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The experiment on the saturation polarization of Rb vapour*

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A cylindrical capacitor containing rubidium vapour is made. The capacitance of it at different voltages is measured under a certain Rb vapour pressure. The experimental C–V curve shows that the saturation polarization of Rb vapour is easily observed. The experiment further supports the idea that the Rb atom has a large permanent electric dipole moment.

Keywords: saturation polarization, Rb vapour, permanent electric dipole moment
PACC: 0365, 0390

1. Introduction

If the Hamiltonian of a system commutes with the unitary space-inversion operator U_1, the energy eigenstate $|\Psi_{\rm E}\rangle$ of the system can be chosen to have well-defined parities. For this state we obtain the zero permanent electric dipole moment (PEDM).[1] However, some physicists think that a state vector $|\Psi_{\rm E}\rangle$ does not describe a single particle but an ensemble consisting of particles having the same energy E.[2–6] $\langle\Psi_{\rm E}|e\boldsymbol{r}|\Psi_{\rm E}\rangle = 0$ does not mean that PEDM of a single atom is zero. We guess that hydrogen-like atoms may have large PEDM from the analysis of hydrogen atoms.[6–8] This guess is supported by experiments on Rb and Cs atoms.[7,8] Though the experiment of Ref.[9] shows that the PEDM of Cs atoms is zero, the result comes from the measurement in strong noises. In the experiment of Refs.[7,8], Rb or Cs vapour is filled in a cylindrical capacitor. The capacitance of the cylindrical capacitor is measured by a digital capacitance meter. The resolution of the meter is 0.1pF and the accuracy of it is 0.5%. The measured capacitance of the cylindrical capacitor containing Rb or Cs vapour is over several hundreds of pF. It means that the measured effect is very strong. The results of the two experiments show that Rb and Cs vapours both have large dielectric constants. These large dielecteic constants cannot come from the induced electric dipole moments of atoms but come from the PEDM of the atoms.[7,8] Certainly, if Rb and Cs atoms had non-zero PEDM, Rb and Cs vapours would show a behaviour of saturation polarization. The reported experiment on the saturation polarization of the Rb vapour strongly supports the idea that the Rb atom has a large PEDM.

2. Experimental apparatus

The experimental apparatus is a closed glass container. It resembles a Dewar bottle in shape. The longitudinal section of the container is shown in Fig.1. The internal and external surfaces of the container are plated with silver separately, as shown by A and B in Fig.1. These two silver layers build up a cylindrical capacitor. When the container is empty, it is pumped to a vacuum $P = 1 \times 10^{-4}$Pa in a temperature range 20–250°C.The aim of the operation is to remove impurities such as oxygen adsorbed on the inner walls of the container. The measured capacitance C_0 of the cylindrical capacitor is approximately constant, $C_0 \approx$66pF in the mentioned temperature range.

The next step is to input some Rb vapour into the cylindrical capacitor. In order to control the quantity of Rb vapour that enters into it, the container is connected by a glass tube from the top to another small container that contains the Rb material.

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These two containers are slowly heated to 210°C in a temperature-controlled furnace and then the designed experimental container is sealed. We use the experimental apparatus shown in Fig.1.

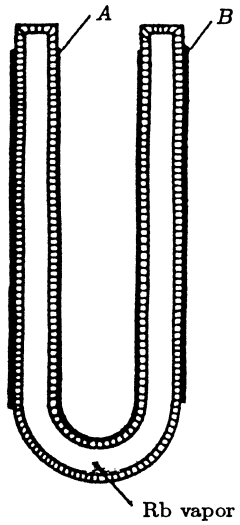


Fig.1. Schematic illustration of the longitudinal section of a Dewar-like glass container. Silver layers A and B build a cylindrical capacitor into which the Rb vapour is filled.

3. Statistical distribution

Consider a gas consisting of molecules that have a PEDM $\boldsymbol{\mu}$, and suppose that an electric field $\boldsymbol{E}$ is applied along the z-axis. The probability $P(\theta)\mathrm{d}\theta$ of the PEDM $\boldsymbol{\mu}$ having an inclination of the dipole axis to the direction of the z-axis between θ and $\theta + \mathrm{d}\theta$ is[10]

$$p(\theta)\mathrm{d}\theta = A\mathrm{e}^{\mu E\cos\theta/kT}\sin\theta\mathrm{d}\theta, \tag{1}$$

where A is a normalized constant

$$A = \left[\int_0^\pi \mathrm{e}^{\mu E\cos\theta/kT}\sin\theta\mathrm{d}\theta\right]^{-1}. \tag{2}$$

In the calculation of polarization of the gas, we need the mean value of $\cos\theta$,

$$\overline{\cos\theta} = A\int_0^\pi \cos\theta\mathrm{e}^{\mu E\cos\theta/kT}\sin\theta\mathrm{d}\theta = L(a), \tag{3}$$

where $a = \dfrac{\mu E}{kT}$, $L(a)$ is called the Langevin function

$$L(a) = \frac{\mathrm{e}^a + \mathrm{e}^{-a}}{\mathrm{e}^a - \mathrm{e}^{-a}} - \frac{1}{a}. \tag{4}$$

For the vapour formed by Rb atoms, the PEDM of a Rb atom is still denoted by $\boldsymbol{\mu}$. We should use an energy parameter w_d instead of kT in Eqs.(1)–(4). For the atom vapour, the rotation freedoms of the atoms have no contribution to the specific heat of the vapour. The collision between atoms is always through their mass centres. When an atom collides with another atom, its PEDM $\boldsymbol{\mu}$ cannot be changed. Parameter w_d describes the intensity of interactions between PEDM and PEDM, as well as between PEDM and other electric noises.

