Isotope effect and momentum-transfer scaling in the elastic-scattering differential cross sections for hydrogen-isotope collision systems

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A projectile-dependent isotope effect was found for the elastic-scattering differential cross sections in the hydrogen-isotope collision systems. All four differential cross sections lie on a common curve if they are divided by the square of the reduced mass and plotted against momentum transfer. The experimental results are in satisfactory agreement with a simple Glauber-approximation calculation.

This Brief Report is an addendum to recent work in which we investigated both experimentally and theoretically an isotope effect in the hydrogen-isotope collisional systems.[1,2] Both electron-capture differential cross sections and excitation differential cross sections of the atomic target to its $n=2$ level for protons and deuterons with equal velocity ($E=40$ keV/amu) colliding with atomic hydrogen or deuterium targets showed a projectile-dependent effect in the laboratory frame at very small scattering angles.[1,2]

It is of interest to investigate the isotope dependence of the elastic-scattering differential cross sections for protons and deuterons colliding with atomic hydrogen or atomic deuterium. We have studied the processes

$$\begin{bmatrix} p \\ d \end{bmatrix} + \begin{bmatrix} \mathrm{H}(1s) \\ \mathrm{D}(1s) \end{bmatrix} \rightarrow \begin{bmatrix} p(\theta) \\ d(\theta) \end{bmatrix} + \begin{bmatrix} \mathrm{H}(1s) \\ \mathrm{D}(1s) \end{bmatrix}$$

at a laboratory collision energy of 40 keV/amu ($v=1.26$ a.u.).

A general description of the University of Missouri–Rolla ion-energy-loss spectrometer and the method employed in ion-energy-loss spectrometry have been given in detail in Refs. 3–5. The method used for extracting the elastic differential cross section out of the raw data is described in Ref. 5. The apparatus is a linear accelerator-decelerator system with an angular resolution of 120 μrad. This angular resolution, together with the accuracy of ± 0.03 eV in determining the energy-loss scale, permits an unambiguous identification of the elastically scattered ions. The necessary atomic gas target of either atomic hydrogen or atomic deuterium was provided through our high-temperature reactive scattering cell.[6] In order to obtain absolute differential cross sections for the elastic-scattering process we normalized the atomic gas target length l by using the known excitation differential cross sections of the atomic gas target to its $n=2$ level. The target density n inside the scattering cell was determined from pressure measurements by a Baratron Model 170 pressure meter.

Figures 1 and 2 display, in the laboratory system, the experimental elastic-scattering differential cross sections for all four possible collisional systems of the hydrogen isotopes. The measurements cover the angular scattering range from 0.16 to 1.2 mrad in the laboratory system and display the typical features of differential cross sections. They are sharply peaked in the forward direction and fall off rapidly in magnitude with increasing scattering angle. To our knowledge there are no other experimental elastic-scattering differential-cross-section data with which we can compare our results.

Displayed in the laboratory system the elastic-scattering differential cross sections for protons on either atomic hydrogen or atomic deuterium have the same shape and magnitude. The same result is true for deuterons on either atomic hydrogen or atomic deuterium. Thus in the laboratory system the elastic-scattering differential cross section is independent of the atomic hydrogen or deuterium target and only depends upon the projectile ion. However, the dif-

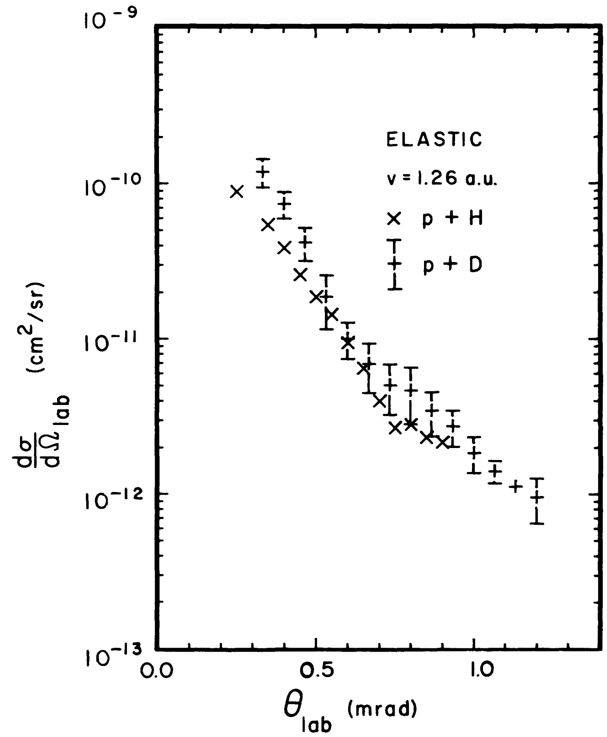

FIG. 1. Experimental angular differential cross sections for the elastic scattering of 40-keV protons from atomic hydrogen and atomic deuterium, in the laboratory frame. The error bars, shown only for the ($p+$D) system, represent 1 standard deviation from the mean.

