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DOUBLE IONIZATION OF HELIUM BY PARTICLE IMPACT.

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abstract

In this communication we review experimental results of the ratio, $R^{(2)}$, of double to single ionization of He by proton, antiproton, electron and positron impact in the energy range from 0.15 to about 10 MeV/amu. At high velocities (>1-2 Mev/amu) values of $R^{(2)}$ caused by electron impact merge with those for the antiproton while the positron results merge with those for the proton with the $\bar{p}$, e^- values being up to a factor of 2 greater than that for the p, e^+. At these velocities the single ionization cross sections caused by impact of any of these four particles are indistinguishable.

Double ionization by charged particle impact is a fundamental collision channel in which two electrons are removed from the target atom. Experimentally, this collision channel has been studied for a variaty of target atoms for different projectiles[1-10]. Since it was discovered that the cross section for double ionization, σ^{++}, of He by electron, e^-, impact exceeded that for the proton, p, by a factor of 2 at a velocity of 1-2 MeV/amu[1,6] much effort has been devoted to the study of this collision process. The question arose whether this difference in σ^{++} was due to a charge or a mass effect. A later experiment with antiprotons[6-7], $\bar{p}$, on He showed that the difference in σ^{++} for p and e^- was mainly a charge effect. In the latter experiment it was found that σ^{++} for $\bar{p}$ merge with that for e^- at a velocity of 1-2 MeV/amu. Recently, this picture was confirmed in a positron, e^+, experiment[8] where it was shown that σ^{++} for this projectile merge with that for p at around 1 MeV/amu.

In simple terms, we may consider three types of collisions which can cause double ionization of He. The first is the so-called shake off mechanism, SO, in which the projectile ionizes one electron and as a result of electron - electron correlation in the initial state the second electron is ionized. Secondly, the projectile may collide with one of the electrons which thereafter collides with the second one resulting in ionization of both electrons. This two step process we label TS-I, where I indicates a single projectile interaction. Finally, the direct process in which the projectile hits and ionizes both electrons, TS-II. Individually, the cross sections of these three mechanisms depend on the projectile charge, q, as q^2, q^2 and q^4 and as such give no hint that σ^{++} depends on the projectile charge. However, as was first pointed out by McGuire an interference in the final state between the direct channel (TS-II) and the shake-off process could lead to a term in σ^{++} proportional to q^3. A similar effect can also occur due to interference between TS-I and TS-II.

Rather than measuring the values of σ^{++}, it is the ratio, $R^{(2)}$, of double to single ionization that is experimentally determined. At high

