Vol 16 No 12, December 2007
1009-1963/2007/16(12)/3647-08

Chinese Physics

© 2007 Chin. Phys. Soc.
and IOP Publishing Ltd

Novel electrostatic trap for cold polar molecules*

Xu Xue-Yan (许雪艳)[a)b)], Ma Hui (马 慧)[a)], and Yin Jian-Ping (印建平)[a)†]

[a)] *Key Laboratory for Optical and Magnetic Resonance Spectroscopy of the Ministry of Education, Department of Physics, East China Normal University, Shanghai* 200062, *China*

[b)] *Department of Physics, Chaohu College, Chaohu* 238000, *China*

(Received 1 March 2007; revised manuscript received 17 May 2007)

We propose a novel scheme in which cold polar molecules are trapped by an electrostatic field generated by the combination of a pair of parallel transparent electrodes (i.e., two infinite transparent plates) and a ring electrode (i.e., a ring wire). The spatial distributions of the electrostatic fields from the above charged wire and the charged plates and the corresponding Stark potentials for cold CO molecules are calculated; the dependences of the trap centre position on the geometric parameters of the electrode are analysed. We also discuss the loading process of cold molecules from a cold molecular beam into our trap. This study shows that the proposed scheme is not only simple and convenient to trap, manipulate and control cold polar molecules in weak-field-seeking states, but also provides an opportunity to study cold collisions and collective quantum effects in a variety of cold molecular systems, etc.

Keywords: electrostatic trap, cold polar molecules
PACC: 3260S, 9430H, 6180L

1. Introduction

In recent years, some new methods, such as the photon-association spectroscopy[1] or magnetically-tuned Feshbach resonance[2] in ultracold atoms, the supersonic molecular beam and its Stark deceleration with a time-varying electric field,[3−6] the buffer gas cooling,[7] optical Stark decelerator with a pulsed light field[8] or pulsed travelling optical lattices,[9] energy low-pass filter based on bend molecular guiding[10,11] and so on, have been developed to produce cold (or ultracold) molecules. The creation of cold molecules offers unique possibilities for studying cold collisions and collective quantum effects in a wide range of cold molecular systems,[12,13] dipole-dipole interaction,[14] even cold-molecular spectroscopy with a high resolution.[15]

On the other hand, some trap schemes, such as magnetic traps,[16,17] optical dipole traps,[18] electrostatic traps,[19−22] and storage-ring trap,[23,24] have been developed to trap cold molecules. In particular, the electrostatic traps are very useful and versatile because their depths can reach the order of about 1K. So far, many different electrostatic field distributions and trapping potentials have been generated using various geometric parameters (R, r, L) of the charged-wire layout.[20−22,25] One of the typical electrostatic trap schemes is composed of a charged ring wire (electrode) and two end-caps with a hyperboloid surface.[20−22,25] Obviously, it is not easy to fabricate and install such an electrostatic trapping device due to the complex hyperboloid surface of the two end-caps, and it is difficult to detect the trapped cold molecules in the trap by means of a fluorescence measuring method because there is not a large enough free space around the trap. So it would be interesting and worthwhile to find a simple and efficient trapping scheme and realize an electrostatic trapping and fluorescence detecting for the cold polar molecules in weak-field-seeking states.

In this paper, we propose a novel and simple scheme to trap cold polar molecules in the weak-field-seeking states using a ring electrode and two transparent plate electrodes,[26] and calculate the spatial distributions of the electrostatic field from the above wire layout. The dependences of the trapping field and the corresponding Stark potentials for cold CO molecules on the geometric parameters of the present trap setup are analysed in some details. We also dis-

*Project supported by the National Natural Science Foundation of China (Grant Nos 10174050, 10374029, 10434060 and 10674047), the National Basic Research Program of China (Grant No 2006CB921604), the Science and Technology Commission of Shanghai Municipality (Grant No 04DZ14009), Shanghai Priority Academic Discipline, the 211 Foundation of the Ministry of Education, China.

†Corresponding author. E-mail: jpyin@phy.ecnu.edu.cn

cuss the loading process of cold molecules and some potential applications of the present trapping scheme in molecular optics.

2. Electrostatic trap scheme for cold polar molecules

The present trap scheme is shown in Fig.1 and consists of two parallel transparent plate electrodes and a ring electrode, in which one of the two plate electrodes is charged, and the other is grounded. As shown in Fig.1, the radius of the ring electrode is R and that of the electrode-wire itself is r; the distance between the two plate electrodes is $2L$, and the ring electrode is placed at the centre between the two plate electrodes. In Fig.1, a high voltage $+U_2$ ($+U_2 \geq 0$V) is applied to the left infinite plate electrode, and the right one is grounded; another high voltage $+U_1$ is applied to the ring electrode. To enable the molecular beam to pass through the present trap setup along the z axis (i.e., the propagation direction of the incident molecular beam), the 2 mm diameter holes are made in the centre of two plate electrodes.

