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Theoretical and Experimental Proof of Alkali-Metal Atom as Polar Atom

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Abstract

In addition to polar molecules, there is no polar atom in the natural world, which is a deep-rooted traditional concept that has lasted for more than a century. However, our research showed that alkali-metal atoms form an exception. In theory, we proved that alkali atom may be polar atom doesn't conflict with quantum mechanics, which is a great breakthrough in measurement theory of quantum mechanics. Variation of the capacitance with temperature and density offers a means of separating polar and nonpolar atom, but no one has done these experiments so far. If alkali atom is nonpolar atom, its capacitance should be independent of temperature and density, because atomic nucleus located at the center of the electron cloud. Our experiments showed that Na, K, Rb and Cs atoms are polar atoms, because their capacitance is not only related to temperature, but also to density. Unlike alkali atoms, the capacitance of Hg gas is independent of temperature and density, so mercury is nonpolar atom. Therefore atoms can be divided into two categories: polar and nonpolar atom, this discovery will lead to an exciting revolution in Bose-Einstein condensation (BEC) research and condensed matter physics. BEC experiments have been carried out for decades, but the number of condensed atoms is still very small ($<10^7$) because scientists has never applied an electric field. Our innovation lies in the application of an electric field, we don't need magnetic field and lasers. When V=390 volts, condensates contained up to 2.51×10^{17} sodium atoms; when V=350 volts, condensates contained up to 1.93×10^{17} cesium atoms, large-scale BEC at T=343 K or 353 K has been observed. Now scientists generally assume that polar molecules may be used as candidate materials for quantum computers. In the future, polar atoms will replace polar molecules as candidate materials for quantum computers, because of its very small moment of inertia.

Keywords: Polar atom and nonpolar atom; Ensemble interpretation of wave function; Variation of capacitance with temperature and density; Capacitance of Na, K, Rb and Cs atoms at different temperature and density; Large-scale Bose-Einstein condensation of sodium and cesium; Candidate materials for quantum computers

Introduction

It is a general point of view that a ground-state neutral atom has no permanent dipole moment (PDM) because of their spherical symmetry, and therefore all kinds of atoms are nonpolar atoms. In fact, this deep-rooted traditional concept is an untested assumption, which misleads scientists all over the world. Our theoretical and experimental research shows that alkali atoms form an exception. The realization that there is one small nucleus, which contains the entire positive charge and almost the entire mass of the atom, is due to the investigations of Rutherford, who utilized the scattering of alpha particles by matter. He found that when swiftly-moving alpha particles are allowed to collide with gold atoms, they are sometimes deflected through 180°, implying that a strong force is at work. This experimental phenomenon led Rutherford to propose the nuclear model of the atom in 1911. The force is just the electrostatic repulsion experienced by an alpha particle when it chances to approach close to the nucleus of a gold atom [1]. Since the times of Rutherford, physicists and chemists commonly believed that in the absence of an external electric field, the nucleus located at the center of the electron cloud, so atoms don't have PDM. As a result, there is no polar atom in the natural world.

If alkali atom is a non-polar atom, has this conclusion been verified by experiments?

Answer: No! The results of such experiments have never been reported in the history of physics! Therefore, this deep-rooted traditional concept has not been proved by experiments. By mere guesswork, scientists generally believed that alkali atoms don't have PDM, they are nonpolar atom. This is an idealist philosophy. Since scientists never measured the capacitance of alkali atoms at different temperature and density, so they missed this significant discovery.

The Indian physicist S. N. Bose wrote to Einstein in 1924 describing his work on the statistical mechanics of photons. Einstein followed up Bose's work by generalizing it to non-relativistic particles with non-zero mass, and in 1925 he predicted the phenomenon now known as Bose-Einstein condensation (often abbreviated to BEC). For many years, this phenomenon was regarded as a purely theoretical proposal, until Fritz London rediscovered it in 1938 to explain the superfluid transition of liquid helium. BEC in dilute atomic gases was first pursued in spin-polarized hydrogen, and subsequently was successfully observed in rubidium and sodium vapors [2,3]. These experiments led to new experimental and theoretical interest in the study of appropriate densities of alkali atom gases (densities ranging from 10^{13} to 10^{15} cm^{-3}). They can be prepared inside magnetic ion traps. All stable alkali species – Li (4), Na (3), K (5), Rb (2), and Cs (6) - have been condensed using the newly developed techniques of laser cooling. In BEC experiment, scientists never applied an electric field, because they think that all kinds of alkali atom are nonpolar atoms. Although many advanced technologies are used, but the vast majority of atoms are randomly oriented, and the number of condensed atoms is very few ($<10^7$) [2-6]. In November 1995, Davis et al. used a cloud of sodium to create BEC with 5×10^5 atoms [3]. Eight years later, R. Grimm et al. used a cloud of

