01 Nov 1986

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Recommended Citation

H. G. Vogt et al., "Experimental Test of Higher-Order Electron-Capture Processes in Collisions of Fast Protons with Atomic Hydrogen," *Physical Review Letters*, vol. 57, no. 18, pp. 2256-2259, American Physical Society (APS), Nov 1986.
The definitive version is available at https://doi.org/10.1103/PhysRevLett.57.2256

Experimental Test of Higher-Order Electron-Capture Processes in Collisions of Fast Protons with Atomic Hydrogen

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(Received 17 July 1986)

We present measurements of the angular distribution of fast hydrogen atoms formed by electron capture of 2.8- and 5.0-MeV protons in atomic hydrogen. In the angular region of the Thomas peak (0.47 mrad) the experimental results obtained with this pure three-body collision system are in reasonable agreement with a strong-potential Born calculation and the impulse approximation, but not with other higher-order theories.

PACS numbers: 34.70.+e

At present there is great interest in electron capture in ion-atom collisions at high projectile velocity. High velocity here means that the projectile velocity is much higher than the Bohr electron orbital velocities in the initial and final states. Because of the rapid transfer of the electron from the target bound state to the fast-moving projectile bound state, a large change of electron momentum and energy is required which must be transferred to a third particle, which can be, in the case of nonradiative capture, the target nucleus. This process is theoretically attractive,[1,2] since higher-order terms of the electron-nucleus interaction become important in order to mediate this energy and momentum transfer. Formally, higher-order terms can be described by perturbative series expansions like the Born series. In the last few years different approaches to these series expansions have been developed, e.g., second-order Born (B2),[3-5] strong-potential Born (SPB),[6-9] impulse (IA),[10-12] continuum distorted-wave (CDW),[13,14] and eikonal approximations (EA).[15]

The higher-order terms in the capture amplitude can be interpreted as multiple scattering of the electron at the target and projectile potentials. In this view the second-order term is a double scattering for the capture of the electron, where the electron is first scattered at the projectile and then at the target nuclear potential as described first classically by Thomas.[16] This leads to a peak at a forward angle $\theta = (m/M_p)\sin 60°$ (m is the electron mass; M_p is the projectile mass) in the angular-differential capture cross section. The shape and absolute magnitude of the differential cross section may be determined not only by first- and second-order, but also by higher-order terms in the series expansions mentioned above.[12] However, in such treatments and at high collision velocities the description of the asymptotic states even to first order is a difficult task.[17] The ultimate experimental test of these theories can only be performed with a pure three-body collision system. We have therefore studied the three-body collision system p-H by measuring the angular-differential electron-capture cross sections at 2.8 and 5.0 MeV.

Among the different experimental approaches to test higher-order contributions to the electron-capture amplitude were studies of the electron cusp from capture into projectile continuum states. In these experiments, some signature of higher-order terms could already be identified.[18,19] In total cross sections of electron capture the higher-order terms might dominate the first-order term at very high collision energies,[1] e.g., for p on H above 100 MeV, where, however, the cross sections are extremely small. Calculations in a relativistic approach[20] show that the nonrelativistically expected[1] asymptotic energy dependences do not occur. For the measurement of the Thomas peak in the angular distribution of the charge-changed projectiles which should arise above 2 MeV for p on H, one has to measure very small scattering angles, 0.47 mrad for p as projectiles. Horsdal-Pedersen, Cocke, and Stöckli[21] have recently been able to identify the Thomas peak at such small angles; however, a decisive test of the theoretical models could not be accomplished. This is due to their choice of two-electron targets (He and H_2), which makes the comparison of their results with the three-body calculations currently available somewhat questionable, since not only are higher-order theories themselves tested but also the methods through which the second electron is incorporated in these calculations.

Even experimental data of total electron-capture cross sections of p in H at energies up to 5 MeV were not available until now, because of the lack of an atomic-hydrogen target with a low enough level of heavy-atom impurities. In the present work we were able to overcome this problem and to observe for the first time in the angular-differential capture cross sections for protons in atomic hydrogen a clear peak which is due to higher-order effects in the electron-capture amplitude.

The experiments were performed at the model EN tandem accelerator of the Max-Planck-Institut für Kernphysik, Heidelberg, where proton beams of 2.8 and 5.0 MeV after collimation to less than 0.05 mrad divergence impinged on an atomic-hydrogen gas target. Before entering the target region the beam was cleaned of charge-state impurities by magnetic deflection. Behind the target an electrostatic deflection of about 10 kV/cm was used to deflect the proton beam into a Faraday cup for normalization. The angular (θ) distribution of the neutralized projectiles relative to the beam axis was measured by a position-sensitive surface-barrier Si detector, located about 5 m away from the target. This detector was covered with a mask which allowed us to measure $d\sigma/d\theta$ and simultaneously to align and to control the position of the detector relative to the neutral-beam axis. The position calibration of the detector (position resolution 0.1 mm) was done with a collimated Am alpha source, which could be scanned across the detector.