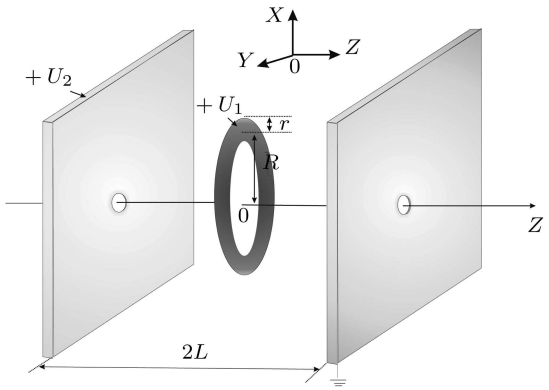


Fig.1. Schematic diagram of electrostatic trapping for cold polar molecules by using a single ring electrode with an applied voltage $+U_1$ and a pair of infinite transparent plate electrodes with an applied voltage $+U_2$.

It is well known that when a polar molecule with a permanent electric dipole moment (EDM) μ moves in an inhomogeneous electrostatic field, due to the first-order Stark effect, it will experience a dipole gradient force from the electrostatic field, which can be used to realize an electrostatic trapping or guiding of cold polar molecules.[27] In consideration of the interaction between a polar molecule with a permanent EDM and an inhomogeneous electrostatic field $\boldsymbol{E}$, the interacting Stark potential for cold polar molecules is given by

$$W_{\text{Stark}}(r) = -\boldsymbol{\mu} \cdot \boldsymbol{E}(r). \tag{1}$$

We find from Eq.(1) that when the molecular EDM $\boldsymbol{\mu}$ is parallel to the electric field $\boldsymbol{E}$, the molecules in the strong-field-seeking states will be attracted to the maximum region of the electrostatic field, which can be used to trap or guide cold strong-field-seeking molecules.[19,28] As the molecular EDM $\boldsymbol{\mu}$ is anti-parallel to the electrostatic field $\boldsymbol{E}$, the molecules in the weak-field-seeking states will be repelled to the minimum region of the electric field, which can be used to realize the electrostatic trapping or guiding of cold weak-field-seeking molecules.[20−24,27]

For a CO molecule in the metastable $a^3\Pi(J = 1, M\Omega = -1)$ state, it has a relatively large permanent EDM with 1.37Debye (4.6×10^{-30} C·m) and a strong first-order Stark effect; when the electrostatic field used to trap the CO molecules is lower than 50 kV/cm, the second-order Stark effect can be neglected. In this case, when the angle θ between the EDM and the external electric field $\boldsymbol{E}$ is fixed, we can introduce an effective dipole moment $\mu_{\text{eff}} = \mu\langle\cos\theta\rangle$, where μ is the magnitude of the permanent EDM, and $\langle\cos\theta\rangle$ represents the quantum-mechanical averaging over all the angle, then Eq.(1) can be rewritten as

$$W_{\text{Stark}}(r) = -\mu_{\text{eff}}E(r) = -\mu E(r)\left\langle\cos\theta\right\rangle. \tag{2}$$

In consideration of the internal quantum levels ($v = 0$, $J = 1$, $M\Omega = -1$) of a weak-field-seeking CO molecule in the metastable $a^3\Pi$ state, the Stark trapping potential for CO molecules in the weak-field-seeking states is given by

$$W_{\text{Stark}}(r) = -\frac{M\Omega}{J(J+1)}\mu E(r), \tag{3}$$

and the corresponding dipole gradient force from the electrostatic field, acting on the cold polar molecules, is given by

$$\boldsymbol{F} = -\nabla W_{\text{Stark}} = -\mu_{\text{eff}}\nabla\boldsymbol{E}. \tag{4}$$

It is clear from Eq.(4) that when μ_{eff} is negative, the molecules in the weak-field-seeking states will be repelled to the minimum region of the electrostatic field due to the repulsive gradient force $\boldsymbol{F}$.

3. Theoretical calculation and analysis

3.1. Calculation of contour distribution of electrostatic trapping field

From Fig.1, we can see that due to the symmetry of our wire layout, the spatial distribution of the electrostatic field in the plane $x0z$ is the same as that in $y0z$, so we only need to calculate the electric field distributions in planes $x0y$ and $x0z$. Also, it is clear that the electric field distribution in the x direction is the same as that in the y direction, so we only need to study the electric field distributions in the x and z directions.

