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Ion source effect on the bond length of $^4HeH^+$*

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The bond length of $^4HeH^+$ resulting from collision-induced destruction is measured at 1.4420 MeV using the Coulomb Explosion Technique. The measured bond length of $^4HeH^+$ is 0.094±0.003nm. The bond length of $^4HeH^+$ obtained with our radio frequency (RF) ion source is larger than that obtained with a duoplasmatron ion source at Argonne National Laboratory (ANL), but the bond lengths of H_2^+ and H_3^+ obtained separately by ANL and by us with the two different ion sources are consistent with each other, which implies that there exists an ion source effect on the bond length of $^4HeH^+$. The main reason why the $^4HeH^+$ bond lengths obtained by the two different ion sources are different is also discussed.

Keywords: ion source effect, $^4HeH^+$, formation mechanism, bond length
PACC: 3400, 3500, 3600, 8200

1. Introduction

The $^4HeH^+$ molecular ion is one of the simplest diatomic heleronuclei ions known for their electronic structures. The observation and analysis from the sun and other closer stars indicate that hydrogen and helium are the two elements with the highest abundance in the cosmic space. It contains about 70% hydrogen, 28% helium and 2% other elements heavier than hydrogen and helium.[1] It is also found that there exists a lot of $^4HeH^+$ in the outer space.

$^4HeH^+$ is the ion studied most in the molecular ion family. To our knowledge, the investigations were carried out in the following areas. Peyerimhoff began to study on the potential energy curve of $^4HeH^+$ early in 1960s, [2] Kolos *et al*,[3] Green *et al*[4] and Macias *et al*[5] provided a very accurate calculation. Chupka *et al*[6] and Govers *et al*[7] studied the collision reaction to the formation of $^4HeH^+$. Roberge *et al*[8] reported the formation of $^4HeH^+$ under different conditions in interplanetary space. The measurements in collision experiments were made on the recombination after dissociation in an energy range from 1eV[9] to 50eV.[10−12] The angular distribution and fragment charged state were detected separately by Schopman *et al*[13] and by Kantor *et al*[14] after the collision-reduced dissociation of $^4HeH^+$ in an energy range of 10keV–900keV. Recently, Coelho *et al*[15] studied the dissociation of $^4HeH^+$ produced by the van de Graaff accelerator and collisions with He, Na, Ar, and obtained the dissociation cross-sections at several different incident energies. We studied the stereochemical structure of various ion microclusters of H_2^+, H_3^+, D_2^+, D_3^+, and HD^+ etc.[16,17] The measurement of bond length of $^4HeH^+$ was made with a duoplasmatron ion source by ANL only.[18]

In this paper, we present the measurement of the bond length of $^4HeH^+$ generated by our radio frequency (RF) ion source, and find that there exists an ion source effect on the bond length of $^4HeH^+$. To our knowledge, such a result has not been reported so far.

2. Experiment

The method of determining the structure of $^4HeH^+$ is just to measure the energy spectra for H^+ and for He^{2+} after a $^4HeH^+$ beam passes through a carbon foil. When the $^4HeH^+$ beam is incident upon the carbon foil at energy ∼MeV, all of its bonding

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electrons will be turned off within the first layers of atoms encountered in the target, and the remaining molecular constituents will then continue exploding apart as a cluster of bare nuclei under the influence of their mutual Coulomb repulsion. The process is called Coulomb explosion. In the Coulomb-explosion model, due to fast light projectiles transmitting a thin carbon target, modifications to the factors such as multiple scattering, electronic screening, and vibrations and rotations in the incident molecules can be ignored for their values are slightly changed only. Based on the process, the inter-bond length between a proton and a He is determined from the energy spectra of H^+ and He^+ fragments measured in the beam direction after their complete explosion. Thereby the structure of $^4HeH^+$ is determined.

