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COLLISION EXPERIMENTS WITH ANTIPROTONS

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Abstract

From the upgraded CERN antiproton ($\bar{p}$) "factory" high intensity and low emittance $\bar{p}$ -beams in the keV-MeV region will be available for detailed atomic collision experiments. The very first investigations of $\bar{p}$ collisions in He, Ne, and Ar gases gave the most surprising results: The double ionization cross section for $\bar{p}$ on He is up to twice as high as that for protons. Similar effects are found in Ne and Ar. The x rays emitted after the $\bar{p}$ capture in atoms offers very interesting possibilities within atomic, nuclear and particle physics. Many new collision experiments are already in preparation.

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I. Introduction

With the completion of the antiproton collector (ACOL)/antiproton accumulator (AA) system at CERN the amount of available antiprotons ($\bar{p}$) will be strongly increased. Through the modified low energy antiproton ring (LEAR) keV-MeV antiproton beams will now be available with sufficiently high intensity to permit detailed investigations of $\bar{p}$ -interactions with gases and solids. Further on the low emittance of LEAR allows interesting experiments on directional effects in single crystals.

The interaction of MeV-ion beams with gaseous and solid targets has been subject to very detailed investigations during the last some fifty years. A large part of the work has been concentrated on the following subjects: Energy-loss, range measurements, collision phenomena, atomic and nuclear excitations, implantation, and directional effects in crystalline targets. The possibility of having a low-momentum, high-quality antiproton beam with a high intensity has already led to a variety of new experiments, which will solve some of the questions that still remain open within the above subjects. The possibility of experiments with protons and antiprotons creates many new and interesting opportunities and will serve to elucidate the discriminatory manner in which matter interacts with positive and negative particles of the same kind.

In the following is given a short description of "the antiproton factory" at CERN. Then the first ionization experiments in gases using MeV antiprotons are discussed. Also ionization due to antiproton capture will be touched upon. Finally some new and approved experiments are described.

II The LEAR FACILITY

The low energy antiproton ring (LEAR) is a small storage and stretcher synchrotron. The antiprotons are injected into the ring from the CERN $\bar{p}$ -production facility which is shown in fig.1. The machine complex consists of a Linac, the booster (PSB), the 26 GeV Proton synchrotron (PS), the antiproton collector (ACOL) and the antiproton

Fig. 1. Schematic layout for the CERN $\bar{p}$ factory and LEAR.

accumulator (AA). Antiprotons are produced by 26 GeV/c protons, from the PS incident on an external target. ACOL accepts $\bar{p}$ at their production optimum of 3.5 GeV/c in order to obtain the maximal possible $\bar{p}$ flux.

In around 2 sec the stochastic cooling system of ACOL compresses the $\bar{p}$ -burst in phase space and the batch is transferred to AA. Here this $\bar{p}$ -burst is again cooled by the AA stochastic cooling system before placed into a storage orbit. By this technique around 5×10^{10} $\bar{p}$ /hour should be accumulated.

After having filled AA, the high intensity $\bar{p}$ -beams can now be peeled off from the AA-stack and then injected into the PS. Here the antiprotons are decelerated to 0.6 GeV/c and then injected into LEAR.

The antiprotons in LEAR can either be accelerated or decelerated down to below 1 MeV. The average number of $\bar{p}$ available for LEAR physics is $\sim 10^6$ $\bar{p}$ /sec with ultraslow extraction.

III. Inelastic collisions

Ionization in gases due to penetration of particle beams has been the subject of numerous theoretical and experimental investigations. Despite this, however, many questions remain unanswered, often due to lack of the right beams. The theoretical treatment of inelastic collisions is usually concerned with one of the two regimes, i.e., (i) those collisions in which the projectile velocity v is high compared to a mean velocity of atomic electrons in the shell under consideration, and (ii) those where the velocity is low compared to that of the atomic electrons. For (i), Bohr¹ early in this century published a theory, and more than fifty years ago, Bethe² developed his quantum-mechanical perturbation theory based upon the Born approximation. For a recent review, see Ref.3.