Since there is not an analytical solution to calculate the electrostatic field distribution in a 3D free space generated by the present charged electrode layout (see Fig.1), we have to use a commercial finite element software (Maxwell) to calculate the spatial distribution of the electrostatic field from the present charged electrode layout in free space, and the contour distributions of the corresponding electrostatic field $|\boldsymbol{E}(r)|$ in the planes $x0y$ and $x0z$ are shown in Figs.2(a) and 2(b) respectively for $+U_1 = 10\,\mathrm{kV}$, $+U_2 = 0\,\mathrm{V}$, $R = 4\,\mathrm{mm}$, $r = 1\,\mathrm{mm}$, and $L = 3\,\mathrm{mm}$. We can see from Fig.2 that the electrostatic field produced by the charged electrode is a 3D closed hollow E-field distribution with a central minimum of $E(0) = 0$ at $(0, 0, z_0)$, which can be used to trap cold polar molecules in the weak-field-seeking states. It is worth noticing that when $+U_2 = 0\,\mathrm{V}$, we obtain the trapping central position $z_0 = 0$. While for $+U_2 > 0$, we have $z_0 < 0$, that is, the trapping central position z_0 will be moved to the left of the geometric centre of the electrode setup along the z axis, which can be used to efficiently load cold molecules into the electrostatic trap from a cold molecular beam. We will discuss the efficient loading of cold molecules in Section 4.

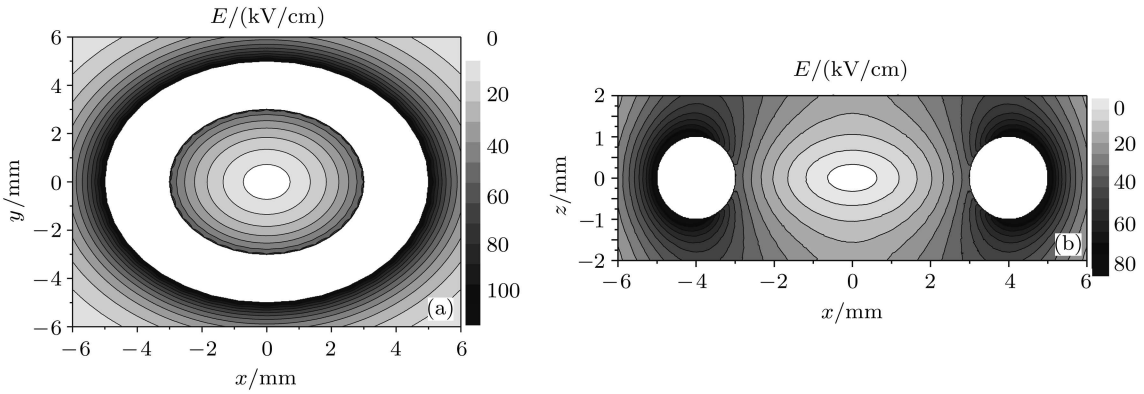


Fig.2. The contours of the electric field distribution in (a) $x0y$ and (b) $x0z$ planes. The interval of contours is 6 kV/cm.

3.2. Dependence of trapping centre position z_0 on system parameters

In order to know the trapping centre of cold molecules even to manipulate and control them, we study the relationships between the position z_0 of the trapping centre (i.e., the position of the minimum electric field) and the parameters $(R, r, L, +U_2)$ of the trap setup, and the calculated results are shown in Fig.3. It is clear from Fig.3 (a) that with the increase of the ring radius R from $R = 3.0$ to $5.0\,\mathrm{mm}$ ($\Delta R = 2.0\,\mathrm{mm}$), the position z_0 of the trapping centre will be almost linearly reduced from –0.04 mm to –0.098 mm ($\Delta z_0 = 58\mu\,\mathrm{m}$), that is, the position z_0 will be moved left along the z axis. Figure3 (b) shows that with the increase of the wire radius r from 0.4 to 1.6 mm ($\Delta r = 1.2\,\mathrm{mm}$), the position z_0 of the trapping centre will be changed from –0.105 to –0.055 mm ($\Delta z_0 = 50\mu\,\mathrm{m}$), i.e., the trapping centre z_0 will be moved right along the z axis. Figure3(c) shows that with the increase of the half space L from 2.25 to 4.75 mm ($\Delta L = 2.5\,\mathrm{mm}$), the position z_0 of the trapping centre will be slightly increased from about -0.084 to $-0.064\,\mathrm{mm}$ ($\Delta z_0 = 20\mu\,\mathrm{m}$). Figure3 (d) displays that with the increase of the applied voltage $+U_2$

from 0 to 800 V, the position z_0 of the trapping centre will be changed linearly from 0.000 to -0.118 mm ($\Delta z_0 = 118\mu$m). This shows that the applied voltage $+U_2$ can be used to efficiently load cold molecules from a cold molecular beam into the electrostatic trap, even to manipulate and control cold molecules in the trap.