The experimental apparatus is shown in Fig.1, which has been described elsewhere.[16] Briefly, the $^4HeH^+$ molecular ions were produced by an RF ion source. An adequate beam of $^4HeH^+$ was provided by mixing about 90–95 percent He and 10–5 percent H_2 in the ion source gas. The mass-analysing magnet of the accelerator separated $^4HeH^+$ from other ions.

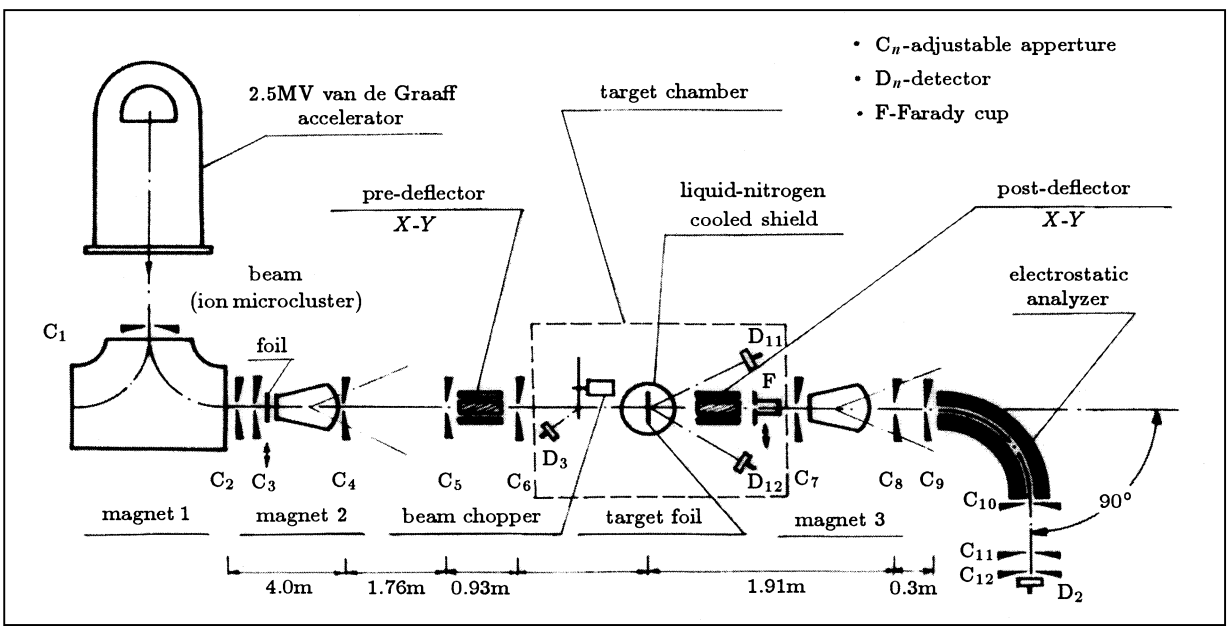


Fig.1. Schematic diagram of the experimental arrangement.

The overall energy resolution of the detection system was $\Delta E/E=\pm 1.5\times 10^{-4}$, which was deduced from the measured energy distribution of a primary H_2^+ beam by use of a 90 electrostatic analyser with a radius of 0.8m as shown in Fig.2. The angular divergence of the incident beam was $< \pm 4.5 \times 10^{-5}$rad. and the angular acceptance of electrostatic analyser was $< 0.75 \times 10^{-4}$rad. A set of electrostatic X and Y deflector plates was placed in the upstream of the target, thereby the contaminants in the beam can be eliminated before their reaching the target. Carbon foils ($\sim 3\mu g/cm^2$) were used as targets and mounted on a movable ladder holder so that individual foil could be positioned in the beam without breaking the vacuum. The beam line pressure was maintained at 2–7×10^{-5}Pa during the measurement, enclosing the target with a liquid-nitrogen cooler could minimize carbon build-up on the target.