1. Single ionization

At sufficiently high projectile velocities v i.e., $v \gg v_0$ (Bohr velocity), the process of single ionization is essentially a two-body process and the first Born approximation can be applied. For singly charged particles it is found that

$$\sigma^+ = \frac{q^2}{v^2} \ln v \quad (1)$$

where q is the particle charge. Here it is seen that σ^+ contains explicitly the particle velocity rather than the kinetic energy. For single ionization by heavy charged particles the cross section σ^+ is well known both theoretically and experimentally. Further it should be noted that results from such perturbation treatment scale with q^2 . This means that the single-ionization cross section for equi-velocity electrons and protons is expected to be the same.

2. Multiple Ionization

For multiple ionization the understanding is far from complete. Even for the simplest cases the situation is obscure. In single ionization the process is satisfactorily described in the independent electron model whereas in multiple ionization the correlation between the atomic electrons is of great importance - especially in low- z atoms.

For the case of He double ionization can be produced in three different ways and can be visualized as shown in fig.2.

Fig.2. Schematic drawing of the three different mechanisms for double ionization in He, i.e., (a) shake-off, (b) Two-step one (TS1), and (c) Two-step two (TS2).

A fast ($v \geq 20v_0$) incident projectile with charge q knocks out one electron from the He atom. Then the other relaxes onto the electron states of He^+ . The projection onto the new continuum is finite and as a result the second electron has a non-vanishing probability for leaving the atom. This is called the shake-off (SO) mechanism (fig.2a).

On the other hand, it could also happen (fig.2b) that the first ejected electron may collide with the second electron resulting in double ionization. This process is called: Two-step one (TS1) since the projectile only interacts with one target electron.

In both processes the projectile only interacts with one of the target electrons through the perturbation $\Omega_i = -q e^2/r$ whereas the second electron is ejected as a result of electron-electron interaction. The total transition amplitude may therefore for these two processes be written as

$$\tilde{a}_I^{fi} = -q a_I^{fi} \quad (2)$$

where i and f are initial and final states, respectively and a_I^{fi} is independent of projectile charge. The first Born approximation predicts that

$$\sigma^{++} \propto \sigma^+ \propto (q/v)^2 \ln v \quad (3)$$

For lower projectile velocities the particle may collide with both target electrons (fig.2c) and thereby create double ionization. This process is called a two-step 2 (TS2) process. For such processes the transition amplitude may be written equivalent to (3), i.e.

$$\tilde{a}_{II}^{fi} = q^2 a_{II}^{fi} \quad (4)$$

where also a_{II}^{fi} is independent of q . Because of the two consecutive close particle-electron collisions the cross section σ_{TS2} is:

$$\sigma_{TS2}^{++} \propto (q/v)^4 \quad (5)$$

Due to the rapid fall-off with velocity, TS2 is only important at moderate values of v .

3. Electron-proton result

It was quite surprising when it was found⁴ for particle velocities $v \sim 10v_0$ that the ratio between the double- and single-ionization cross sections $R^{(2)}$ was not the same for equivelocity proton and electron impact, the latter giving $R^{(2)}$ -values a factor of two larger than the former. This inspired McGuire⁶ to suggest that the observed effect was due to an interference between the SO-process and the TS2-process leading to

$$\sigma^{++} \propto |a|^2 = |qa_{SO} + q^2 a_{TS2}|^2 \quad (6)$$

This of course gives a difference between $q=1$ and $q=-1$. In this model, the electron-proton difference is a charge effect. The addition of scattering amplitudes in the McGuire model was questioned and it was suggested⁷ that the difference is due to kinematic differences between the electron and the proton - even at these large particle velocities.

Inspired of this situation it was clear that a comparison of ionization from equivelocity protons and antiprotons could possibly clear up the situation.

VI Antiproton Results

1. Helium

In fig.3 is shown the experimental setup used in the first LEAR experiment with MeV-antiprotons for ionization investigations, Here the incoming beam (1) is going through degraders into the gas cell.

Fig. 3. Schematic drawing of the experimental setup used in the LEAR p experiments and for proton impact at the Tandem in Aarhus. The dashed lines indicate the beam size (FWHM) for 4 MeV p. The numbers refer to: 1) accelerator facility, 2) time-of flight tube, 3) channeltron detector, 4) stop detector.

