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Ramsauer-Townsend effect in the total cross section of ^{4}He + ^{4}He and ^{3}He + ^{3}He

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Total scattering cross-section measurements for ^{4}He + ^{4}He and ^{3}He + ^{3}He are presented for velocities between 60 and 900 m/sec and 105 to 1000 m/sec, respectively. For ^{4}He + ^{4}He, a Ramsauer-Townsend effect is resolved and s and d phase shifts are obtained. The behavior of the s phase shift suggests that this system is not bound. For ^{3}He + ^{3}He a virtual state at 135 m/sec is resolved and some p phase shifts are obtained. A fit to the data for both pairs indicates that mass-polarization effects are negligible.

The purpose of this paper is to present some relative total cross-section results for ^{4}He + ^{4}He and ^{3}He + ^{3}He for which the collisional energy is sufficiently small that the attractive part of the potential is probed, the Ramsauer-Townsend effect is clearly resolved,[1-5] a virtual state for ^{3}He + ^{3}He is observed,[1] and the phase shifts for different momenta δ_l, $l = 0, 1, 2$, are obtained over a limited range of velocity. The results permit us to discuss the questions of mass-polarization effects for these scattering pairs[6] and the possible existence of a bound state for ^{4}He + ^{4}He.[1]

Relative total cross sections were measured over the relative velocity range (g) of 60 to 900 and 105 to 1000 m/sec for ^{4}He + ^{4}He and ^{3}He + ^{3}He, respectively, by merging at 21° two variable-temperature nozzle beams in a scattering chamber.[7] Both beams were chopped at different frequencies, and signals proportional to the attenuation, the primary beam density, and the secondary beam density, along with the time of flight, were simultaneously measured from which the relative total cross section vs relative velocity was determined. The primary and secondary beams were collimated to have angular full widths at half-maximum of 0.75° and 5.5°, respectively, and after being detected by electron bombardment detectors, each of the beams was directed into a trapped diffusion pump. The secondary beam had its nozzle at a fixed temperature; the velocity dependence was obtained by varying the temperature of the primary beam nozzle.

Figures 1(a) and 2(a) show the total cross-section results. Some errors in cross section are given; they represent both the experimental uncertainty and the uncertainty from the χ^2 fitting procedure. The errors in g were those from the time-of-flight measurements, the uncertainty in distance, and electronic effects.

All cross-section data had the secondary beam at a velocity (^{4}He) of 220 m/sec and (^{3}He) of 258 m/sec, except those shown by crosses, which had this beam (^{4}He) at a velocity of 190 m/sec. These latter data were normalized by a straight line to the adjoining low-velocity data and thus carry substantially larger uncertainty. Our relative cross sections have been least-squares fitted with absolute total cross sections obtained at velocities greater than 320 m/sec for ^{4}He + ^{4}He and 400 m/sec for ^{3}He + ^{3}He; the χ^2's for the fits (one degree of freedom) were 15 for 16 points and 29

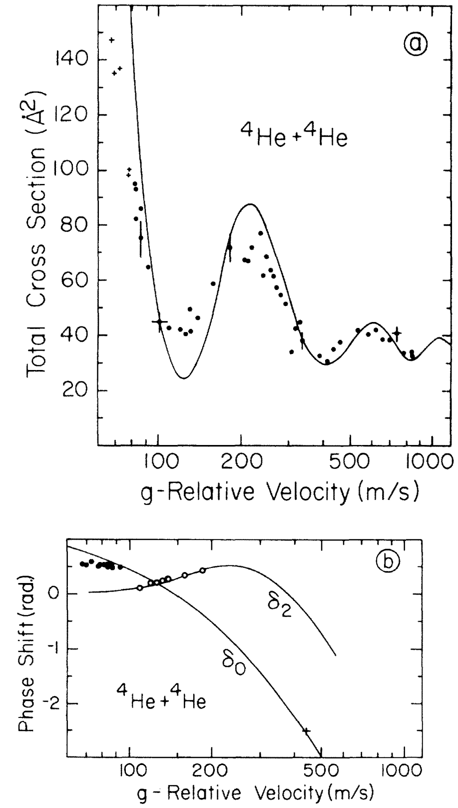

FIG. 1. (a) Total cross section vs relative velocity for ^{4}He + ^{4}He. The solid curve is obtained from the MLJ-D potential. The data are normalized to the solid curve at $g \geq 320$ m/sec. (b) Experimental values for the δ_0 and δ_2 phase shift. The solid curve is from the MLJ-D potential.

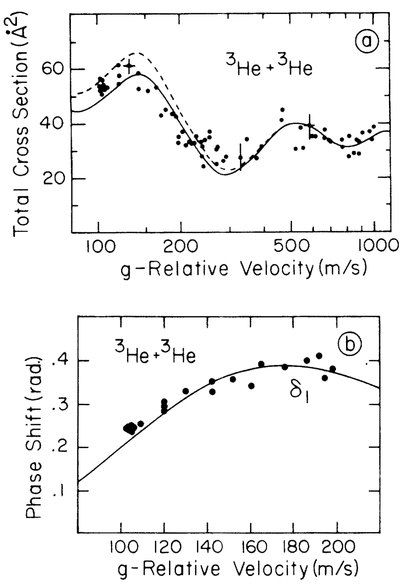

FIG. 2. (a) Total cross section vs relative velocity for ^{3}He+^{3}He. The solid and dashed curves are calculated from the MLJ-D and MLJ-D 3.4 potentials, respectively. (b) Experimentally determined phase shifts for δ_1. The solid curve is calculated from the MLJ-D potential.

for 24 points, respectively. Since the MLJ-D potential[1,6] produced a ^{4}He+^{4}He cross section that agreed well with absolute cross sections in the velocity range above 320 m/sec our results were normalized to it. (Similar arguments hold for the ^{3}He case.) This forces our results to agree with measurements above 320 m/sec, but allows for the extraction of information from the cross section at the velocities below 320 m/sec.