The $^4HeH^+$ beam from the RF ion source was accelerated to 1.4420MeV using a 2.5MeV van de Graaff accelerator made in China. A set of high-resolution magnetic analysers was established on it for beam selection. It had a main radius of 850mm, two-way 90°-sector, entrance-exit gap less than 1mm and magnetic stability better than 1.6×10^{-5}/8 hours. The collimator length was 1.76m, and the aperture size could be continuously changed from $10\mu m\times 10\mu m$ to 8mm×8mm. A variety of mixed particles, such as $^4He^+$, $^4He^{2+}$, $^4He^0$, $^4He^-$, H^+, H^0, H^- etc. were produced due to the collision of $^4HeH^+$ with residual gases in beam line along the path of beam about 5m from the magnetic analyser to the target. In order to

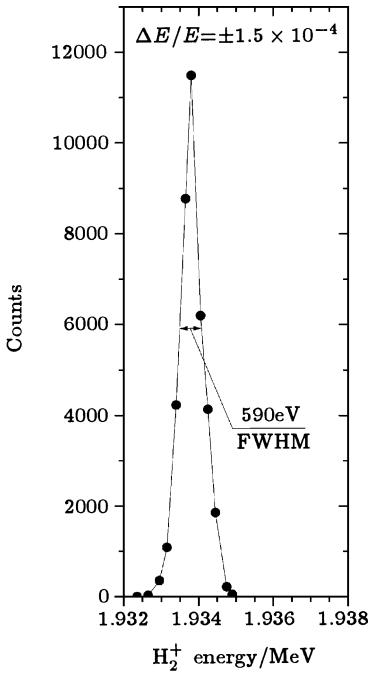


Fig.2. Incident 1.9338MeV H_2^+ energy profile recorded with the high-resolution arrangement.

obtain a pure $^4HeH^+$ beam reaching the target, another electrostatic deflection system was used prior to the particle entering the target. The mixed clusters of $^3HeD^+$ and HD_2^+ did not exist in beam because ^3He and deuterium had not been fed into the ion source for a long time.

3. Results and discussion

3.1. $^4HeH^+$ formation mechanism

To measure the bond length we must have a high-quality MeV $^4HeH^+$ beam, so the formation mechanism of $^4HeH^+$ should be studied first in an RF ion source.

$^4HeH^+$ is formed rapidly through the reaction of H_2^+ and ^4He

$$H_2^+ + {}^4He \rightarrow {}^4HeH^+ + H. \quad (1)$$

Additionally, $^4HeH^+$ is also formed through the reaction of H^+ and ^4He

$$H^+ + {}^4He \rightarrow {}^4HeH^+ + h\nu. \quad (2)$$

But the reaction (2) proceeds slowly due to the smaller cross-sections. Nevertheless, $^4HeH^+$ formed from the reactions (1) and (2) may be reduced due to the following reaction:

$$^4HeH^+ + H \rightarrow H_2^+ + {}^4He. \quad (3)$$

Obviously, the $^4HeH^+$ formation is related to the existence of H^+, especially H_2^+ with vibration energy level $\nu \geq 3$, but the loss of $^4HeH^+$ in the ion source depends on how many H atoms exist.

According to the above analysis, the structure, material and parameter of the RF ion source must be studied in detail. Among a number of parameters the pressure of ion source is considered to be a key factor to acquire a high-quality beam. At a lower pressure, the yield of H_2^+ is higher than that of H^+, but the yield of H is smallest. In that case the reactions (1) and (2) for producing $^4HeH^+$ should be maintained but the reaction (3) causing the loss of $^4HeH^+$ should be restrained, thereby we can obtain a high current $^4HeH^+$ beam with the largest $I_{H_2^+}/I_{H^+}$ that, sometimes, is much larger than 1, and the lowest $I_{H_3^+}/I_{H^+}$. That is our main consideration to satisfy the optimum condition of $^4HeH^+$ formation.

The ratios of ^4He to H_2 in the mixed gas fed into the ion source were 9.5:0.5 and 9:1. It was indicated experimentally that the former ratio could produce a more intensive current $^4HeH^+$beam.

