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Momentum-transfer scaling in hydrogen-isotope collision systems

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The differential cross sections for excitation of atomic hydrogen isotopes to their $n=2$ states by proton or deutron impact are found to follow a simple scaling relationship. The momentum-transfer-scaled differential excitation cross sections, for a projectile velocity of 1.26 a.u., produce one differential cross-section curve for all four possible hydrogen-isotope collision systems. The experimental results are in excellent agreement with our Glauber-approximation calculations.

Recent experimental measurements and theoretical calculations at the University of Missouri—Rolla (UMR) have shown an interesting effect for angular differential electron-capture cross sections for hydrogen isotopes.[1] The angular differential electron-capture cross sections for proton and deuteron projectiles at the same velocity display a crossing at a very small scattering angle. This effect has not been observed for the different hydrogen-isotope target gases, hydrogen or deuterium. However, the total electron-capture cross sections are equal for protons and deuterons at the same velocity independent of the hydrogen-isotope target. These cross sections are of interest not only because of their application for high-intensity ion sources for thermonuclear fusion reactors,[2] but also because of the fundamental interest in the collision processes between hydrogen isotopes. The wave functions of the post and prior collision states are known exactly, and a comparison of theory with experiment provides a direct test of the validity of the approximations made in the theoretical predictions. It is generally expected that deuterons and protons of the same velocity will exhibit the same cross sections.[2,3] This statement has been shown to be true for the total cross sections but incorrect for the angular differential cross sections.[1] In addition, measurements of differential cross sections provide a better test for theoretical approximations because they strongly probe the impact parameter dependence of the cross section. The logical extension of the previous electron-capture differential cross-section investigation is presented in this paper. We have studied the excitation of both atomic hydrogen and atomic deuterium during the scattering of protons p and deuterons d through the scattering angle θ,

$$\begin{bmatrix} p \\ d \end{bmatrix} + \begin{bmatrix} \mathrm{H}(1s) \\ \mathrm{D}(1s) \end{bmatrix} \rightarrow \begin{bmatrix} p(\theta) \\ d(\theta) \end{bmatrix} + \begin{bmatrix} \mathrm{H}^*(n=2) \\ \mathrm{D}^*(n=2) \end{bmatrix} ,$$

at a laboratory collision energy of 40 keV/amu ($v=1.26$ a.u.). The apparatus has an angular resolution of 120 μrad, which made possible the measurements of the differential cross sections for the above-mentioned collision systems at very small scattering angles.

The differential cross sections for the excitation of atomic hydrogen or atomic deuterium from their ground state to their $n=2$ level by incident hydrogen-isotope ions have been obtained using an ion-energy-loss spectrometer. The apparatus and general method employed in measuring the differential cross sections have been discussed in detail elsewhere.[4,5] The hydrogen-isotope projectile ions are produced in a low-voltage discharge source (Colutron Model G2), whose operating parameters were identical for both proton and deuteron production. The recently described procedure was used to obtain the maximum purity of the deuteron projectile beam.[1]

The projectile ion beam, focused by an Einzel lens and mass analyzed by a Wien filter, is accelerated and steered through the high-temperature furnace target chamber. After traversing the scattering region, the projectile ions pass through the exit collimator. An analyzing magnet separates the ions undergoing electron capture from elastically or inelastically scattered ions. Beyond the analyzing magnet they enter the decelerator column. A 127° electrostatic energy analyzer equipped with an electron multiplier provides the ion-energy-loss detection of the incoming projectile ions.

The high-temperature furnace target is constructed of coaxial tungsten tubes, which are Joule heated to approximately 2700 K. Current flows coaxially along the furnace wall and returns through an adjacent coaxial shield. Atomic hydrogen or atomic deuterium is obtained by a catalytic dissociation of the molecular species on the hot tungsten surfaces. In this experiment it is not necessary to know accurately the percentage of molecular hydrogen or deuterium in the furnace because the 10.2-eV energy-loss peak in the energy-loss spectra of the atomic species is well resolved from the 12.5-eV energy-loss peak corresponding to the excitation of the molecular states. As the furnace is heated, the 10.2-eV energy-loss

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peak in the spectrum, which is attributed to the excitation of the atomic target gas to its $n=2$ level, appears. This peak increases with further heating while the peak at 12.5 eV, which belongs to the molecular target gas spectrum, decreases. An analysis of the spectra, taken before and after data acquisition, indicated a contamination of less than 5% molecular gas in the target furnace.[4,5]

Owing to the unknown thickness of the atomic gas target, the differential excitation cross sections are normalized to the measurements of the total excitation cross section of Park *et al.*[6] These experimental data for the total excitation cross section are normalized to the Born-approximation result of Bates and Griffing[7] [$\sigma(n=2)=6.637\times10^{-17}$ cm^2] for 200-keV proton impact excitation of atomic hydrogen to its $n=2$ level. Although there are significant differences between the Born approximation and more recent and reliable theoretical calculations, the Born approximation is considered to be fairly accurate for proton impact energies greater than 200 keV for total cross sections for excitation of low-lying strongly coupled states.[8]

The experimental data in Fig. 1 show that the angular differential excitation cross sections are independent of whether the target is atomic hydrogen or atomic deuterium if the data are displayed in the laboratory system. Here again the total excitation cross sections are all equal for any of the four systems considered for incident protons or deuterons with a common velocity.

