Table I. Observed position of elastic scattering resonances in H_2, and comparison of the resonance spacing with vibrational spacings in H_2 and H_2^+.

Resonance energy (eV)	Resonance spacing (eV)	Vibrational spacing H_2 $1s\sigma 2p\sigma\ ^1\Sigma_u^+$ (eV)	Vibrational spacing H_2^+ ground state (eV)
11.62			
	0.29	0.285	0.269
11.91			
	0.27	0.268	0.253
12.18			
	0.28	0.268	0.237
12.46			
	0.25	0.238	0.221
12.71			
	0.23	0.220	0.208
12.94			
	0.19	0.205	0.192
13.13			
	0.18	0.188	
13.31			

resonances correspond closely with vibrational spacing of the C state,[14] but show small but significant differences from the H_2^+ vibrational spacings.

If the resonances are ascribed to compound state formation with an excited state of H_2, then it might be expected that the vibrational spacings would be similar to those of H_2^+, modified in the same direction as in the excited states of H_2. This appears to be the case.

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RESONANT EXCITATION IN HELIUM ION-ATOM COLLISIONS*

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(Recieved 20 January 1964)

An energy resonance in the production of helium metastable atoms has been observed for helium ions impacting on helium atoms. The peak of the resonance occurs at 28 eV in the center-of-mass system for metastables scattered in the forward direction.

This resonance was first observed as an apparent resonance in the ionization cross section for helium atoms impacting on hydrogen molecules. The technique for measuring such ionization cross sections has been reported in detail previously.[1-4] It involves the neutralization of an ion beam by charge transfer in order to produce the fast neutral beam. The neutral beam passes between parallel plates in a low-pressure ionization chamber and all negative charge due to ionizing interactions is measured. Figure 1, curve He-H_2, shows the results obtained when a neutral helium beam, obtained from He^+ in He charge-transfer neutralization, impacted on molecular hydrogen.[5] "Ionization cross section" here means total cross section for production of electrons (or negative ions). The energy scale for Fig. 1 is the kinetic energy in the He-H_2 center-of-mass system minus 15.5 eV, and is therefore the excess energy over ionization of the hydrogen molecule. The ionization cross section measured[5,6] for H_2-He (fast neutral hydrogen molecular beam impacting on helium atoms) is also given in Fig. 1. The energy scale is the same.[7]

One would expect the He-H_2 results to be identical to the H_2-He results when the energy is expressed

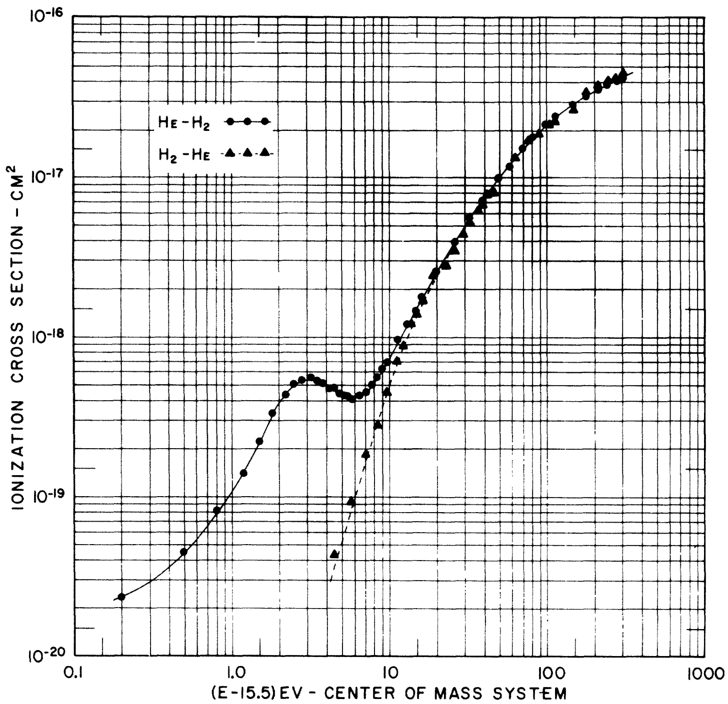

FIG. 1. Ionization cross sections measured for He-H_2 and H_2-He.

in center-of-mass energy. The difference indicates that one, or both, of the neutral beams had a metastable component. This difference between the curves of Fig. 1 is plotted in Fig. 2, and is a measure of the excitation. The energy scale for Fig. 2 is kinetic energy expressed in the He^+-in-He center-of-mass system.