Calculations were made to determine the distortion on a theoretical cross section by velocity and angular dispersion in the beams. The effects were sufficiently small so that they were not included in these fits. The first minimum seen in Fig. 1(a) is due to the Ramsauer-Townsend effect[1-6] (i.e., the phase shift $\delta_0 = 0$ at some relative velocity). We find this velocity by realizing that for $g < 90$ m/sec the largest contribution to the cross section is from the δ_0 term. We thus find δ_0 vs g below 90 m/sec from our results, and extrapolate to those obtained by Feltgen *et al.*[2] We find $\delta_0 = 0$ around $g = 147$ m/sec. Since the ^{4}He+^{4}He system obeys Bose statistics, only even phase shifts contribute to the cross section; thus with δ_0 determined, we extract δ_2 versus velocity g. The results are shown in Fig. 1(b), where the cross data point is from Feltgen's paper.[2] The undulations in the cross section at $g > 150$ m/sec (called backward glories) are due to the Bose statistics; they have been discussed by several authors.[1,2,6,8]

The ^{3}He+^{3}He system (spin $\frac{1}{2}$) obeys Fermi statistics. This leads to conditions on the cross section which suppress the cross-section contribution from the even partial waves and enhance the part from the odd ones.[1,3] Thus in our low-velocity range ($g \lesssim 200$ m/sec) the δ_0 contributions to the cross section are small. The $l = 1$ partial waves lead to a maximum near 135 m/sec (a virtual state[1]) and a minimum near 240 m/sec (a Ramsauer-Townsend effect,[6,9] $\delta_1 = 0$). Guided by the size of the partial total cross sections for the different l values for the MLJ-D potential we realize that in the velocity range 105–200 m/sec the $l = 1$ partial wave dominates the total cross section. We use this information to find δ_1 from the total cross section [Fig. 2(b)]. The Ramsauer effect and the structure in the total cross section above 240 m/sec have been discussed by several other investigators.[6,9]

There have been suggestions that mass-polarization effects might explain why some previous low-velocity cross-section measurements on these two helium isotopes could not be fitted by the same potential.[6,10] In the previous work[6] the ^{4}He+^{4}He measurements agreed with calculated cross sections from a MLJ-D potential, while a slightly deeper potential, the MLJ-D 3.4, was needed for the ^{3}He+^{3}He fit. We have calculated the χ^2 fit for the cross section obtained from the MLJ-D 3.4 potential at $g > 400$ m/sec and found $\chi^2 = 30$ for 24 data points [Fig. 2(a)]. Even though the χ^2 values and thus the fit to the data above 400 m/sec are the same for these two potentials, the fit at the low-velocity end is better for the MLJ-D than the MLJ-D 3.4 potential, and $\chi^2 = 151$ and 198, respectively, for the two potentials when all of the data are included. If the calculated cross sections from each of these potentials is separately fitted over the entire velocity range to the data, the MLJ-D case produces a $\chi^2 = 147$ and the MLJ-D 3.4 has $\chi^2 = 168$ for 69 points and one degree of freedom. These results, while not decisive, do not favor mass polarization.

We ask what the results tell us about the possible existence of a bound state in ^{4}He+^{4}He. Levinson's theorem indicates that $\delta_0 \rightarrow n\pi$ as $g \rightarrow 0$, $n = 1$, if there is a bound state. The results in Fig. 1(b) are not definitive enough to answer that question. In exploration with model potentials, it appeared that δ_0 values near $g = 10$ m/sec would be needed to use Levinson's theorem, and this approach requires further experimental work. However, we can express with some confidence that this system is unbound by observing that the experimentally determined δ_0 phase shifts lie below those calculated from the MLJ-D potential.[1] Since this potential does not contain a bound state (i.e., $\delta_0 \not\to \pi$ as $g \to 0$), it is unlikely that our value of δ_0, which lies below the calculated one, will reach π. In fact the experimentally derived phase shifts have nearly stopped rising for decreasing g.

We have made several other complete measurements of the ^{4}He + ^{4}He system in which the secondary beam was not adequately trapped by a diffusion pump after scattering. They are not included here, because there was additional background that tended to raise the cross section at the low-velocity end. Even so, the experimental δ_0 values were still less than those calculated from the MLJ-D potential.

The cross sections calculated from the MLJ-D potential do provide relatively good fits to these data; however, there are significant deviations at the very-low-velocity end for both the ^{4}He + ^{4}He and ^{3}He + ^{3}He cases. Interpretation of these deviations will be the subject of a forthcoming publication. The relationship between the scattering cross sections in these two systems will also be considered with a view to obtaining information about possible differences between the two effective potentials.

Calculations of total cross sections at velocities below those measured show them to be very large. They further depend only upon one partial wave. It is now of great interest to measure these cross sections down to a few m/sec to obtain the phase shifts, to elucidate further the bound-state problem, and to extract further potential information.

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