter.

For example, these studies include those concerning exotic atoms formed when a negatively charged particle takes the place of an electron in an ordinary atom. The most common of such species are muonic and antiprotonic atoms, which are, of course unstable. Yet they persist long enough to allow observation of dominant spectral lines and are often formed in excited states which non-radiatively deexcite, ejecting electrons. Thus comparison of theory and experiment regarding observation of these electromagnetic and electron spectra provide fundamental tests. In addition, great practical interest exists in muon catalyzed fusion (see reviews by Bracci and Fiorentini 1982, Cohen 1989) in which a negative muon replaces an electron in a heavy isotope of molecular hydrogen thereby reducing the mean internuclear separation, leading to an enhancement of the spontaneous fusion rate. The study of antiprotonic atoms, or other hadronic (e.g. pionic, kaonic or hyperonic) atoms, is also of interest since they consist of particles interacting through the strong nuclear interaction and provide information to test theories of this force (see e.g. Pennington 1985). These experiments are often limited by the fact that the degree of ionization of the atom which occurs during the deexcitation following formation is unknown and recent investigations have been performed to further understand this problem (see e.g. Bacher *et al* 1988).

Other exotic bound states include such species as positronium, protonium and muonium. For example, positronium ($e\bar{e}$, Ps) and protonium ($p\bar{p}$) consist of particle-antiparticle pairs and may be formed in charge transfer collisions of antimatter with matter. Positronium, theoretically predicted by Ruark (1945) and Wheeler (1946) and observed experimentally by Deutsch (1951, 1953), and aspects of its formation in this manner were discussed above. Similarly, protonium has been formed by the bombardment of a high density hydrogen target by antiprotons and, as has been recently proposed, it may be produced in the future by collisions of corotating beams of antiprotons and H^- in the LEAR at CERN (see references in Cohen 1987). Muonium ($\bar{\mu}e$, Mu) was first observed in vacuum by Bolton *et al* (1981) in a beam foil experiment at LAMPF. That group has also recently observed the negative muonium ion ($\bar{\mu}ee$, Mu^-) (Kuang *et al* 1989) and in addition, Mills (1981) has reported observation of the nagative ion of positronium ($e\bar{e}e$, Ps^-). The production of these systems ($e\bar{e}$, $p\bar{p}$, $\bar{\mu}e$, $\bar{\mu}ee$, $e\bar{e}e$) is significant because of the intriguing nature of their constituents and since they provide important tests of fundamental theory. Positronium and muonium are composed only of leptons and are consequently important systems testing quantum electrodynamics, as is, on the other hand, protonium concerning the strong interaction. Further, Mu^- and Ps^- provide a test of our understanding of the three-body problem.

Perhaps the most interesting species made possible by the availability of low energy antimatter is antihydrogen, the bound state of an antiproton and a positron. Antihydrogen is the mirror image of ordinary hydrogen and its creation would represent the first realization of an antimatter atom. Fundamental tests based on the study of spectral energy levels of antihydrogen would lead to strenuous tests of *CPT* invariance (Poth 1989) and gravitation and would hold significance for cosmological theories. Further, its production and isolation would lead to a practical scheme for producing polarized antiprotons for atomic and nuclear collision studies. Due to its net charge neutrality, perhaps even the storage of antihydrogen for use as an energy source will eventually be possible. Three principal methods of production have been suggested and have been reviewed recently in some detail by Charlton (1988) and Poth (1989).

The first method was suggested by Budker and Skrinsky (1978) and relies on the spontaneous radiative recombination of a positron by an antiproton in a colliding beam arrangement. Enhancement of the capture process by stimulation from laser irradiation (Neumann *et al* 1983) has been considered as well and predictions of formation rates have been made for the operating parameters of the LEAR by Poth (1987). This method is most efficient at high energies where radiative processes dominate the yield obtained with other methods such as mechanical charge transfer. At lower collision energies, antihydrogen may be formed by the charge transfer of a positron from positronium to an antiproton, as suggested by Deutch *et al* (1986). In this scheme, positronium is first produced in a trap and antihydrogen is formed in the subsequent bombardment by a burst of low energy antiprotons (Deutch *et al* 1988). The cross section for capture has been calculated by a number of authors (Humberston *et al* 1987, Ermolaev *et al* 1987, Darewych 1987, Nahar and Wadehra 1988) and its maximum value is quite large (on the order of 10^{-15} cm^2). Accordingly the rate of antihydrogen formation is high for this method, but it requires the production of antiprotons of kinetic energy as low as a few keV where the cross section peaks.

It should be noted that not only have antiprotons been cooled from GeV to MeV energies at LEAR, but further cooling to the meV range has been reported by Gabrielse and coworkers (Gabrielse *et al* 1989b). These authors had previously (Gabrielse *et al* 1986) utilized an ion trap to store antiprotons with energies less than 3 keV and by the introduction of a buffer gas of cold-trapped electrons within the trap, have observed cooling below 100 meV. Energy widths as small as 9 meV were obtained and the cold antiprotons were stored for a period of days. The availability of such very low energy antiprotons, along with their application in other fundamental studies, has suggested the third possible method of antihydrogen production. Gabrielse *et al* (1988) have proposed the use of nested Penning traps in which cold antiprotons and positrons are confined. The reaction proceeds through the three-body interaction of an antiproton with two positrons, one of which combines with it to form antihydrogen and the other carrying away the energy required by conservation.

Thus, a number of alternative methods to produce antihydrogen, which rely on different reactions, require different experimental arrangements and proceed at a wide range of kinetic energies, have been suggested and are in various stages of preparation.

8. Conclusion

Recent works clearly evidence the fact that the thrust of both experiment and theory are being greatly influenced by the intriguing possibilities raised by the advent of low energy antimatter projectiles suitable for use in atomic physics. Furthermore, comparisons of matter- and antimatter-atom collisions have served to highlight the underlying collision dynamics and have provided a very useful tool in the study of atomic collision processes.

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