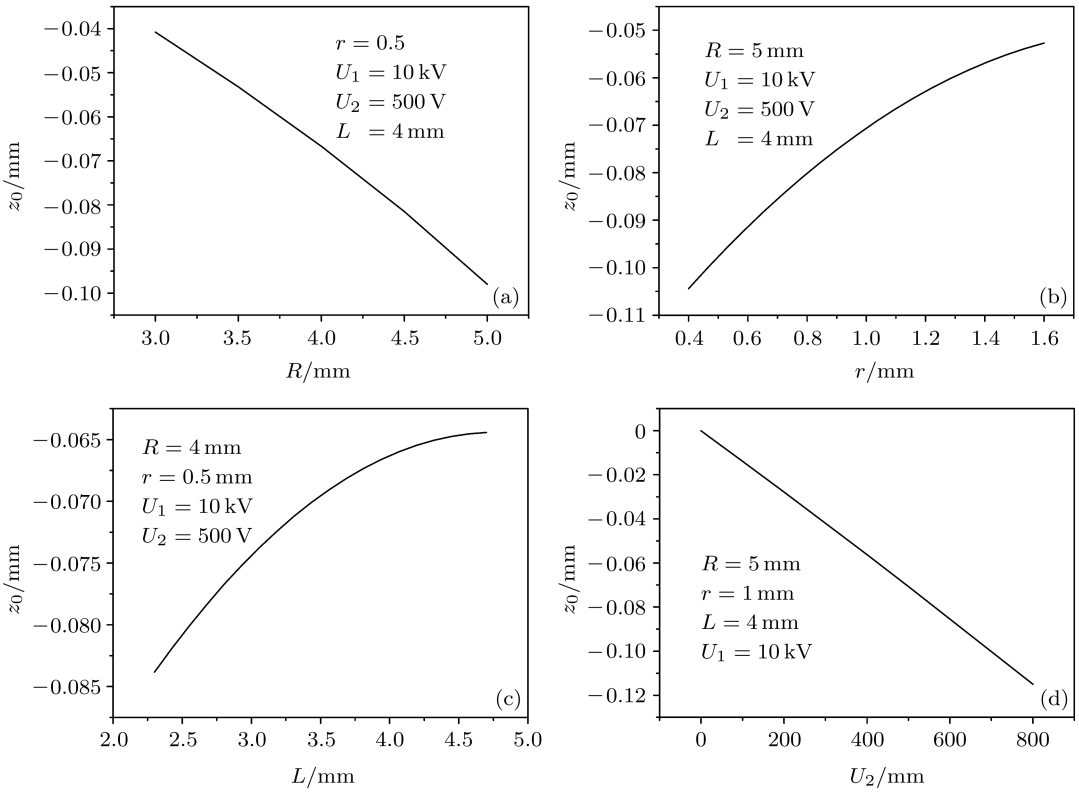


Fig.3. The dependence of the position z_0 of the trapping centre on (a) the radius R of the ring electrode, (b) the radius r of the ring wire, (c) the half space L, and (d) the applied voltage $+U_2$ on the left plate electrode.

3.3. Dependence of efficient trapping potential on geometric parameters of the system

We study the relationships between the spatial distribution of the electric field ($E(x)|_{y=0,z=z_0}$ or $E(z)|_{x=y=0}$) in free space and the geometric parameters (R, r, L) of the trap scheme, and analyse the relationships between the corresponding Stark potential ($W(x)_{\rm Stark}|_{y=0,z=z_0}$ or $W(z)_{\rm Stark}|_{x=y=0}$) for CO molecules and the geometric parameters (R, r, L) of the trap scheme, where, $E(x)|_{y=0,z=z_0}$ ($W(x)_{\rm Stark}|_{y=0,z=z_0}$), and $E(z)|_{x=y=0}$ ($W(z)_{\rm Stark}|_{x=y=0}$) are the spatial distributions of the electric field E (its Stark potential $W_{\rm Stark}$ for CO molecule) in the x and z directions. Next, we will present the calculation results and the corresponding theoretical analysis.

First, we study the relationship between the electric field E (or Stark trapping potential $W_{\rm Stark}$) and the ring radius R, and the calculated results are shown in Fig.4. We can see from Fig.4 (a) that the larger the ring radius R is, the smaller the gradient of the electric field $E(x)$ near the trapping centre will be, and the higher the efficient Stark potential $W(x)_{\rm Stark}$ in the x direction will be. In particular, when $r = 1$ mm, $L = 4$ mm, $+U_1 = 10$ kV , $U_2 = 0$ V, and $R = 3$, 4 and 5 mm, the efficient Stark potentials $W(x)_{\rm Stark}$ are 325, 450 and 550 mK, respectively. Figure 4(b) indicates that: (i) with the increase of the ring radius R, the gradient of the electric field $E(z)$ will be reduced. (ii) The larger the ring radius R is, the smaller the efficient Stark potential $W(z)_{\rm Stark}$ in the z direction will be, and when the ring radius R is increased from 3 to 5 mm, the efficient Stark potential $W(z)_{\rm Stark}$ will be reduced from about 420 to 275 mK. (iii) In particular, when $R = 3$ mm, $r = 1$ mm, $L = 4$ mm,