The produced gas ions are accelerated by 800 V/cm^2 and finally focused into a detector kept on -3900V . The transmitted beam particles are stopped in a scintillator (4). Figure 4 shows typical time-of-flight spectra for incident p and $\bar{p}$. Clearly the ratio $R^{(2)} = \sigma^{++}/\sigma^+$ is simple to measure in this setup. For a parallel narrow beam in addition accurate absolute cross sections can be measured, but this is not the case for broad degraded beams because of collection problems, variation in gas pressure, etc.

Fig.4. Time-of-flight spectra obtained with 4.5 MeV p and $\bar{p}$ incident on a He gas (3m torr). The two spectra are normalized to the same He^+ yield.

In fig.5 is shown the measured ratio $R^{(2)} = \sigma^{++}/\sigma^+$ as a function of particle energy for electrons protons and antiprotons on He^5 . In general there is good agreement for electron and proton results with other experimental work. For the antiprotons $R^{(2)}$ is more than a factor of two above the proton results - a most surprising result.

The open question whether the difference in double ionization of He with e^- and p impact above 1MeV/amu is due to the different masses or different charges^{6,7} is now solved. The present results with antiprotons from LEAR clearly demonstrate that the difference is a charge effect. The difference for p and $\bar{p}$ is about a factor of two between 0.5MeV/amu and 5MeV/amu . The data indicate that the difference in $R^{(2)}$ disappears at about 50MeV/amu , where the data for e^- and $\bar{p}$ seems to merge.

When $E(\text{MeV/amu})$ is below ~ 5 , the data for e^- and $\bar{p}$ impact give different ratios $R^{(2)}$. Most of this difference is caused by different double-ionization cross sections, since the single-ionization cross sections are identical except at very low velocity. The rapid fall-off in $R^{(2)}$ for electrons is attributed to the finite threshold energy for double ionization, which for He is 79eV , corresponding to 0.14MeV/amu . It is noted that the data obtained with electrons and antiprotons merge at about 5MeV/amu . Evidently, the energy threshold

Fig. 5. The ratio $R^{(2)}$ between double- and single ionization cross sections for protons (p), antiprotons ($\bar{p}$) and electrons (e^-) colliding with He.

at 79 eV influences the dynamics of the double-ionization process for electrons, even at an energy in the excess of 2keV.

For proton impact, $R^{(2)}$ increases rapidly at low energy ($<0.5\text{MeV/amu}$) due to the increasing importance of electron capture and to the dominance of two-step collisions with the projectile (TS-2). In the Born approximation TS-2 leads to a value of $R^{(2)}$, which is proportional to $q^2 v^2 (\ln v)^{-1}$. For antiprotons there is no charge transfer and the raise is solely caused by TS-2.

2. Interference Effects

As mentioned above it was McGuire⁶ who first suggested the e^- - p difference to be an inference between SO and TS2 but this was questioned by Reading and Ford⁷.

Since the appearance of the present antiproton data⁵ the question of correlation between atomic electrons has been discussed eagerly by different authors^{7b,8,9}.

In general the antiproton data supports the idea by McGuire that interferences between different double ionization mechanisms may cause projectile charge effects even at relatively high velocities. A new "ab initio" calculation by Reading and Ford^{7b,c} gives an enhanced ratio $R^{(2)}$ for $\bar{p}$ impact, but only 50% of the measured increase for $R^{(2)}$ is obtained. In addition an overall 30% correction had to be introduced for all particle data: protons, electrons, and antiprotons. Some of the effects in fig.5 are also reproduced below 1 MeV by a classical Monte Carlo calculation⁹.

Very recently it was suggested that the large difference in the double ionization cross section of He by positive and negative charged particles might be due to an interference between the two second Born mechanisms TS-1 and TS-2¹⁰. In the present velocity range their amplitudes are comparable.

At high projectile velocities, where electron capture may be neglected, the cross section for double ionization is given by the sum of Eqs. (2) and (4), i.e., the cross section attains the value

$$\begin{aligned}
 \sigma^{++} &= \sum_f |\tilde{a}_I^{fi} + \tilde{a}_{II}^{fi}|^2 \\
 &= q^2 \sum_f |\tilde{a}_I^{fi}|^2 + q^4 \sum_f |\tilde{a}_{II}^{fi}|^2 - q^3 \sum_f (\tilde{a}_I^{fi} \tilde{a}_{II}^{fi*} + \tilde{a}_I^{fi*} \tilde{a}_{II}^{fi}) \\
 &= q^2 \sigma_I + q^4 \sigma_{II} - q^3 2\sigma_{int},
 \end{aligned} \tag{7}$$

where σ_I and σ_{II} are the cross sections for double ionization as a result of one and two interactions with the projectile, respectively. σ_{int} is the contribution due to interferences between the two processes.