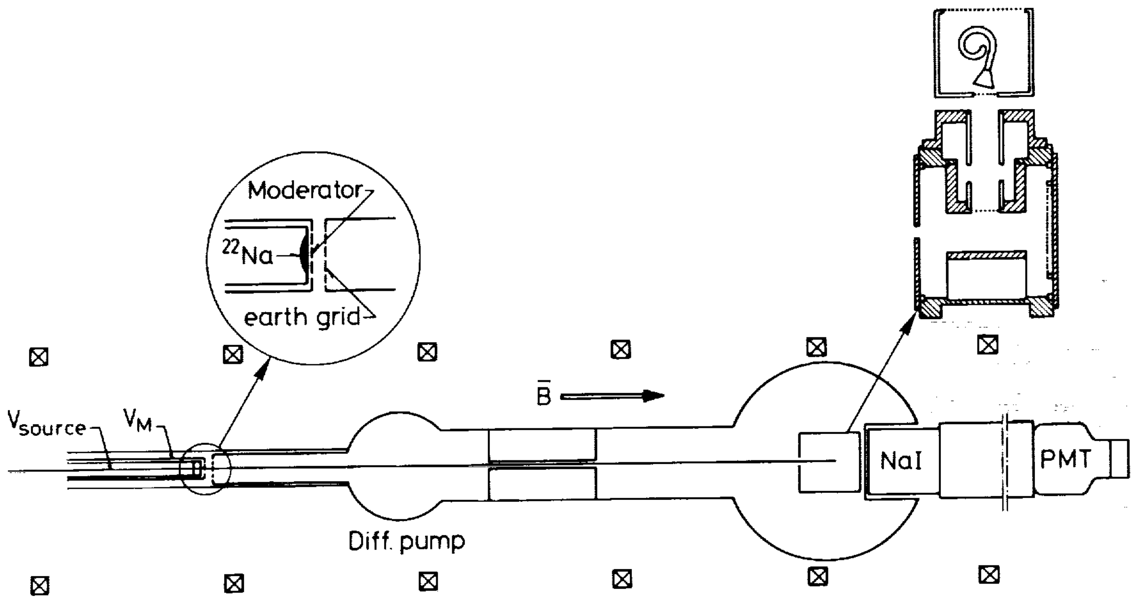

Fig. 1 The positron beam used for collision studies. The left insert shows the source - moderator configuration and the right one details of the scattering cell.

impact velocities it is well known that the single ionization cross sections of helium are indistinquishable for e^-, e^+, $\bar{p}$ and p with same velocities[7,11] and are well described within the Born approximation. Below, a brief description of the experimental procedures in the determination of $R^{(2)}$ is given. This is followed by a review and discussion of the experimental results.

Fig. 1 showns the experimental setup used in the positron measurements. The e^+ beam with an intensity of 10^4 sec^{-1} and an energy spread of 2 - 3 eV is obtained from a 2 mCi ^{22}Na source and an annealed tungsten mesh as moderator. After acceleration to the desired energy the beam is transported to the gas cell by an axial magnetic field of 50 gauss. At the end of the gas cell the e^+ are further accelerated into an annihilation target of aluminium and then detected by a 125 mm x 100 mm NaI detector. The gas cell contained a pair of parallel plate electrodes 40 mm long and separated by 20 mm, which were electrically biased to provide an extraction field for the ions. One of the electrodes contained a 10 mm aperture covered with a high transmission grid. Some of the ions produced by positron impact were able to pass through this grid into a flight tube where they were further accelerated by a factor of 4.5 Q (Q being their charge state) and focussed onto the cone of a ceratron detector. Just prior to impact on the cone the ions were additional accelerated 3.9 Q keV. This impact energy resulted in unity detection efficiency for He^+ and He^{++} ions.

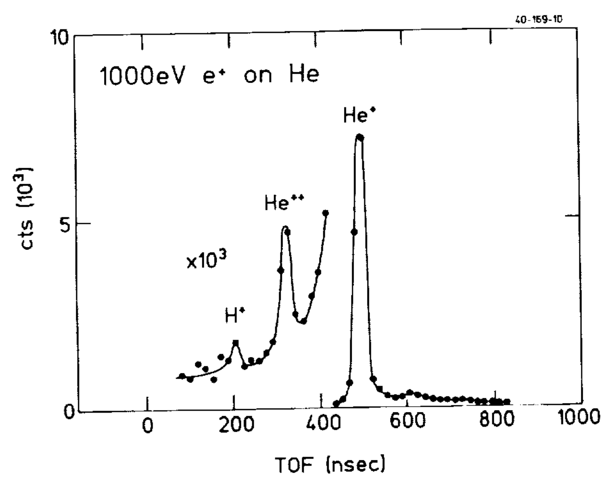

Fig. 2 shows a time of flight spectrum obtained for positrons colliding with the He target at an impact energy of 1 keV.

The extraction field for the ions was such that the total flight times were independent of their position of creation in the viewed portion of the gas cell. The ratio $R^{(2)}$ were determined by the Time Of Flight technique, TOF, in which the ceratron signal was used as a start in an inverted TOF coincidence setup with the stop signal supplied by the NaI detector. An example of a TOF spectrum is shown in Fig. 2. As observed, a tail appears on the single ionization peak due to delayed arrival of some of He^+ caused by resonant charge transfer reations in the gas. It was possible to account for all the single ionization events by including the tail when integrating over these events[8].