$+U_1 = 10\,\mathrm{kV}$ and $U_2 = 0\,\mathrm{V}$, we have the maximum effective trapping potential $W(z)_{\mathrm{eff}} \approx 418.87\,\mathrm{mK}$, which is far higher than the transverse and longitudinal temperatures ($\sim 11\,\mathrm{mK}$ and $250\mu\,\mathrm{K}$ respectively) of cold polar molecules from the Stark decelerator.[5]

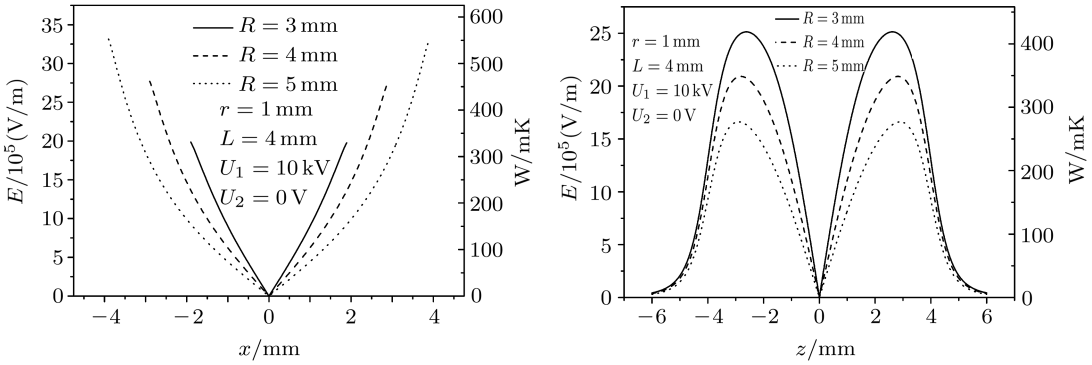


Fig.4. The electric field distribution and its corresponding trapping potential for CO molecules in (a) x and (b) z directions for $r = 1\,\mathrm{mm}$, $L = 4\,\mathrm{mm}$, $+U_1 = 10\,\mathrm{kV}$, $+U_2 = 0\,\mathrm{V}$, and $R = 3$, 4 and 5 mm.

Secondly, we investigate the relationship between the electric field E (or Stark trapping potential W_{Stark}) and the radius r of the ring wire itself, as shown in Fig.5. We can see from Fig.5 (a) that the larger the wire radius r is, the larger the gradient of the electric field $E(x)$ near the trapping centre will be, and the smaller the efficient Stark potential $W(x)_{\mathrm{Stark}}$ in the x axis. Figure 5(b) shows that: (i) with the increase of the wire radius r, the gradient of the electric field $E(z)$ will be increased. (ii) The larger the wire radius r is, the higher the efficient Stark potential $W(z)_{\mathrm{Stark}}$ in the z direction will be, and when the electrode radius r is increased from 0.5 to 1.5 mm, the efficient Stark potential $W(z)_{\mathrm{Stark}}$ will be increased from about 200 to 340 mK. (iii) When $R = 3\,\mathrm{mm}$, $L = 4\,\mathrm{mm}$, $+U_1 = 10\,\mathrm{kV}$, $U_2 = 0\,\mathrm{V}$ and $r = 1.5\,\mathrm{mm}$, we have the maximum effective electric field $E(z)_{\max} \approx 20.43 \times 10^5\,\mathrm{V/m}$ and the maximum effective Stark trapping potential $W_{\mathrm{Stark}} \approx 340\,\mathrm{mK}$.