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cesium to create BEC with 1.6×10^4 atoms. The number of condensed atoms not only did not increase, but was reduced to three percent of the original [6]. This fact indicates that this deep-rooted traditional concept has seriously hindered the progress of science, so that the experimental research of BEC is still stagnant. This article provides an important innovation for BEC experiment.

Theoretical breakthrough

In theory, we proved that alkali atoms may be polar atom doesn't conflict with quantum mechanics. In order to prove that a neutral ground state atom has no PDM, quantum mechanics usually has two representations. The first statement is as follows. "An atom can have a permanent electric dipole moment (energy change proportional to E) only when the unperturbed state is non-degenerate and does not have well-defined parity or is degenerate and contains components of opposite parities" [7]. For alkali atoms, its ns and np states are not degenerate, and have well-defined parity, and therefore the expectation value of PDM is zero, and have result $<\psi_E|er|\psi_E>=0$ [7]. The second statement is as follows. If the Hamiltonian operator H of a system commutes with the unitary space-inversion operator U_I, the energy eigenstate of the system can be chosen to have well-defined parities. For this state we obtain the zero PDM. Obviously, these two statements assumed that the ground state alkali atom doesn't have PDM, and have result $<\psi_E|er|\psi_E>=0$. However, many physicists think that the quantum state $|\psi_E>$ doesn't describe an individual particle but an ensemble of particles with the same energy [7-9]. Ballentine made a brilliant exposition in an article entitled "The statistical interpretation of quantum mechanics". The abstract of this article is as follows.

"The statistical interpretation of quantum theory is formulated for the purpose of providing a sound interpretation using a minimum of assumptions. Several arguments are advanced in favor of considering the quantum state description to apply only to an ensemble of similar prepared systems, rather than supposing, as is often done, that it exhaustively represents an individual physical system. Most of the problems associated with the quantum theory of measurement are artifacts of the attempt to maintain the latter interpretation. The introduction of hidden variables to determine the outcome of individual events is fully compatible with the statistical predictions of quantum theory. However, a theorem due to Bell seems to require that any such hidden-variable theory which reproduces all of quantum mechanics exactly (i.e. not merely in some limiting case) must possess a rather pathological character with respect to correlated, but spacially separated systems" [8]. Griffiths also stresses that "The expectation value is the average of repeated measurements on an ensemble of identically prepared systems, not the average of repeated measurements on one and the same system" [10]. So $<\psi_E|er|\psi_E>=0$ doesn't prove that the PDM of a single alkali atom is zero, only means that the average PDM of large number of alkali atoms is zero.

Hydrogen atom can provide an interesting proof. In 1913, Stark observed a splitting of the lines of the Balmer series of hydrogen in an electric field, and he was awarded the 1919 Nobel Prize in Physics. "The shift in the energy levels of an atom in an electric field is known as the Stark effect. Normally the effect is quadratic in the field strength". "But the first excited state of the hydrogen atom exhibits an effect that is linear in the field strength." [7]. Landau is particularly stressed that "the hydrogen atom forms an exception; here the Stark effect is linear in the field" [11]. There was no explanation for the Stark effect in classical theory, only quantum mechanics indicated how to understand this phenomenon. As we know, the hydrogen levels are n^2-fold degenerate, i.e. four eigen-functions belong to the first excited state of the unperturbed hydrogen. These wave functions are ψ_{200}, ψ_{210}, ψ_{211} and ψ_{21-1}. The wave function of perturbed hydrogen is $\psi_{2(1)}$, $\psi_{2(2)}$, $\psi_{2(3)}$ and $\psi_{2(4)}$. Landau once stated that "The presence of the linear effect means that, in the unperturbed state ψ_{2lm}, the hydrogen atom has a dipole moment whose mean value is $d=3ea_0$." [11]. Schiff also put forth a famous conclusion that "It is also possible, as in the case of the hydrogen atom, that unperturbed degenerate states of opposite parities can give rise to a permanent electric dipole moment." [12]. Griffiths emphasizes particularly that "Spin is irrelevant to this problem, so ignore it, and neglect the fine structure". "Notice that the results are independent of the applied field, --- evidently hydrogen in its first excited state can carry a permanent electric dipole moment" [10]. That is, $d(\psi_{200})\neq 0$, $d(\psi_{210})\neq 0$, $d(\psi_{211})\neq 0$ and $d(\psi_{21-1})\neq 0$.