Experimentally, $R^{(2)}$ has been measured with $q=+1$ (protons), $q=-1$ (antiprotons, electrons) and $q=2$ (alpha particles). Under the assumption that $\sigma^+(p) = \sigma^+(\bar{p})$ and $\sigma^+(\text{He}^{2+}) = 4\sigma^+(p)$, which are valid in the energy range $>1\text{MeV/amu}$ to be considered in the following, it is obtained from Eq.(7)

$$R_I \equiv \sigma_I / \sigma^+(p) = R_p^{(2)} + \frac{1}{3} R_{\bar{p}}^{(2)} - \frac{1}{3} R_{\text{He}^{2+}}^{(2)} \tag{8}$$

$$R_{II} \equiv \sigma_{II} / \sigma^+(p) = -\frac{1}{2} R_p^{(2)} + \frac{1}{6} R_{\bar{p}}^{(2)} + \frac{1}{3} R_{\text{He}^{2+}}^{(2)} \tag{9}$$

$$R_{int} \equiv \sigma_{int} / \sigma^+(p) = -\frac{1}{4} (R_{\bar{p}}^{(2)} - R_p^{(2)}). \tag{10}$$

In fig 6a are shown the experimental data for the three types of projectiles (p , $\bar{p}$ and α -particles) fitted with smooth curves. From the experimental $R^{(2)}$ -values R_I , R_{II} , and R_{int} can be found (fig.6b). It is seen that R_I is nearly energy independent in agreement with the definition of σ_I . Furtheron R_{II} is essentially proportional to $1/E$ - also in agreement with the definition of σ_{II} . It should be noted that R_{int} , which contains the important new information, is proportional to v^{-1} - as expected from the velocity dependence of σ_I and σ_{II} .

The experimental curves (R_I, R_{II}) in fig.6b are compared to theoretical curves calculated by dividing the cross section σ up into contributions from close and distant collisions, i.e.

$$\sigma = \sigma_c + \sigma_d. \tag{11}$$

The distant collision part is calculated using the virtual photon model by Weizsäcker-Williams (for details ref.5b). By using simple analytical fits to experimental photoabsorption cross sections σ_d^+ and σ_d^{++} is found. For σ_d^{++} the calculations give

$$\sigma_d^{++} \propto q^2 \ln v / v^2 \tag{12}$$

Fig 6. a) Smoot curve fit to experimental data for $R^{(2)}$ in the He gas. b) R_I , R_{II} and R_{int} as a function of $E(\text{MeV/amu})$ in He. Solid curves represent R_I , R_{II} and R_{int} as obtained from fits to experimental data for protons, antiprotons, high-energy electrons and alpha particles as shown in (a). The dashed curves result from theoretical estimated as discussed in the text.

In this model the limiting impact parameter d between close and distant collisions appear underneath a logarithm so the exact choice is not very important. In the Williams model d corresponds to energy transfer to the electron in excess of the ionization energy. Consequently in the close collision the particles can be considered as free and a Thompson cross section can be used. This leads to the following σ_c^+ for the two processes TS-1 and TS-2:

$$\sigma_{c,TS1} \propto q^2 (v_0/v)^2 \quad \text{and} \quad (13)$$

$$\sigma_{c,TS2} \propto q^4 (v_0/v)^4 \quad (14)$$

At high velocities $v \sim 10v_0$ and heavy projectiles the impact parameter relative to the nucleus is well defined, so no interference effect can occur between close and distant collisions. This means in the present model that distant collisions cannot contribute to σ_{int} since $\sigma_d^+ \propto q^2$ and thereby the ionization amplitudes scale linearly with q .

The good agreement between calculated and measured R_I and R_{II} values shown in fig.6b gives confidence to the result from the simple estimates of the model.