Basically, the experimental procedures followed in the e^-, $\bar{p}$ and p measurements were the same as that used for the e^+ with differences being: 1) the use of thin degrader foils to change the impact energy in the case of the $\bar{p}$ and in addition applying a TOF measurement for a more accurate determination of the $\bar{p}$ energies[7,10], 2) the use of a pulsed deflection system to provide a timing signal in the e^- case[8] and 3) applying a bunched beam delivered from a tandem accelerator in the p studies[7]. Furthermore, for the three latter particles the experiments were performed in a magnetic field free region. The effect of the magnetic field present in the e^+ case on the detection efficiency of the He ion were investigated and found unimportant for extraction fields greater than 100 V/cm[8]. For more detailed information on the experimental techniques employed in the e^-, e^+, $\bar{p}$ and p studies the reader is referred to the original papers.

Fig. 3 displays experimental results. The solid lines represent values for e^-, $\bar{p}$ and p with the latter results being average values as measured by several groups[1,5,7]. As observed the e^+ results merge with that of the p data and as such comfirm the results obtained by Andersen et.al.[7] that the large difference between the e^- and the p data is caused by a charge rather than a mass effect.

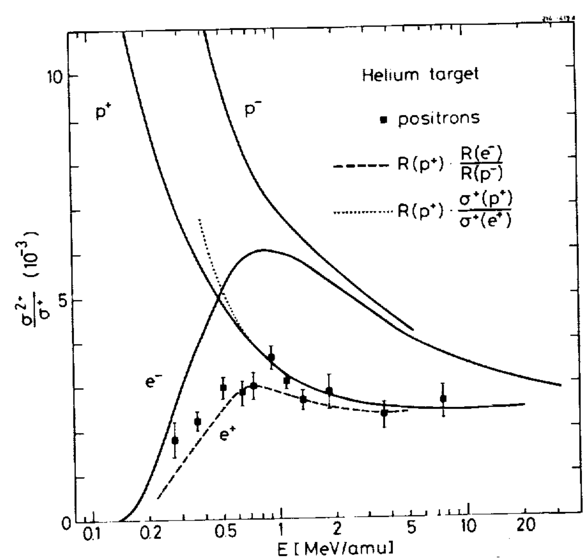

Fig. 3 shows the ratio of double to single ionization of He for protrons, antiprotons, electrons and positrons as a function of impact energy.

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At lower energies the values of R for e^- and e^+ falls below that for $\bar{p}$ and p, respectively. This is probably mainly due to the much lower kinetic energy of the light particles resulting in fewer available final states for these projectiles compared to that of the much heavier $\bar{p}$ and p. A similar effect is observed when single ionization cross sections for e^+ and e^- are compared to that for the proton. To see whether this mass effect is similar for e^- and e^+ it has been suggested[8] to write $R^{(2)}(e^+)$ as:

$$R^{(2)}(e^+) = R^{(2)}(p)(R^{(2)}(e^-)/R^{(2)}(\bar{p}))$$

and the result of this relation is shown as the dashed line in Fig. 3 and fits fairly well the positron results at impact energies in excess of 0.5 MeV/amu. This may indicate that the deviation between the e^- and $\bar{p}$ results (and correspondingly that for the e^+ and p) at energies between 0.5 and 2-5 MeV/amu is due to kinematic effects. At lower energies the results for the p and e^+ are influenced by electron capture resulting in the formation of H and Ps, respectively. In the e^+ experiment it was not possible to deduce the significance of double ionization of the He atom with Ps in the final state.