The current intensity of MeV $^4HeH^+$ acquired was between 0.4–0.8μA. The entrance and exit gaps of the accelerator magnetic analyser were both 1mm. The result showed that the analysis on formation mechanism of $^4HeH^+$ was correct. We also found that $^4HeH^+$ was difficult to generate by the RF ion source.

3.2. $^4HeH^+$ bond length

The energy spectra were obtained by varying the voltage applied to the analyser. Figure 3 shows the distribution in energy along the beam direction for protons arising from 1.4420 MeV $^4HeH^+$ ions incident upon a carbon foil. The accurate beam energy was measured by using a electrostatic analyser at first. The two energy groups at θ=0 (the beam direction) corresponded to the forward protons and backward ones through the foil. The energy separation between the two peaks was ΔE_{max}=10.23keV.

$^4HeH^+$ incident upon the carbon foil consisted of the ion microclusters with ^4He and H atoms, and two electrons. Because the two bound electrons of $^4HeH^+$ were stripped as long as the cluster entered the thin foil, $^4HeH^+$ turned into two bare nuclei with two positive charges of $^4He^{2+}$ and H^+, which were repelled rapidly by the Coulomb force. The $^4HeH^+$ potential energy was converted into the kinetic energy of $^4He^{++}$ and H^+ fragments. The high energy peak shows the H^+ explosion in the forward direction ,and the low

energy peak shows the H^+ explosion in the backward direction in the centre-of-mass system. The later was higher than the former, as predicted by Bohr in 1948, which indicates that the "wake effect" existed, and appeared when the positive ions passed through the solid.[19]

According to the laws of energy conservation and momentum conservation, by ignoring interactions of the projectile nuclei with the target foil, the average bond length of ion microcluster $\bar{\gamma}_0$ consisting of dual-atoms is given by the following formula:

$$\bar{\gamma}_0 = \frac{16 Z_2 Z_3 e^2 m_2 m_3}{m_1^2} \times \frac{E_1}{(\Delta E_{\max})^2}, \qquad (4)$$

where m_1 and E_1 are the mass and energy of incident ion microcluster, $Z_2 e$ and $Z_3 e$ are the charges of fragments with the mass of m_2 and m_3 produced by the Coulomb explosion respectively, $\Delta E_{\max}$ is the energy difference between two fragments emerging at 0^0 direction by the Coulomb explosion.

For $^4HeH^+$, the peak separation in the H^+ energy spectrum $\Delta E_{\max}$ was 10.23keV, as shown in Fig.3. The energy E_1 of incident $^4HeH^+$ measured by the electrostatic analyser was 1.4420MeV, its velocity was 0.745×10^7m/s. The time for the $^4HeH^+$ beam to pass through a carbon foil with a mass density of $3\mu g/cm^2$ was 2.4fs, when the mass density of carbon foil was taken as 1.65 g/cm^3 (the mass density of diamond is 3 g/cm^3, and that of graphite is 2.25g/cm^3). The Coulomb explosion took place in the first layers of the target, and the potential energy of $^4HeH^+$ was converted into the kinetic energy. But this process was performed almost entirely all in the carbon foil. Therefore the charge of H^+ in carbon could not be taken as 1, and the effective charge must be used instead. From Ref.[20], we took the effective charge as 0.994, when 0.2884 MeV H^+ passed through the carbon foil. The effective charge was easily obtained to be 1.865, when $^4He^{2+}$ with 0.2884 MeV/amu passed through the carbon foil. By ignoring the extremely small corrections due to the wake effect, i.e the difference in energy loss between both forward and backward peak and multiple scattering, we could acquire the most probable bond length of $^4HeH^+$ being 0.094±0.003nm.

Comparing with theoretical value of $^4HeH^+$ bond length in ground state (0.0774nm), [3] our measured value is slightly large, which indicates that the $^4HeH^+$ bond length measured is the one for vibration-excited states.