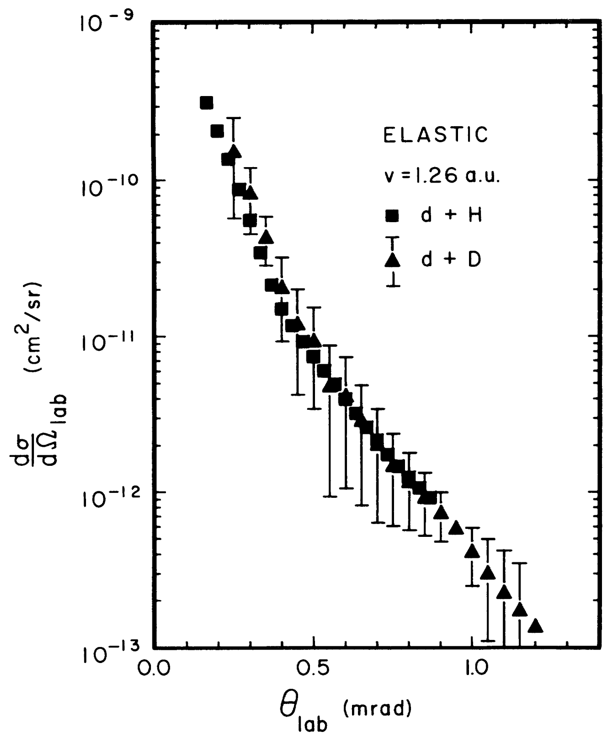

FIG. 2. Experimental angular differential cross sections for the elastic scattering of 80-keV deuterons from atomic hydrogen and atomic deuterium in the laboratory frame. The error bars, shown only for the $(d+D)$ system, represent 1 standard deviation from the mean.

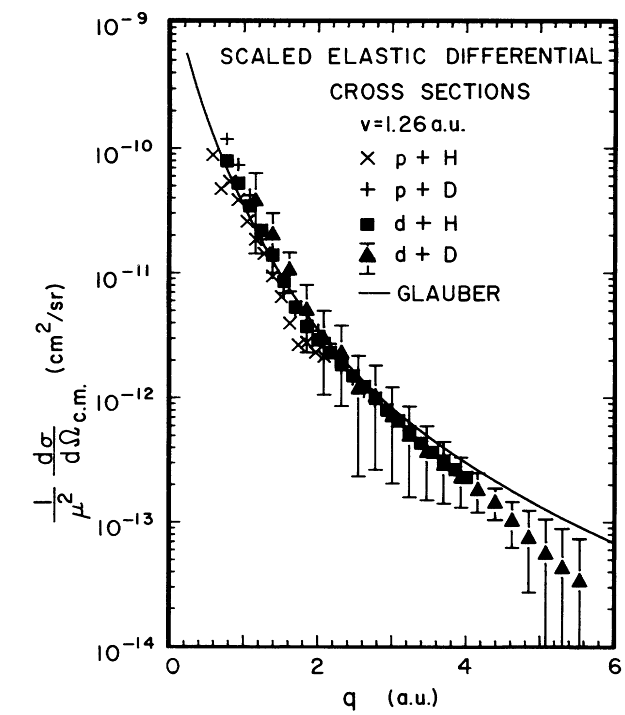

FIG. 3. Comparison of the measured and calculated elastic-scattering differential cross sections, scaled by momentum transfer, for the hydrogen-isotope collision systems. The solid line is the result of our Glauber-approximation calculation. The individual symbols represent the experimental data.

ferential cross sections of the proton-projectile collision systems are greater than in the deuteron-projectile collision system and, at the largest observed scattering angles, the differential cross sections differ almost by a factor of 10.

The differential cross sections of the deuteron-projectile collision systems are expected to cross over the differential cross sections of the proton-projectile collision systems and be larger in magnitude as the scattering angle goes to zero. However, in contrast to the previous measurements of both the electron-capture and $n=2$ excitation differential cross sections we were not able to observe the crossing of the elastic-scattering differential cross sections.[1,2] At the very small scattering angles, where the crossing should occur, the incident projectile beam is already indistinguishable from the elastically scattered ion beam. This interference of the incident projectile beam places a lower limit on the scattering angle that can be measured. Thus all of the elastic-scattering differential cross sections for the hydrogen-isotope system start out at a nonzero scattering angle.

We applied our recently developed simple scaling of $[(1/\mu^2)(d\sigma/d\Omega_{c.m.})]$ plotted against momentum transfer $q\sim\mu v\theta_{c.m.}$, where μ is the reduced mass and $\theta_{c.m.}$ is the center-of-mass scattering angle for the elastic-scattering differential cross sections.[1,2] The results together with our full Glauber-approximation[7] calculation which follows the techniques developed by Thomas and Gerjuoy[8] are shown in Fig. 3. As in the case of the electron-capture and $n=2$ excitation differential cross sections the experimental elastic-scattering differential cross sections scale with momentum transfer and produce one curve for all four collision systems. However, the theoretical Glauber-approximation result is not in as good agreement with the elastic case as it was for the $n=2$ excitation case.[2] At the smaller q values the Glauber-approximation calculation has the best agreement with the deuteron–hydrogen-atom collision system. However, if the error bars were displayed for the other hydrogen-isotope collision systems, they would all overlap the Glauber-approximation results. Likewise, the experimental results for the proton–hydrogen-atom collision system appear to be systematically lower than the rest of the data. But again the error bars associated with the proton–hydrogen-atom data overlap the other data with their error bars as well as overlap the Glauber-approximation results. For larger q values the Glauber-approximation produces an elastic-scattering differential cross section which is higher than the experimental data. Considering, however, the simplicity of the Glauber-approximation result,[7] that $[(1/\mu^2)(d\sigma/d\Omega_{c.m.})]$ should be only a function of the relative velocity v and the momentum transfer q of the colliding systems, the agreement is quite satisfactory.

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