There have be a number of theoretical studies of double ionization of the He target since McGuire[12,13] suggested that the difference in σ^{++} for p and e^- was due to interference between the two different double ionization mechanisms SO and TS-II. Later Sørensen[7] argued that the observed difference of R for p and $\bar{p}$ could be explained by an interference between the two two-step mechanisms TS-I and TS-II. At impact energies greater than 1-2 MeV/amu of interest here one may question whether it is reasonable to speak about two distinct processes when considering the SO and TS-I mechanisms. In both of these cases the energy transfered by the projectile to the "first" e^- is generally low such that dynamic correlation between this e^- and the other target e^- should not be ignored. Double ionization by high energy photons results in the ejection of a fast electron and the subsequent electronic relaxation may result in ionization of the second e^-. The high energy limit of $R^{(2)}$ of He by photons is about one order of magnitude greater than that for particle impact[14].

In order to illustrate how interference in the final state may influence the values of $R^{(2)}$ differently for positive and negative projectiles we follow the ideas of Andersen et.al.[7]. In the SO and TS-I types of collisions the projectile interacts only with one electron through the perturbation $-Qe^2/r$, while the second e^- is ionized as a result of e^- - e^- correlation. Consequently, we may write the total transition amplitude for these processes as

$$a_I = -QC_I \tag{1}$$

where C_I is a constant. In the direct process, TS-II, where the projectile interacts with both electron we may write the total transition amplitude as

$$a_{II} = (-QC_1)(-QC_2) = Q^2 C_{II} \tag{2}$$

with C_{II} being another constant. By ignoring any other processes which may lead to double ionization, we can express σ^{++} as

$$\begin{aligned}\sigma^{++} &= \Sigma\,|a_I + a_{II}|^2 \\ &= Q^2\Sigma|C_I|^2 + Q^4\Sigma|C_{II}|^2 \\ &\quad - Q^3\Sigma|C_I C_{II}^* + C_I^* C_{II}| \\ &= Q^2\sigma_I + Q^4\sigma_{II} - Q^3 2\Sigma_{int}\end{aligned} \tag{3}$$

where σ_I and σ_{II} are the cross sections for double ionization as a result of one and two projectile interactions and Σ indicates a summation over the final states. σ_{int} is the contribution due to interference between these two processes. Under the assumption that $\sigma^+(He^{++}) = 4\sigma^+(p)$ then we obtain from Eq. 3

$$R_I = R^{(2)}(p) + [R^{(2)}(\bar{p}) - R^{(2)}(He^{++})]/3$$

$$R_{II} = -R^{(2)}(p)/2 + R^{(2)}(\bar{p})/6 + R^{(2)}(He^{++})/3$$

$$R_{int} = (R^{(2)}(\bar{p}) - R^{(2)}(p))/4 \qquad (4)$$

By applying Eqs. 4 to the experimental results for $\bar{p}$, p and He^{++} Andersen et. al.[7] obtained the results displayed in Fig. 4. The dashed lines in Fig. 4 are obtained from theory/estimates detailed in ref. 7. As observed R_I is independent of the projectile energy in agreement with expectation as σ_I like σ^+ is caused by a single projectile interaction. R_{II} is proportional to 1/E in rough agreement with the interpretation that σ_{II} is caused by two successive first Born types of collisions between the projectile and the target electrons. The interference term R_{int} is approximately proportional to $E^{-1/2}$ which is to be expected from the energy dependence of σ_I and σ_{II}.