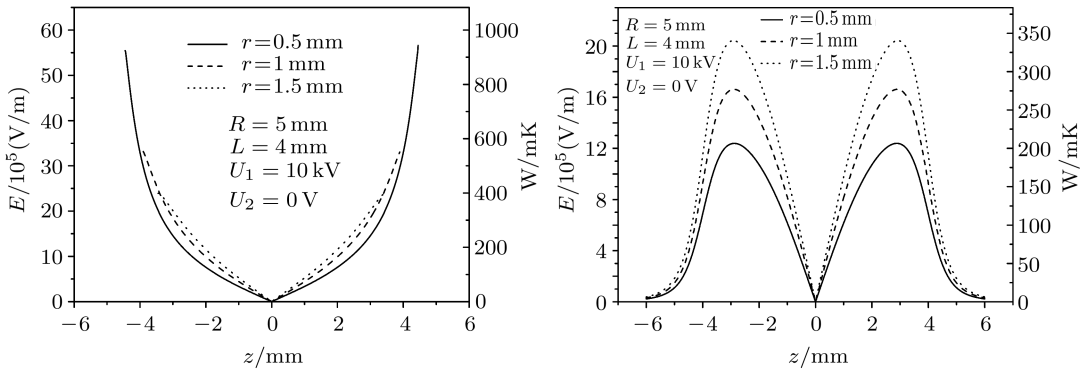


Fig.5. The electric field distribution and its corresponding trapping potential for CO molecules in (a) x and (b) z directions for $R = 3\,\mathrm{mm}$, $L = 4\,\mathrm{mm}$, $+U_1 = 10\,\mathrm{kV}$, $+U_2 = 0\,\mathrm{V}$, and $r = 0.5$, 1 and 1.5 mm.

Finally, we also study the relationships between the distribution of the electric field E (or Stark trapping potential W_{Stark}) and the half space L among the centre of the ring electrode and the plate electrode, as shown in Fig.6. We can find from Fig.6 (a) that with the increase of the half space L, the gradient of the electric field $E(x)$ and the efficient Stark trapping potential $W_{\mathrm{Stark}}(x)$ will be decreased. When the half space L is increased from $L = 2$ to 4 mm, the efficient trapping potential $W_{\mathrm{Stark}}(x)$ will be reduced from about 750 to 350 mK. Figure 6(b) shows that the gradient of the electric field $E(z)$ near the trapping

centre will be increased rapidly with the reduction of the half space L. The smaller the half space L is, the higher the efficient trapping potential $W_{\rm Stark}(z)$ will be. When $R = 3\,$mm, $r = 1.5\,$mm, $+U_1 = 10\,$kV, $U_2 = 0\,$V and the half space L is reduced from 4 to 2 mm, the efficient trapping potential $W_{\rm Stark}(z)$ will be increased from about 400 to 550 mK.

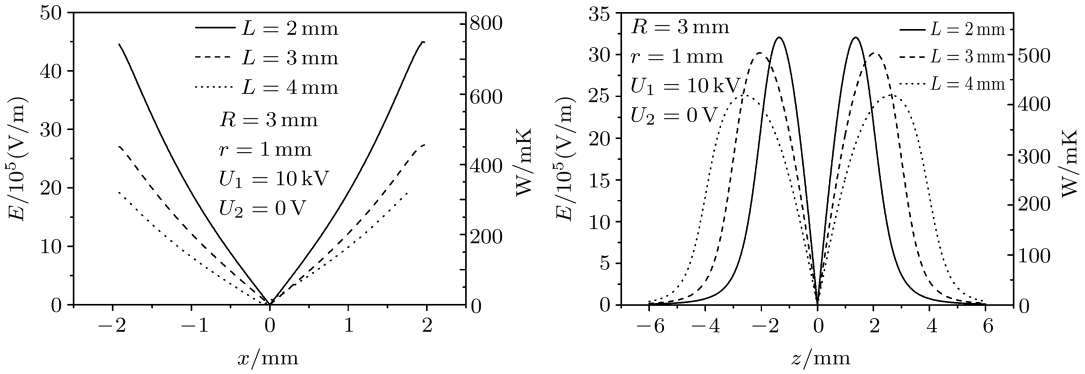


Fig.6. The electric field distribution and its corresponding trapping potential for CO molecules in (a) x and (b) z directions for $R = 3\,$mm, $r = 1\,$mm, $+U_1 = 10\,$kV, $+U_2 = 0\,$V, and $L = 2$, 3, and 4 mm.

4. Discussion and comparison

4.1. Efficient loading of cold polar molecules

To make efficient loading of cold molecules from a cold molecular beam into the trap, we also investigate the relationship between the electric field $E(z)$ (or efficient Stark trapping potential $W_{\rm Stark}(z)$) in the z direction and the applied voltage $+U_2$, as shown in Fig.7. It is clear from Fig.7 that with the increase of $+U_2$, the effective trapping potential $W(z)^{\rm left}_{\rm eff}$ for cold CO molecules at the left side of the trapping centre z_0 will be greatly reduced, and when the voltage $+U_2$ is increased from 0 to 7 kV, the trapping potential $W(z)^{\rm left}_{\rm eff}$ will be reduced from about 550 to 15 mK, and the corresponding trapping centre will be shifted left from $z_0 = 0$ to about -2.8 mm, which is a very useful method to efficiently load cold polar molecules into the trap from a Stark-decelerated cold molecular beam.