3. Neon and Argon

Enhancements in the double ionization of He as found for $\bar{p}$ impact have also been observed for antiproton impact on Ne and Ar targets. However, in the case of triple to single ionization ratios (Fig.7),

Fig. 7. Ratio of triple to single ionization cross sections of neon and argon as a function of the impact energy for the antiprotons.

of a factor of four is found for Ne, whereas equal values are found for $\bar{p}$ and p on Ar targets. This can be understood when multiple ionization probabilities due to inner-shell vacancies and subsequent ejection of electrons are considered. As is known from x-ray ionization experiments, the triple ionization of argon is dominated by such Auger processes, whereas for neon, outer-shell ionization is the important process, both in double and triple ionization.

4. Ionization by $\bar{p}$ -capture

When the incident $\bar{p}$ are decelerated to thermal energies they are captured in the Coulomb field from the target atoms. The antiprotons are captured in high n -states and from thereon cascade down through the Bohr-orbits. The cascade proceeds mainly through radiative and Auger transitions.

If electrons are present in the capturing target atom the Auger process is the dominant mode requiring energy conservation. In neon, argon, and krypton the Auger mode is dominant for $n \geq 7, 9$ and 13, respectively¹¹. In fig.8a is shown the emitted x-ray spectrum from the radiative cascade in Ne. In fig.8b is shown the same type of spectrum

Fig. 8. X-ray spectra from the antiproton cascade in a) Ne (20 mbar gas) b) Ar (50 mbar gas) and c) Kr (25 mbar gas).

for argon. Here it should be noticed that transition 17→16 and 16→15 are suppressed. The energy of these two transitions correspond to the binding energies of the two K-shell electrons when all the other electrons are stripped off, so the last K-shell electrons are emitted by Auger effect. In fig.8c the same spectra are shown for krypton where also the L-shell electrons are peeled off through the transitions 28→27 to 25→24. From thereon radiative transitions show up until the x-ray energies are large enough to eject the K-shell electrons, which correspond to transitions 16→15 and 15→14.

The three cases show how it is possible to completely ionize atoms through antiproton capture followed by $\bar{p}$ -cascading down through Bohr orbits. The ionization proceeds through a peeling off the electrons from outer to inner shells.

VII Future Experiments

Very recently a new LEAR experiment (PS194^{II}) was approved at CERN. In the proposed investigations the energy range for the incident $\bar{p}$ beams will be extended downwards to around 100 keV and upwards to 21 MeV. Hereby it is possible to investigate the ionization in the SO and TS2 limits. By measuring the impact parameter dependence of the ionization it can be cleared up whether the interference effect belong solely to the close collisions as indicated by eq.(12,13,14). Dramatic differences in the inner-shell excitations are predicted for antiproton impact compared to proton^{12,13}. It is also proposed to continue the experiments on the difference in ionization energy loss for protons and antiprotons (the Barkas effect). Here it is hoped to clear up the longstanding discrepancy between the two theories on Z_1^3 corrections to stopping power by Jackson, McCarthy¹⁴ and Lindhard¹⁵. Lindhard pointed out that close and distant collisions contribute equally to the Barkas effect contrary to Jackson, McCarthy. Therefore the Lindhard Z_1^3 correction is approximately twice that of Jackson, McCarthy.

The ionization experiments will be continued by measuring the specific K-shell excitation for p and $\bar{p}$ impact. Finally the first channeling experiments with $\bar{p}$ are proposed.

VIII Conclusion

The low energy antiproton beams from LEAR - mainly set up for particle physics - have shown extremely interesting applications in atomic physics.

The very first experiments in atomic collisions with MeV antiprotons gave very surprising results and will clear up longstanding questions. New problems have been brought up which ask for more investigations. In conclusion it has been found that single ionization cross sections of He, Ne, and Ar for p and $\bar{p}$ impact are the same in the energy range from 0.5 MeV to 5 MeV. In the same energy region the double ionization cross section for $\bar{p}$ is about a factor of two larger than that for p. The difference has motivated extensive theoretical work on interference effects in different collision mechanisms. Simple estimates have resulted in a separation of the interference terms and experimental data on these terms have been obtained from p, $\bar{p}$, e^- and α particle impact.

The multiple ionization of Ne and Ar have also shown surprising results. The triple-ionization cross section of Ne by $\bar{p}$ impact is

around a factor of four larger than that for p in contrast to the Ar case where the cross sections are equal.

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