However, although ψ_{2lm} is four-fold degenerate, but the calculation in quantum mechanics shows that the expectation value of the PDM is zero: $d=<\psi_{2lm}|er|\psi_{2lm}>=0$! That is, $<\psi_{200}|er|\psi_{200}>=0$, $<\psi_{210}|er|\psi_{210}>=0$, $<\psi_{211}|er|\psi_{211}>=0$, $<\psi_{21-1}|er|\psi_{21-1}>=0$. This zero result exceeded all scientists' expectations. Up to now, no quantum mechanical textbook explains this contradictory result. In fact, the linear Stark effect of hydrogen has not been satisfactorily explained. If someone declared that the Linear Stark shift of hydrogen is a very well understood problem, this statement is certainly not honest. The result showed that $<\psi_{2lm}|er|\psi_{2lm}>=0$ does not demonstrate that the PDM of a single hydrogen atom (n=2) is zero, only prove that the average PDM of a large number of hydrogen atoms is zero.

As everyone knows, alkali atoms can be described as hydrogen-like atoms because only one valence electron in the outermost layer. [13] In addition, the Quantum Mechanical model of the atom can be tested by atomic radius and ionization energy. The ionization energy of ground state alkali atoms, ranging from 3.9 eV to 5.4 eV, is far less than the ground state hydrogen (13.6 eV), but approximates to its first excited state (3.4 eV). For alkali atoms, the atomic radius (1.52 Å ~ 2.62 Å) is far greater than the ground state hydrogen (0.53 Å), but approximates to its first excited state (2.12 Å). So $<\psi_E|er|\psi_E>=0$ only means that the average PDM of large number of alkali atoms is zero, but doesn't mean that the PDM of an individual alkali atom is zero. This is the important breakthrough in measurement theory of quantum mechanics in this century.

How does distinguish the polar and non-polar atom experimentally?

The electric susceptibility is defined as $\chi_e=C/C_0-1$, where C_0 is the vacuum capacitance, C is the capacitance of the capacitor filled with the material. For polar atoms or molecules, the electric susceptibility is given by:

$$\chi_e=n\alpha + n\, d\, L(a)/\varepsilon_0 E \qquad (1)$$

where d is PDM of polar atom or molecule, α is the atomic or molecular polarizability, and a=d E/kT, Langevin function $L(a)=[(e^a + e^{-a})/(e^a - e^{-a})] - 1/a=\coth a - 1/a$ [14]. $L(a)$ equals the average value of cosθ.

$$L(a)=<\cos\theta>= f\int_0^{\pi}\cos\theta\exp(d_0E\cos\theta/kT)\sin\theta d\theta\,,$$

$$f=\left[\int_0^{\pi}\exp(d_0\,E\cos\theta/kT)\sin\theta\,d\theta\right]^{-1} \qquad (2)$$

where f is normalized constant, θ is the angle between d and E. When a<<1, $L(a) \approx a/3$, we obtain the familiar Langevin-Debye formula [14].

$$\chi_e=n\alpha+n\,d^2/3k\,\varepsilon_0\,T \qquad (3)$$

The electric polarizability of alkali atom is $\alpha<6\times10^{-29}$ m^3 [14], the density of alkali vapor $n<3.4\times10^{23}$ m^{-3}, and induced susceptibility $\chi_e=n\alpha<2\times10^{-5}$ can be neglected. We obtain an applicable formula:

$$\chi_e=nd\,L(a)/\varepsilon_0 E \quad (4)$$

Two cases of vapor density fixation and change are discussed as follows.