The possibility that excitation in the hydrogen molecular beam produced the observed results is ruled out by the following considerations. First, if the He-H_2 curve were characteristic of the He-H_2 ground-state interaction, the hydrogen beam would have had to be predominantly excited in order to wipe out all the structure. Second, a mechanism would have to be found to explain why excited hydrogen should show no resonance in contrast to the ground state. Third, the shape of the He-H_2 curve (Fig. 1) indicates that the resonance reaction occurred below the minimum ionization energy of the H_2. Hence a chemical combination would have had to be occurring between the He and the H_2. A mass spectrometic search for such ions gave negative results.

By contrast, the hypothesis that the neutral helium beam contained a metastable component gives a consistent and satisfactory explanation for the difference in the He-H_2 and H_2-He curves (Fig. 2). If one assumes that the Penning (Jesse) ionization cross section varies slowly with energy, and uses the value for helium metastables in hydrogen given by Sholette and Muschlitz,[8] the helium neutral beam need have contained only 0.3% metastables. The ionization mechanism is known, and the reactions are energetically possible.

The following two consistency checks were made on the hypothesis of the excited neutral helium

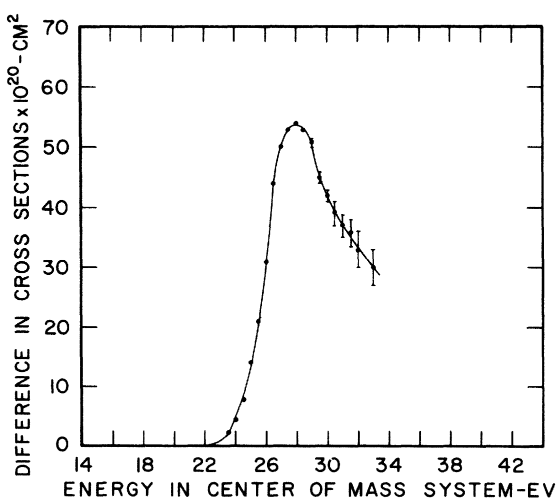

FIG. 2. Difference between He-H_2 and H_2-He cross sections.

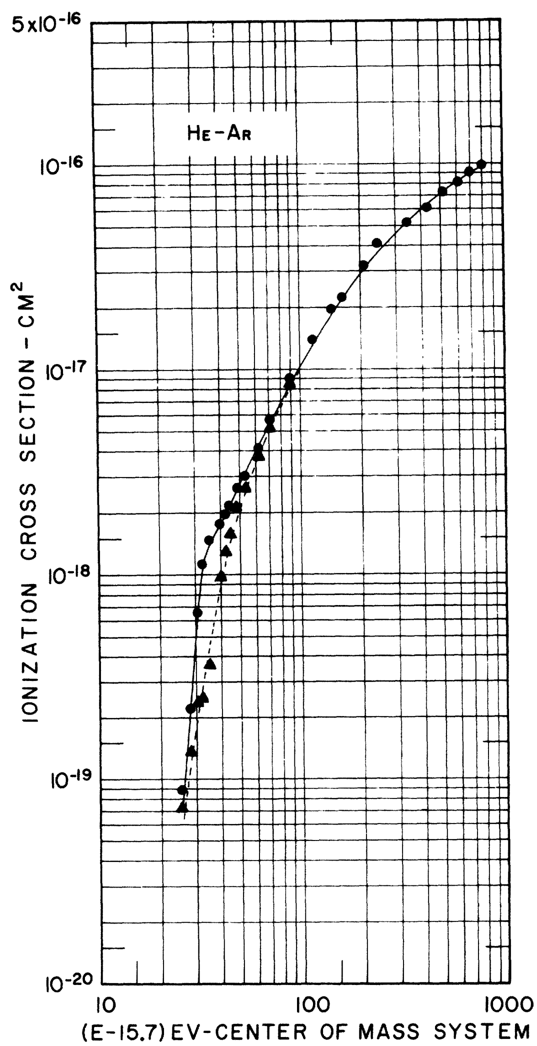

FIG. 3. Ionization cross section for He-Ar.

beam component. The ionization cross sections for He-Ne[5] and He-Ar were measured. No structure was observed in He-Ne, as would be expected since the Penning ionization cross section is zero for helium metastables in neon. On the other hand, structure was observed for He-Ar. Figure 3, round dots and solid line, shows the ionization cross section for He-Ar measured with the present neutral helium beam. The triangles and dashed line were obtained by subtracting two times the values of Fig. 2 from the raw He-Ar data (black dots). It is seen that the structure was removed by this process. It should be noted that the structure occurred in both He-H_2 and He-Ar at the same laboratory beam energy, while at very different center-of-mass system energies. The ratio of 2 used in correcting the He-Ar data is smaller than the ratio found by Sholette and Muschlitz[8] between the Ar and H_2 Penning cross sections. However, the discrepancy is not considered serious in view of the much higher kinetic energies involved here.