The capacitance of the experimental cylindrical capacitor is $C_0 \approx$66pF at a vacuum condition. After it is filled with the Rb vapour, the polarization of Rb vapour medium will increase the capacitance of the cylindrical capacitor. The polarization of the Rb vapour in the z-axis is

$$\rho = n\mu\overline{\cos\theta} = n\mu L(a), \tag{5}$$

where n is the number density of Rb atoms in the vapour, $a = \dfrac{\mu E}{w_d}$. When the electric field is strong enough so that $L(a)$=1, the polarization of the vapour medium becomes saturation polarization. In this case, the directions of the PEDM of all atoms are in the z-axis. We can expect that the parameter w_d should be very small from the above discussion. This means that observation of the saturation polarization for Rb vapour would not be difficult.

4. Experimental method and result

The experimental cylindrical capacitor can be approximately regarded as a parallel-plane capacitor. More details on the capacitor can be found in Refs.[7,8]. Let S and H be the plate area and the distance between the two plates of the parallel-plate capacitor, respectively, then we have from the energy relation that

$$(C - C_0)V\mathrm{d}V = SHn\mu L(a)\mathrm{d}E, \tag{6}$$

$$C - C_0 = \frac{Sn\mu L(a)}{V}. \tag{7}$$

When the electric field is weak so that $a \ll 1$ and $L(a) = a/3$,[10] we obtain

$$C = C_0 + \frac{Sn\mu^2}{3Hw_d}. \tag{8}$$

When the electric field is strong so that $a \gg 1$, we have from $L(a) = 1$,

$$C = C_0 + \frac{Sn\mu}{V}. \tag{9}$$

The experimental method is shown in Fig.2. Two signals $V_C(t) = V_{C0}\cos\omega t$ and $V_S(t) = V_{S0}\cos\omega t$ are

measured by an oscilloscope having two lines. The two signals have the same circular frequency $\omega = 2\pi \times 5$kHz and the same phase, which can be seen in the oscilloscope. C is the measured cylindrical capacitor, which is in a temperature-controlled furnace and kept at temperature 100°C. C_d=1137pF is a reference capacitor. If capacitor C is an ordinary one, we have the relation from Fig.2,

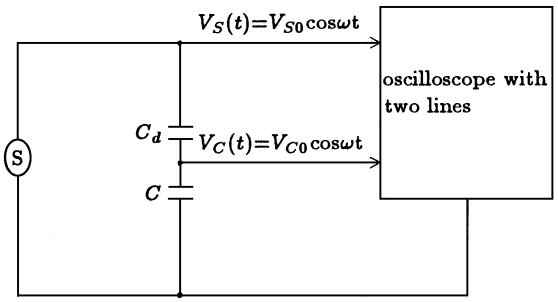


Fig.2. The diagram showing the experimental method, in which C is the measured capacitor and C_d is a standard one.

$$\frac{V_S - V_C}{V_C} = \frac{C}{C_d}, \tag{10}$$

$$C = \left(\frac{V_{S0}}{V_{C0}} - 1\right) C_d. \tag{11}$$

We can determine C from the experiment using Eq.(11).

In the experiment V_{S0} can be adjusted from zero to 250V. The experimental result that the capacitance of capacitor C at different voltages is shown in Fig.3. When $V_{C0} < 1$V, $C \approx$236pF is approximately constant, and the result is consistent with Eq.(8). When $V_{C0} >$100V, $C \approx$70pF which approaches $C_0 \approx$66pF and is consistent with Eq.(9).

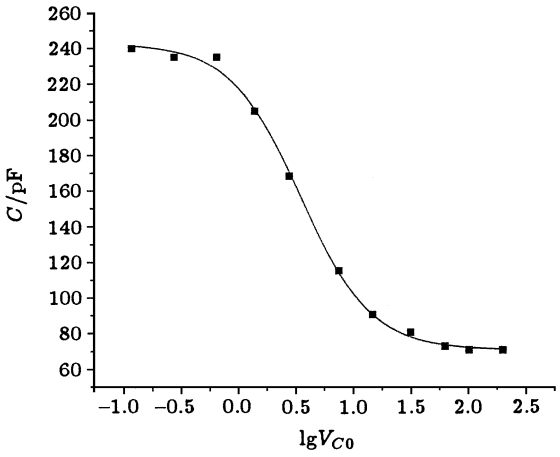


Fig.3. The sturation polarization of Rb vapour as a function of applied voltage. The units of C and V_{C0} are pF and V respectively.

Strictly speaking, Eqs.(10) and (11) are only approximate relations, because C is not an ordinary capacitor. The magnitude of C depends on the voltage applied to it. We cannot use the experimental curve to compare with Eq.(7) and to obtain values of μ and w_d. In spite of this, the experimental curve tells us that the saturation polarization effect of the Rb vapour medium is obvious.

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