The density of the gas remains constant. From eqn. (3), we obtain:

For polar atoms χ_e=A+B/T; for non-polar atoms χ_e=A (5)

where A=nα and B=n $d^2/3k\,\varepsilon_0$ is constant. This kind of experiment has been reported previously, not the focus of this article. Now with cesium gas as the representative, a brief description of the experimental procedure is as follows. The experimental instruments are two cylindrical glass capacitors filled with fixed density cesium vapor and mercury vapor respectively. We measure their capacitance at different temperatures respectively. The capacitance of Cs vapor is related to temperature, χ_e=0.007+282.3/T, from eqn. (5), we can easily know cesium atom is polar atom [15]. Unlike Cs atoms, Hg is nonpolar atom because its capacitance is independent of temperature: χ_e=0.003 [15]. Although these two experiments are simple, but alkali atom is polar atom was first observed in human history.

The density of the gas varies. Atomic polarizability α must ultimately be measured by experiment, but we can estimate their order of magnitude by modeling the atom as a conducting sphere whose radius R is a typical atomic size, R ≈ 10^{-10} m. The induced dipole moment of a conducting sphere is $d_{ind}=4\pi\varepsilon_0 R^3 E=\alpha\,\varepsilon_0 E$, so $\alpha=4\pi R^3 \approx 10^{-29}$m^3 [14]. When the density of the gas is varied, the capacitance of polar and nonpolar substances is also completely different. If alkali atom is polar atom (d≠0), as the temperature increases, both the density and capacitance increase continuously. In our experiment, the induced susceptibility $n\alpha<10^{-4}$ can be neglected. If alkali atom is nonpolar atom, the induced electric susceptibility is temperature independent: $\chi_e=n\alpha<<1$. Conversely, if alkali atom is a polar atom, its capacitance should be proportional to the density. From eqn. (4), when $a<<1$, the significant difference is expressed in the following formula.

For polar atom $\chi_e=nd^2/3k\varepsilon_0 T>>1$, for non-polar atom $\chi_e=n\alpha<<1$ (6)

We measure the capacitance of alkali gas at different temperatures and density. Our experiments showed that Na, K, Rb and Cs atoms are polar atom because their capacitance is related to temperature and density. In recent years, the PDM of Hg atoms has been measured. The aim of these experiments is to infer the electronic PDM from the measured d_{atom} [16,17], so we compared alkali atoms with Hg atom. Unlike alkali atoms, Hg is nonpolar atom because its capacitance is independent of temperature and density. This kind of experiment has never been reported in the history of physics, it is the focus of this article, and we will introduce the process of the experiments in detail.

Our innovation in BEC experiments

Now we derive the single-particle partition function Z, because all thermodynamic quantities can be obtained from it. Consider a system composed of N alkali atoms, which are placed in an external electric field *E*. Note that the collision between these atoms is always through their mass centers, so the nucleus has no contribution to the rotational energy of the atom, its rotational energy can be neglected. The potential energy of alkali atom in the field is $\varepsilon=-dE\cos\theta$. Note that β=1/kT and the chemical potential μ ≈ 0 [18], the single-particle partition function is given by:

$$Z=\int_0^{2\pi}d\varphi\int_0^{\pi}e^{-\beta\varepsilon}\sin\theta d\theta=\int_0^{2\pi}d\varphi\int_0^{\pi}e^{dE\cos\theta/kT}\sin\theta d\theta=2\pi kT(e^{dE/kT}-e^{-dE/kT})/dE \quad (7)$$

The entropy of a system is a measure of the disorder of molecular or atomic motion. Let the coefficient a=dE/kT=dV/kTH, because $S=NK(\ln Z+T\frac{\partial}{\partial T}\ln Z)$ [18], we obtain:

$$S=Nk\,[\ln 2\pi e(e^{a}-e^{-a})/a-a\coth a] \quad (8)$$

When $a>>1$, $e^{-a}\approx 0$ and $\coth a\approx 1$, we obtain a simplified formula:

$$S=Nk\ln 2\pi e/a \quad (9)$$

From S=0, the critical voltage V_c=63 volts (for cesium) or V_c=68 volts (for sodium). When $V<V_c$, many atoms are in random directions, this state has high entropy S>0; when $V>V_c$, the atoms become aligned with the field, this state has low entropy S<0, phase transition occurs. Therefore the entropy can clearly describe the order-disorder transition.