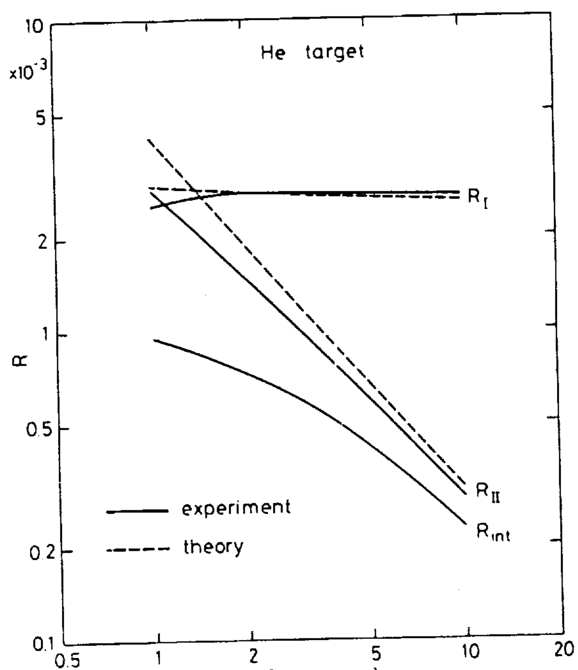

Fig. 4 shows the contributions of the various mechanisms involved in double ionization of the He target, see text for details.

Other theoretical interpretations of $R^{(2)}$ for the He target have been advanced. Reading and Ford[15], Olson[16] and Vegh[17] have all emphasized the role of e^- - e^- correlation in the postulated mechanisms by which this interaction may lead to a charge dependency of σ^{++}. Briefly, Reading and Ford[15] have suggested a model called interception in which they argue in the following way. A positive projectile outside the He atom will pull the nearest e^- away from the second one and thus reducing the probability of the TS-I mechanism while a negative projectile will push the two e^- toward each other. Reading and Ford[15] and Olsen[16] have also pointed out that in close collisions the screening of the nucleus depends on the projectile charge. For negative projectiles a transient decrease in the binding energy occurs which may result in an enhancement of σ^{++} over that for positively charged projectiles.

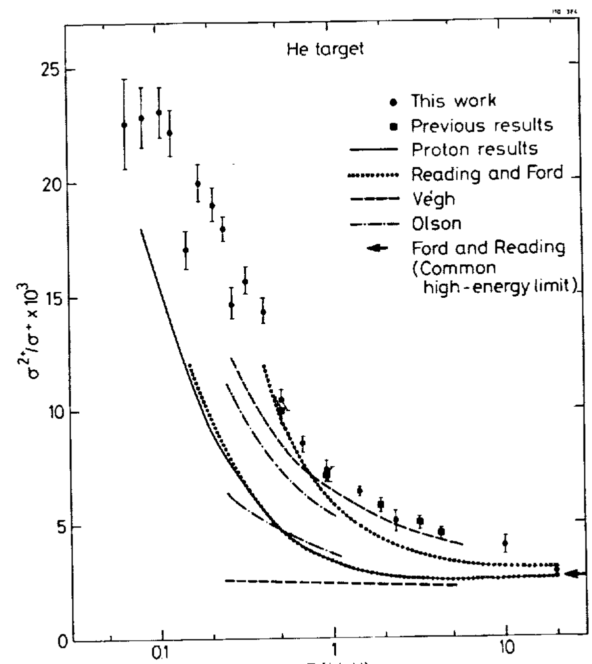

Fig. 5 compares theoretical and experimental results for the ratio of double to single ionization of He by p and $\bar{p}$ impact.

In ref.10 the experimental results of $R^{(2)}$ for p and $\bar{p}$ were compared to theoretical predictions[15-18] and their figure is reproduced in Fig. 5. The calculation of Reading and Ford[15] is based on the so-called forced-impulse methods, FIM, while that of Olson[16] results from a classical trajectory Monte Carlo, CTMC, study. Vegh[17] explains the difference in σ^{++} for p and $\bar{p}$ due to correlated motion of the target electrons during the collision. The results obtained by FIM seems most successful although at higher energies it only account for 50% of the measured effect. In a later calculation of the high energy limit of $R^{(2)}$ Reading and Ford[18] obtained excellent agreement with experiment by including d waves in their expansion.

In conclusion, it seems at present not possible experimentally to sort out which of the many effects in double ionization of He that are dominant for the difference in σ^{++} for positive and negative projectiles. However, what is established is the simularities of the e^+ and p results and correspondingly those of e^- and $\bar{p}$. Hence, further studies of correlation phenomena can be carried out using any of the two sets of projectiles.

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