The molecular hydrogen gas was dissociated in a dc-current-operated discharge tube. The main difficulties which had to be overcome in this experiment were impurities of heavy elements in the atomic-hydrogen target which appeared, e.g., by sputtering in the discharge tube. The cross sections for capture from the heavier atoms in the background gas are orders of magnitude larger than the cross section for hydrogen. Therefore, special treatment of the discharge arrangement was necessary, such as cooling the complete discharge tube by immersion in liquid nitrogen in order to freeze out impurities to a fraction of less than 10^{-5} of the hydrogen pressure (for determination and subtraction, see below). The cooling also helped to raise the dissociation fraction to above 90% by reducing the recombination rate at the target walls. In order to have sufficient target density at a high dissociation fraction the beam passed directly through a 10-cm-long differentially pumped part of the discharge region. By use of energy arguments, the amount of excited or ionized hydrogen atoms in the discharge is estimated to be negligible.

The beam profile at the detector position was measured in order to fold the theoretical predictions with the experimental angular resolution. In the folding procedure the geometrical properties of the detector due to the mask and broadening of the beam profile through multiple scattering in the target gas were also taken into account.

The target thickness was determined from the target-gas pressure and the known target length. This was independently checked by our measuring elastically scattered protons from He, H, and H_2 target gases. For a more detailed description of the experimental setup and measurement of the dissociation fraction and target thickness, see Schwab *et al.*[22]

The results of the angular-differential cross section $d\sigma/d\theta$ obtained in an 8-hour run with 5.0-MeV p capturing in atomic hydrogen are shown in Figs. 1(a) and 2. A clear peak at an angle of about $\theta=0.47$ mrad (the Thomas angle) can be seen. Such a peak does not appear in 5.0-MeV p on Ar [Fig. 1(b)]. In electron capture from argon higher-order contributions to the capture amplitude are negligible at this energy, and therefore a Thomas peak is not expected. The main contributions to systematic errors come from uncertainties of the target-density determination and are estimated to be less than 30%. In order to correct for impurities in the discharge, the dependence of the total capture rate $\dot{N}$ on the hydrogen pressure p_H was measured. From the clearly linear dependence of $\dot{N}$ on p_H a 30% impurity contribution was determined by extrapolation to $p_H=0$ for the

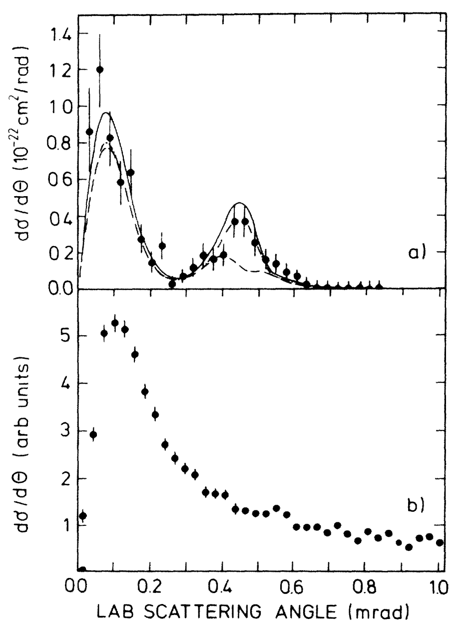

FIG. 1. (a) The measured angular-differential capture cross section $d\sigma/d\theta$ of 5.0-MeV protons in atomic hydrogen. Solid line: SPB-FP calculation for capture from 1s to 1s state. Dot-dashed line: impulse approximation for capture from 1s to 1s state. Dashed line: CDW calculation for capture from 1s to final states up to $n=4$. All calculations are folded with experimental angular resolution. (b) Measured differential capture cross section for 5.0-MeV protons in argon.

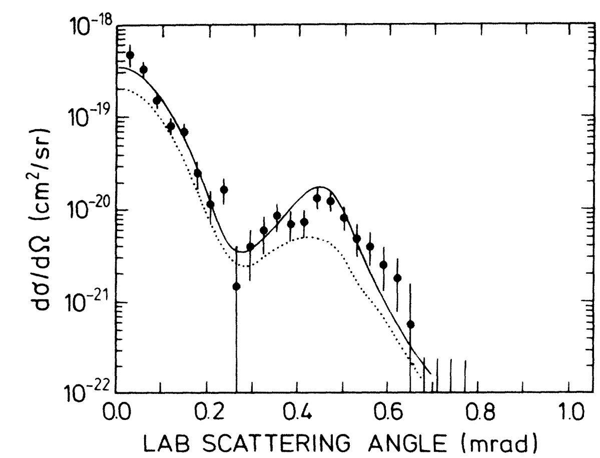

FIG. 2. The measured solid-angle-differential capture cross section $d\sigma/d\Omega$ of 5.0-MeV protons in atomic hydrogen. Solid line: SPB-FP calculation. Dotted line: SPMS calculation for capture from 1s to 1s state.

highest proton energy and the relevant H pressure.[22] In addition to Ar, the angular distribution of the capture cross section was also measured for N_2, and the two were found to be nearly identical in the measured range. Subtraction of an angular distribution with N_2 and Ar adjusted to 30% contribution in the total capture rate did not yield any difference in the H angular distribution within the error bars. So the correction with the Ar angular distribution [Fig. 1 (b)] was chosen. Several experiments with somewhat changed setups were performed[23] with reproducible results.