In March 2016, our experiments show that when the voltage V=390 volts, condensed contains up to 2.506×10^{17} sodium atoms. After a rigorous peer review, this article has been published in a professional journal [16]. Reviewer comments pointed out that "The author presented a good idea (using the critical voltage) to observe the BEC. Moreover, the author shows that the ultra-low temperature is not a necessary condition to verify the existence of BEC. This paper is interesting and certainly deserves publication in the journal." In August 2016, our experiments show that when the voltage V=350 volts, condensed contains up to1.928×10^{17} cesium atoms. This article was quickly accepted and published by a more authoritative journal of materials science [15]. Recently, an academic book based on these two articles has been published. BEC experiments of cesium atoms have been redone. The density of cesium gas increased from 5.65×10^{14} cm^{-3} to 6.72×10^{14} cm^{-3}, and the number of condensed Cs atoms increased from 1.93×10^{17} to 2.56×10^{17} [19]. This book can be searched on Amazon. Experimental alkali material with purity 99.95% was supplied by Strem Chemicals Co., USA.

These objective facts show that our innovative ideas and experiments have been accepted by the scientific community, and they encourage us to challenge this traditional concept, and reported experimental results of atomic classification. In this article, Figures 1-4 will become precious documents, because they clearly show that the alkali atom is a polar atom. A famous theoretical physicist Wilczek,

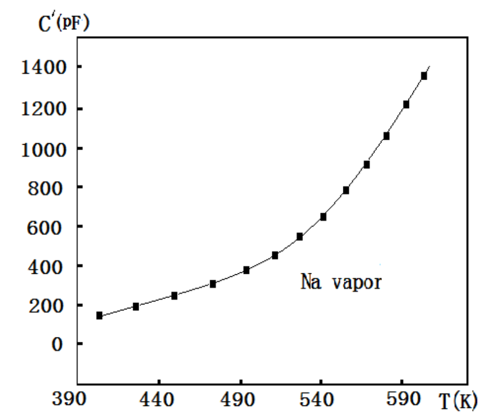

Figure 1: The diagram shows that the capacitance of Na vapor varies rapidly with the density, it proved that d≠0, and $\chi_e=nd^2/3k\varepsilon_0 T$, so sodium is polar atom.

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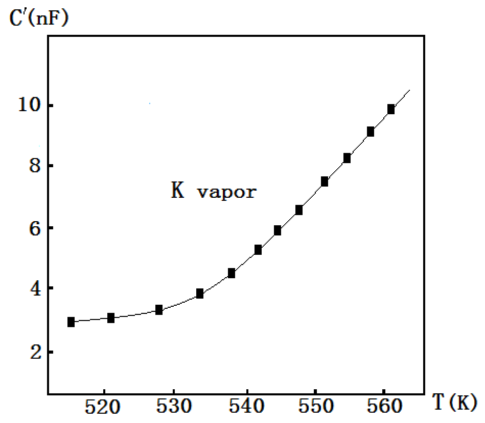

Figure 2: The diagram shows that the capacitance of K vapor varies rapidly with the density, it proved that d≠0, and χ_e=nd²/3kε$_0$T, so potassium is polar atom.

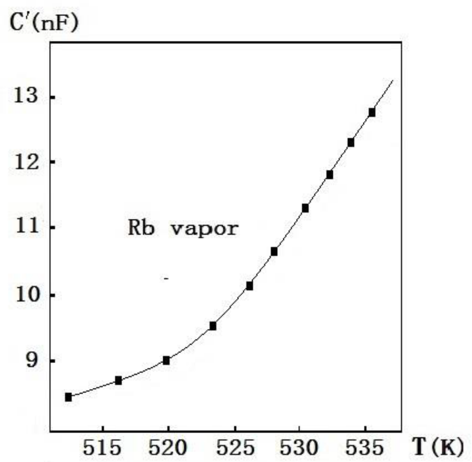

Figure 3: The diagram shows that the capacitance of Rb vapor varies rapidly with the density, it proved that d≠0, and χ_e=nd²/3kε$_0$T, so rubidium is polar atom.