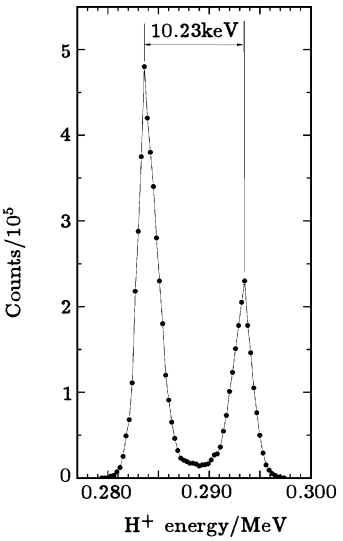


Fig.3. Energy distribution of emergent H^+ fragment in the initial 1.4420MeV $^4HeH^+$ beam passing a $3\mu g/cm^2$ carbon foil.

3.3. Ion source effect on the bond length of $^4HeH^+$

The bond lengths of H_2^+, H_3^+ and $^4HeH^+$ have been measured separately with an RF ion source by our group[16] and with duoplasmatron ion source by ANL[18]. The measured values are 0.119±0.003nm and 0.117nm for H_2^+, 0.098±0.002nm and 0.097±0.003nm for H_3^+. Within the error range they are in good agreement with each other. But a comparison with the measured values for $^4HeH^+$ indicates that they are quite different: the bond lengths of $^4HeH^+$ were measured to be 0.094±0.003nm with our ion source and 0.079nm with ANL's ion source. It shows that there exists an ion source effect on the bond length of $^4HeH^+$. The vibration excitation of $^4HeH^+$ is much higher in the RF ion source than that in the duoplasmatron ion source.

We believe that the $^4HeH^+$ beam can be formed through the molecule–ion reaction (1) of H_2^+ and ^4He by use of either the RF ion source or the duoplasmatron ion source, but their formation conditions are quite different. As mentioned above, the pressure in our experiment was adjusted to a lower value, but the duoplasmatron ion source is another kind of source operating at a high pressure. Therefore the vibration state of H_2^+ in the RF ion source is higher than that in the duoplasmatron ion source. For this reason, $^4HeH^+$ can be formed in a higher vibration state when molecule-ion reaction (1) takes place. We believe that this is the main reason why the $^4HeH^+$ bond lengths

obtained with the two different types of ion sources are different.

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References

[1] Allen C M 1973 *Astrophysical Quantities* (London: Athlone Press) 3rd ed
[2] Peyerimhoff S 1965 *J. Chem. Phys.* **43** 998
[3] Kolos W *et al* 1976 *Chem. Phys.* **12** 381
[4] Green T A *et al* 1974 *J. Chem. Phys.* **61** 5186
[5] Macias A *et al* 1983 *Phys. Rev.* A **27** 286
[6] Chupka W A *et al* 1968 *Chem. Phys.* **49** 5426
[7] Govers T R *et al* 1987 *Chem. Phys.* **113** 677
[8] Koberge W *et al* 1982 *Astrophysical J.* **255** 489
[9] Yousif F B *et al* 1989 *Phys. Rev.* A **40** 4318
[10] Tanabe T *et al* 1993 *Phys. Rev. Lett.* **70** 422
[11] Forck P *et al* 1994 *Phys. Rev. Lett.* **70** 2002
[12] Zajfman D *et al* 1995 *Phys. Rev. Lett.* **75** 814
[13] Schopman J *et al* 1973 *Physica* **63** 518
[14] Kantor J *et al* 1980 *Nucl. Instrum. Methods* **171** 377
[15] Coelho L F S *et al* 1996 *J. Phys.* B **29** 733
[16] Miao J W *et al* 1986 *Nucl. Instrum. Methods* B **13** 181
[17] Shi M G *et al* 1999 *Nucl. Sci. Tech.* **10** 74
[18] Kanter E P *et al* 1980 *Nucl. Instrum. Methods* **170** 87
[19] Bohr N 1948 *K. Dan. Vidensk. Selsk. Mat.-Fys. Medd* **18** 1
[20] Joseph F J 1982 *At. Nucl. Data Tables* **27** 147