The experimental data, shown in Fig. 1, clearly indicate the difference of the collision systems for proton and deuteron projectiles. At very small scattering angles, in the laboratory system, the differential excitation cross sections for deuteron projectiles are higher than for proton impact. For scattering angles larger than 0.20 mrad, in the laboratory system, the differential excitation cross sections for proton impact on both atomic hydrogen and atomic deuterium are definitely larger than for deuteron impact. The intersection of the two cross-section curves lies between 0.1 and 0.2 mrad in the laboratory system. The data points for the two collision systems are well separated to at least 0.8 mrad in scattering angle and distinguishable even though the experimental error bars overlap at some points.

As in the case for the total excitation cross sections for proton impact on atomic hydrogen, the relatively simple Glauber approximation provides surprisingly good agreement for the differential excitation cross sections of the same collision system.[8] Therefore we have calculated the differential excitation cross sections for proton and deuteron projectiles for both atomic gas targets using the Glauber approximation given by Franco and Thomas.[9] The Glauber scatter-

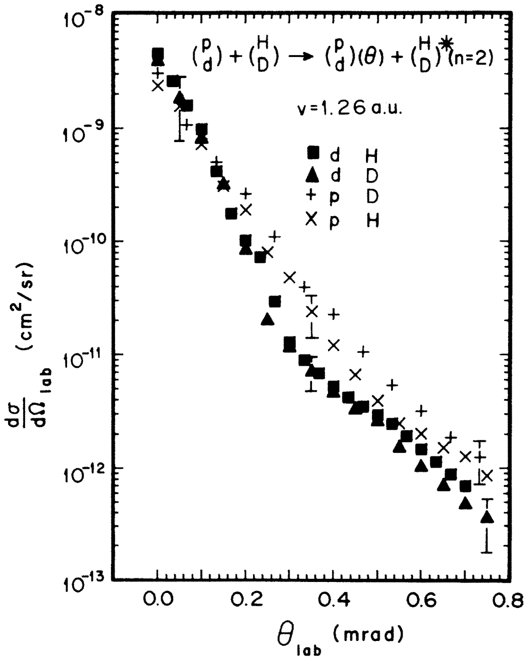

FIG. 1. Experimental angular differential cross section for excitation of atomic hydrogen and atomic deuterium to the $n=2$ by proton or deuteron impact, in the laboratory system. The error bars represent one standard deviation from the mean.

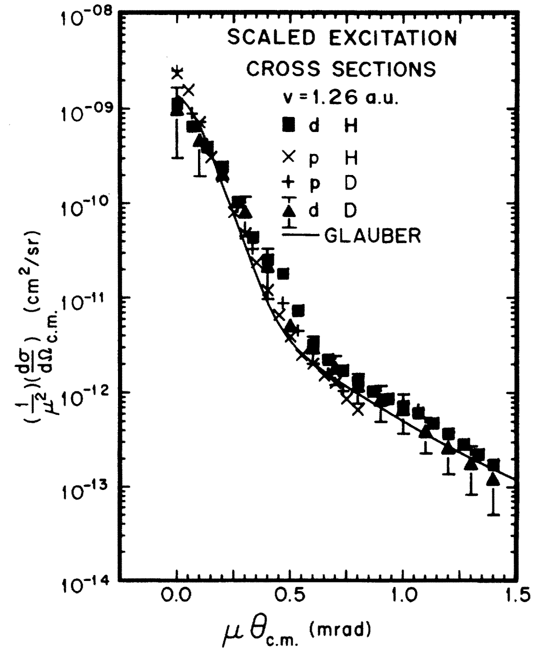

FIG. 2. Comparison of the measured and calculated differential excitation cross sections, scaled by momentum transfer, for the hydrogen-isotope collision systems. The discrete symbols represent our experimental data and the solid line is the result of our Glauber-approximation calculations.

ing amplitudes are given in terms of hypergeometric functions by Thomas and Gerjuoy.[10]

The Born-approximation results, which are not shown in the figures, fit the experimental data quite satisfactorily in the very small angle scattering region. At larger scattering angles, however, the Born-approximation calculation gives results for the excitation of atomic hydrogen by proton impact which decrease much faster than the experimental data.[5]

To check our recently developed simple scaling relationship for different hydrogen-isotope projectiles[1] we have plotted $(1/\mu^2)(d\sigma/d\Omega_{\rm c.m.})$ against $\mu\theta_{\rm c.m.}$, where μ is the reduced mass and $\theta_{\rm c.m.}$ is the center-of-mass scattering angle, for all possible collision systems for a projectile velocity of 1.26 a.u. Figure 2 shows the excellent agreement between the experimental data and the theoretical Glauber calculations for the hydrogen-isotope collision systems. The applied momentum-transfer scaling produces one curve for all four collision systems. This is in accordance with the Glauber-approximation results[9] which predict that $(1/\mu^2)(d\sigma/d\Omega_{\rm c.m.})$ should only be a function of the relative velocity and the momentum transfer between the colliding systems.

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