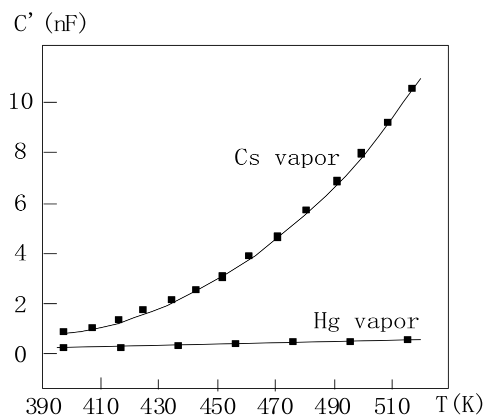

Figure 4: The capacitance of Cs vapor varies rapidly with density (d≠0), but capacitance of Hg vapor does not change (d=0), so cesium is polar atom but mercury is non-polar atom.

he was awarded the 2004 Nobel Prize in Physics, once stated that "The primary goal of fundamental physics is to discover profound concepts that illuminate our understanding of nature. Discovering new particles, as such, is secondary" [20]. Probably, "polar atom" is such concept.

Experimental Methods and Results

The preparatory experiment: accurate measurement of the density of alkali gas under saturated vapor pressure. Chemists think that the measurement of gas density is a difficult problem. In the textbook of physical chemistry experiment, an experiment to measure the molecular dipole moment is included, especially introduces this difficulty. To determine whether an atom is a polar atom depends on whether its capacitance varies with temperature and density. So, we first introduced the structure of the capacitor. Unlike the traditional form of capacitors, this is a glass container resembling a Dewar flask, which is filled with high purity materials. First, we measure the density of the gas in the capacitor as shown in Figure 5. We use cesium as an example. The capacitor contains Cs gas and the remaining solid or liquid Cs material. This capacitor is equivalently connected in series by two capacitors. One is called C′, and contains the Cs gas of thickness H_0=9.60 mm; the other is called C″, and contains the glass medium of thickness h=1.5 mm. The total capacitance is C=C′C″/(C′+C″), where C″ and C can be directly measured [15,16]. The magnitude of capacitance was measured by a digital capacitance meter (DM6031A). The vacuum capacitance is C'_0=(54.0 ± 0.1) pF. We put the capacitor into a temperature-control stove, raise its temperature slowly, and keep it at T_0=473 K for 6 hours. It means that these results are obtained under the saturated vapor pressure. We measured the capacitance is C'_t=(5140 ± 10) pF. The saturated vapor pressure of Cs atoms is $P=10^{6.949-3833.7/T}$ psi (473 K ≤ T ≤ 623 K, 1 psi=6894.8 Pa) [21]. From the ideal gas law, the density of alkali gas is as follows:

$$n=P/kT \quad (10)$$

For example, when T_0=473 K, we obtained P=0.0698 psi=481.3 Pa. The density of Cs vapor is n=P/kT=7.37 × 10^{16} cm^{-3}. The statistical error

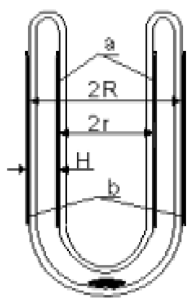

Figure 5: A cylindrical capacitor filled with alkali gas and surplus solid or liquid alkali material. "a and b" represent the two electrodes of the capacitor.

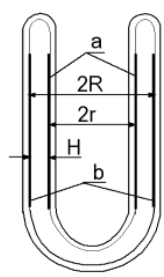

Figure 6: A cylindrical capacitor filled with a fixed density of alkali gas. "a and b" represent the two electrodes of the capacitor. This is the experimental instrument in BEC experiment.

is $\Delta n_i/n \leq 0.03$. Considering all systematic error, we have that $\Delta n_j/n \leq 0.03$, and the density of Cs vapor is $n_0=[7.37 \pm 0.22(\text{stat}) \pm 0.22\ (\text{syst})] \times 10^{16}\ \text{cm}^{-3}$ [15]. This is the density of alkali gas expressed in Figure 5. The measurement of the gas density is shown in Figure 6 will be presented later.