In addition, in order to efficiently load cold molecules into the trap, the entrance for a cold beam must be matched to the acceptance of the trap. This is performed in two steps: the cold molecules are first focused transversely by hexapole poles and decelerated upon entering the trap by applying different voltages asymmetrically to the trapping electrodes according to the need, and the average speed of the cold molecular beam is thereby reduced to zero at the centre of the trap. Afterwards, we switch the voltage on the entrance electrode plate to the ground potential when the cold molecules have come to a near-standstill inside the trap.

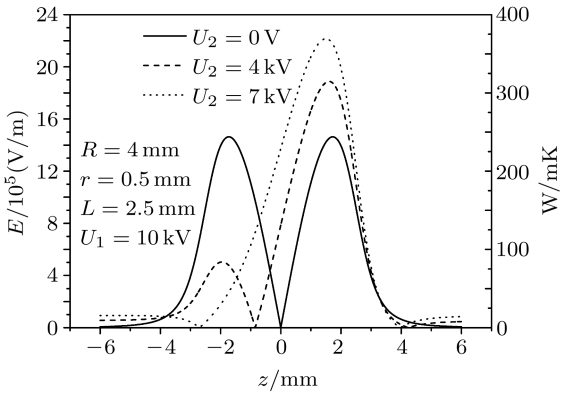


Fig.7. The relationships between the electric field distribution $E(z)$ in the z direction and the applied voltage $+U_2$ for $R = 4\,$mm, $r = 0.5\,$mm, $L = 2.5\,$mm, $+U_1 = 10\,$kV, and $+U_2 = 0\,$V, 4 kV and 7 kV.

In Fig.7, for $U_2 = 7\,$kV, the internal quantum levels ($v = 0$, $J = 1$, $M\Omega = -1$) of a weak-field-seeking CO molecule in a metastable $a^3\Pi$ state along the molecular beam axis are shown. For the transverse and longitudinal focusing of the beam, the electric field distribution near the $z = -5$ to $-2\,$mm region is very important. In this region the potential energy along the molecular beam axis is nearly quadratically dependent on z. The molecules will experience a linear force $F = -k(z - z_0)$, and here z_0 is the position where the quadratic potential starts ($z_0 = -5\,$mm), and k

is the force constant. This force can be written in terms of the position z_s of the synchronous molecules as $F = -k(z - z_s) - k(z_s - z_0)$. Hence the force can be divided into a restoring force towards the synchronous molecules and a force that lowers the velocity of the synchronous molecules. In order to bring the average speed of the molecule beam to zero, the voltages applied to the trap electrodes are asymmetrically. With a voltage of 7 kV on the entrance plate electrode and 10 kV on the ring electrode, the electric field will be small at the entrance of the trap and will increase towards the centre of the trap. When the voltage on the trap electrodes are kept unchanged, the trap will act as a concave mirror for the CO molecules. In order to trap the molecules, the voltage on the entrance plate electrode is switched off once the synchronous molecule has come to a standstill. So we have created a symmetrical electrostatic field with a minimum at the geometrical centre of the trap, and the cold molecules are efficiently loaded into the trap. It is clear from the above analysis that the present trap scheme can not only be used to efficiently trap various cold polar molecules with a temperature lower than ~ 500 mK, but also to realize the efficient loading of cold molecules from a cold molecular beam into the trap.

4.2. Comparison of the present trap scheme with other ones

By comparison with the trap schemes used by other researchers , the present electrostatic trap scheme has some unique characteristics or advantages as follows: (i) With reasonable geometric parameters, the present trap scheme has a higher well depth of $\sim$0.65 K and a bigger trapping volume V of $\sim$0.12 cm^3. On the other hand, if we use the same parameters as those in Ref.[5]: $R = 5$ mm, $r = 1$ mm, $L = 3.5$ mm, $+U_1 = 12$ kV and $+U_2 = 0$ kV, the trap depth for ND_3 is about 342mK. In Ref.[5] the trap depth is about 350mK .From this result, we can see that the depths of the two traps are almost the same. (ii)The two end caps with a hyperboloid surface in Refs.[4,5,20–22, 25] are replaced by two plate electrodes with a simple plane which can be easily fabricated and installed in the present scheme. (iii) It is easy and convenient to detect the trapped cold molecules in the present trap by using the standard laser fluorescent measuring method because the two plate electrodes are two transparent plates (at least the right plate electrode is transparent), or two planar metal-nets (at least the right plate electrode is a planar metal plate). Obviously, the spatial range of the fluorescence detection in the present trap scheme is rather wide, and more information on the trapped cold molecules can be easily obtained. So the present trapping scheme is simpler, more flexible and convenient than other trapping schemes, [4,5,20−23,26] and has some important and wide applications in cold molecular physics and molecule optics, and so on.