The preceding arguments point to a resonance in the production of helium metastables by the process

$$He^+ + He \rightarrow He^+ + He^*. \quad (1)$$

The curve of Fig. 2 is proportional to the cross section for production of metastables by the process of Eq. (1), under the assumption that the Penning ionization cross section changes slowly with energy. The metastables observed here were those scattered within a forward cone of half-angle 5°. Metastables scattered at larger angles were removed by collimation. The incident He^+ ions were produced by bombardment with 45-eV electrons, and thus were in the ground state.

Energy resonances have been observed previously[9,10] in He^+ on He collisions for charge transfer at specified scattering angles. The present measurement differs from the charge-transfer measurements in that the excitation requires a violent collision with change of electronic energy, while the charge transfer involves no change of electronic energy. Furthermore, the present excitation resonance occurs just above the energy threshold, while the charge-transfer resonances occur at keV energies.

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[4]The structure reported in the present Letter should not be confused with that reported for N_2-N_2 in reference 2. There is no apparent connection.

[5]These results will be published in detail at a later date.

[6]All actual data points for H_2-He have been arbitrarily raised 30% so that the He-H_2 and H_2-He curves coincide above the structure. The reason for the discrepancy has not yet been determined, but it is not expected to change the arguments here.

[7]Note that a given laboratory beam energy corresponds to different abscissa values for the He-H_2 and H_2-He

curves because of conversion to center-of-mass energy.

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MEASUREMENT OF THE DEUTERON MAGNETIC FORM FACTOR AT LOW MOMENTUM TRANSFER*

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We have measured at 180° the ratio of the elastic electron-proton and electron-deuteron scattering. We have made the measurement at two values of the primary electron energy: 54 and 68 MeV. These correspond, respectively, to momentum transfers of 0.26 and 0.41 F^{-2}. At our highest momentum transfer point the electric form factor of the proton differs from unity by only 4%. Therefore we have assumed that in the energy range of interest to us, all the nucleon form factors have the same dependence as functions of momentum transfer. Under this assumption we have obtained from our data information on the magnetic form factor of the deuteron. The electron beam from the Mark II Stanford Linear Accelerator was momentum analyzed in a two-magnet achromatic translation system and then brought into the experimental area. There the beam was monitored by a three-foil secondary emission monitor and deflected ~10° by a small magnet. After deflection it entered a liquid deuterium (or hydrogen) target and continued in a large vacuum pipe for five more feet before striking a concrete wall.

The target was 1/2 inch long and the target walls were made of stainless steel foil 0.0005 inch thick. Alternatively hydrogen and deuterium were condensed under pressure in the target which was cooled by a reservior full ot liquid hydrogen. The electrons emitted at 180° in the target passed again through the small deflecting magnet and entered a 120° double-focusing magnetic spectrometer. A system of two scintillation counters in coincidence, placed in the focal plane of the spectrometer, was used as detector. A more detailed description of the apparatus is contained in the paper of Peterson and Barber.[1] The total amount of material traversed by the beam before entering the target was 0.003 inch of aluminum.

In the relativistic limit the scattering at 180° should be entirely magnetic. However, because of the smallness of the magnetic moment of the deuteron, the cross section for magnetic scattering from the deuteron is small, and the contribution to this cross section from electric (Coulomb) scattering is not completely negligible.

This was mainly produced by two causes. First, the usual approximation in which the velocity of the electron is equal to the velocity of light was not true in our case and a small contribution from terms of the order $1-\beta^2$ had to be taken into account. Second, multiple Coulomb scattering in the target introduced some angular dispersion in our beam. For this reason particles undergoing scattering at angles very close to 180° could enter our spectrometer. This effect was larger than the one introduced by the finite solid angle of the spectrometer which was therefore neglected. The contributions from electric transitions were calculated at 54 and 68 MeV to be, respectively, 0.62 and 0.02 of the magnetic scattering. Radiative corrections have been calculated according to Meister and Yennie and found to be practically equal for the proton and deuteron case.[2]

The result of our experiment is indicated in Fig. 1. The experimental value of the form factor normalized to one at $q^2=0$ is defined as follows[3]:

$$[F(q^2)]^2 = \tfrac{3}{2}(\sigma_d/\sigma_p)[\mu_p/\mu_D]^2 \times[1+2E/M_d][1+2E/M_p]^{-1}, \quad (1)$$

where E is the initial electron energy, M_p and M_d are the proton and deuteron masses, σ_d/σ_p is the experimental value for the ratio of the cross sections, and

$$\mu_p/\mu_d = 3.2572 \quad (2)$$

is the experimental measured value.[4]

The static magnetic moment of the deuteron