We compare our data with the SPB, IA, and CDW calculations. In the SPB approximation the intermediate electronic states are described by Coulomb waves that incorporate one of the two potentials to all orders. The impulse approximation (IA) can be deduced from the SPB amplitude by neglect of off-energy contributions. In contrast with the Born-series calculations, the CDW approximation describes the electronic wave functions by appropriate distortion operators. The solid line in Figs. 1(a) and 2 shows the results of the SPB full-peaking (FP) calculation,[8] where further peaking approximations to the SPB amplitude are introduced to evaluate the integrals.[6] The dot-dashed line in Fig. 1(a) gives the results of the IA. The dotted line in Fig. 2 shows the strong-potential McGuire-Sil (SPMS) calculation,[9] which is an improved SPB calculation where the errors are of order $(Z_p/v)^2$, compared to Z_p/Z_t in the SPB-FP calculation (Z_p, Z_t, and v are projectile and target nuclear charge and projectile velocity, respectively). The dashed line in Fig. 1(a) represents the CDW calculation.[13] All theoretical curves were folded with the experimental angular resolution described above. The SPB-FP, SPMS, and IA calculations take into account only nonradiative capture from the 1s target state to the 1s projectile state. The CDW calculation includes nonradiative capture from 1s to final states up to $n=4$. At 5.0 MeV a contribution to the differential cross section in the Thomas-peak region from capture to excited states was estimated to be about 20%.

As can be seen from Figs. 1(a) and 2, the IA and SPB-FP calculations are, in the region of the Thomas peak, in better agreement with our data in magnitude as well as in shape than the CDW and SPMS calculations. Not shown in Fig. 2 are the results of the second Born approximation (B2), where the intermediate electronic states are described by plane waves, which leads to an overestimation of the cross sections.[5,6] The deviation of the theoretical results from the data at very small angles near the forward direction was observed in all measurements and is probably due to strongly forward-peaked[1] radiative-capture contributions, which are not taken into account in the calculations mentioned above.

In Fig. 3 results for p on H at an energy of 2.8 MeV are shown. As in Fig. 2, the solid line shows the SPB-FP calculation, and the dashed line shows the CDW calculation. Both theories are folded with the angular resolution, which is broader in this case than in the 5.0-MeV case. Here only a light shoulder is seen at the Thomas angle. The reason for this comes basically from two factors. First, the higher-order terms become negligible with decreasing scaled velocity, and therefore the higher-order contributions are not so large here as in the 5.0-MeV case. Second, multiple scattering in the target gas is stronger at this lower energy, and this leads to a reduced angular resolution. The gas pressure in a discharge tube can only be varied in a limited range, and therefore it was not possible to avoid multiple scattering totally by reduction of the target pressure. This is also the reason that the systematic errors are about 50%.

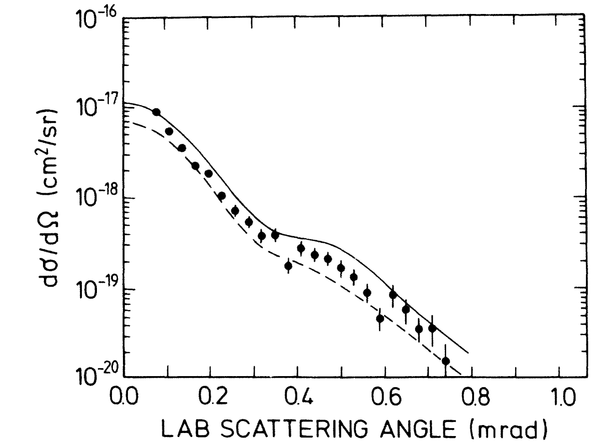

FIG. 3. Differential capture cross section $d\sigma/d\Omega$ for 2.8-MeV protons from atomic hydrogen; lines as in Fig. 1(a).

In conclusion, we give for the first time experimental results of angular-differential electron-capture cross sections in the high-velocity regime with a pure three-body collision system, p on H. At 5.0-MeV collision energy the so-called Thomas peak, produced only by higher-order terms in, e.g., the Born series, clearly appears in the angular-differential cross section. With use of this peak and also the valley at about 0.27 mrad it was possible to test higher-order contributions to the electron-capture amplitude. The magnitude and shape of this Thomas peak were found to be in good agreement with the results of the impulse and SPB-FP approximations, whereas the CDW and the SPMS approximations underestimate its absolute magnitude. The magnitude of the differential cross section around zero degrees angle, which is mainly determined by the first-order term of the capture amplitude, is well predicted by these theories.

We wish to thank J. H. McGuire, R. Rivarola, A. Salin, and L. Spruch for many encouraging discussions and J. H. McGuire and A. Salin for providing us with theoretical calculations. We acknowledge financial support from the Bundesministerium für Forschung und

Technologie.

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