5. Conclusions

We have proposed a novel and simple scheme to trap cold polar molecules by using an electrostatic field, and studied the relationship between the electric field (including the Stark trapping potential) and the geometric parameters of the trapping setup. The result shows that the electrostatic field produced by the charged electrode is of 3D closed hollow E-field distribution with a central minimum of $E(z_0) = 0$, which can be used to efficiently trap cold polar molecules in the weak-field-seeking states.

Moreover, the electrostatic trapping scheme can not only be used to efficiently trap cold polar molecules, but also be conveniently used to manipulate and control cold molecules by changing the high voltage $+U_2$, which may open a new way to study cold molecular spectroscopy,[15] cold collisions,[29] dipolar-dipolar interaction[30] and collective quantum effects in molecular system, even to realize efficient evaporative cooling of the trapped molecules by lowering the Stark trapping potential, and so on.

References

[1] Francoise M S and Pierre P 2001 *Adv. At. Mol. Opt. Phys.* **47** 53

[2] van Abeelen F A and Verhaar B J 1999 *Phys. Rev. Lett.* **83** 1550

[3] Bethlem H L, Berden G and Meijer G 1999 *Phys. Rev. Lett.* **83** 1558

[4] Bethlem H L, Berden G, Crompvoets F M H, Jongma R T, van Roij A J A and Meijer G 2000 *Nature* **406**

[5] Bethlem H L, Crompvoets F M H, Jongma R T, van de Meerakker S Y T and Meijie G 2002 *Phys. Rev.* A **65** 053416

[6] Bochinshi J R, Hudson E R, Lewandowski H J, Meijer G and Ye J 2003 *Phys. Rev. Lett.* **91** 243001-1
[7] Egorov D, Lahaye T, Schollkopf W, Friedrich B and Doyle J M 2002*Phys. Rev.* A **66** 04340
[8] Fulton R, Bishop A I and Barker P F 2004 *Phys. Rev. Lett.* **91** 243004-1
[9] Fulton R, Bishop A I, Shneider M N and Barker P F 2006 *Nature Phys.* 2465
[10] Rangwala S A, Junglen T, Rieger T, Pinkse P W H and Rempe G 2003 *Phys. Rev.* **67** 043406-1
[11] Junglen T, Rieger T, Rangwala S A, Pinkse P W H and Rempe G 2004 *Eur. Phys. J.* D **31** 365
[12] Burnett K, Julienne P S, Lett P D, Teisingna E and Williams C J 2002 *Nature* **416** 225
[13] Williams C J and Julienne P S 2000 *Science* **287** 986
[14] Stuhler J, Griesmaier A, Koch T, Fattori M, Pfau T, Giovanazzi S, Pedri P and L 2005 *Phys. Rev. Lett.* **95** 150406
[15] Hudson E R, Lewandowshi H J, Sawyer B C and Ye J 2006 *Phys. Rev. Lett.* **96** 143004-1
[16] Weinstein J D, deCarvalho R, Guillet T, Friedrich B and Doyle J M 1998 *Nature* **395** 148
[17] van de Meerakker S Y T, Jongma R T, Bethlem H L and Meijer G 2001*Phys. Rev.* A **64** 041401-1
[18] Takekoshi T, Patterson B M and Knize R J 1998 *Phys. Rev. Lett.* **81** 5105
[19] Jongma R T, von Helden G, Berden G and Meijer G 1997 *Chem. Phys. Lett.* **270** 304
[20] Bethlem H L, Berdem G, Crompvoets F M H, Jongma R T, van Roij A J A and Meijer G 2000 *Nature* **406** 491
[21] van de Meerakker S Y T, Smeets P H M, Vanhaecke N, Jongma R T and Meijer G 2005 *Phys. Rev. Lett.* **94** 023004
[22] van Veldhoven J, Bethlem H L, Schnell M and Meijer G 2006 *Phys. Rev.* A **73** 063408-1
[23] Katz D P 1997 *J. Chem. Phys.* **107** 8491
[24] Crompvoets F M H, Bethlem H L, Jongma R T and Meijer G 2001 *Nature* **411** 174
[25] Paul W 1990 *Rev. Mod. Phys.* **62** 531
[26] Choi G W, Kim N H, Seo Y J and Lee W S 2006 *Electron. Lett.* **42** 487 Apr 13
[27] Deng L Z, Xia Y and Yin J P 2007 *Chin. Phys.* **16** 707
[28] Junglen T, Rieger T, Rangwala S A, Pinkse P W H and Rempe G 2004 *Phys. Rev. Lett.* **92** 223001-1
[29] Burnett K, Julienne P S, Lett P D, Teisinga E and Williams C J 2002 *Nature* **416** 225
[30] Goral K, Santos L and Lewenstein M 2002 *Phys. Rev. Lett.* **88** 170406-1