Experiment 1: Accurate measurement of the capacitances of sodium vapor at different density

Figure 5 represents the experimental apparatus, this cylindrical glass capacitor filled with Na gas and surplus liquid sodium. About 8 grams of material is required. The vacuum capacitance is $C_{10}=(59.0 \pm 0.1)$ pF. We put the container into the temperature control stove, raise the temperature of the stove very slow, and measure the capacitances of sodium vapor at different temperature. With the increase of temperature, the liquid sodium is continuously volatilized, the density and capacitance both increases continuously. In the experiment, each experimental point is recorded under the condition that readings of C and T both appear to be stable. This often takes several hours or longer. The saturated vapor pressure of Na atoms is $P=10^{7.553-5395.4/T}$ psi (453 K ≤ T ≤1156 K) [21]. From eqn. (10), we can accurately measure the density of sodium gas. For example, when T=513 K, P=0.00113 psi=7.79 Pa, the density $n=P/kT=1.10 \times 10^{21}\ \text{m}^{-3}$. Table 1 gives a complete experimental data. Experimental graph was shown in Figure 1.

Atomic polarizability of Na is $\alpha/4\pi=23.6 \times 10^{-30}\ \text{m}^3$, and $\alpha=4\pi \times 23.6 \times 10^{-30}\ \text{m}^3=29.6 \times 10^{-29}\ \text{m}^3$ [14]. If sodium is nonpolar atom (d=0), when T=583 K, and $n=1.68 \times 10^{22}\ \text{m}^{-3}$, the susceptibility $\chi_e=n\alpha \leq 5.0 \times 10^{-6}$, the capacitance is only C=59.0003 pF. The change of the capacitance cannot be measured, because the minimum resolution of the capacitance meter is 0.1 pF. Obviously, the polarizability and capacitance are inconsistent with the experimental results. This experiment further proved that sodium atom is a polar atom.

Experiment 2: Accurate measurement of the capacitances of potassium vapor at different density

In a similar way, we made a cylindrical glass capacitor filled with potassium vapor and surplus liquid potassium as showed in Figure 5. About 8 grams of material is required. The vacuum capacitance is $C_{20}=(52.0 \pm 0.1)$pF. We put the capacitor into the temperature-control stove; measure its capacitances at different density. With the increase of temperature, the liquid potassium in the capacitor is continuously volatilized, the density and capacitance both increases continuously. The formula of saturated pressure of potassium is $P=10^{7.183-4434.3/T}$ psi (533 *K* ≤ T ≤ 1033 *K*) [21]. Table 2 gives complete experimental data. The experimental results are shown in Figure 2.

Atomic polarizability of potassium is $\alpha/4\pi=43.4 \times 10^{-30}\ \text{m}^3$, and $\alpha=54.5 \times 10^{-29}\ \text{m}^3$ [14]. If potassium atom is nonpolar atom (d=0), when T=561 K, and $n=1.69 \times 10^{23}\ \text{m}^{-3}$, the susceptibility $\chi_e=n\alpha \leq 9.3 \times 10^{-5}$, the capacitance C=52.005 pF. Obviously, the polarizability and capacitance are inconsistent with the experimental results. This experiment further proved that potassium atom is a polar atom.

Experiment 3: Accurate measurement of the capacitances of rubidium vapor at different density

A cylindrical glass capacitor filled with rubidium vapor and surplus liquid rubidium (Figure 5). About 10 grams of material is required. The capacitance is still measured by the digital meter, and its vacuum capacitance is $C_{30}=(56.0 \pm 0.1)$pF. We put the capacitor into the temperature-control stove, and measure its capacitances at different density. With the increase of temperature, the liquid rubidium in the capacitor is continuously volatilized, the density and capacitance both increases continuously. In the experiment, when the readings of C and T are stable, the experimental point is recorded. The saturated pressure of rubidium is $P=10^{6.976-3969.5/T}$ psi (523 K ≤ T ≤ 643 K) [21].

Table 3 gives a complete experimental data. The experimental results are shown in Figure 3.

Atomic polarizability of rubidium is $\alpha/4\pi=43.4 \times 10^{-30}\ \text{m}^3$, and $\alpha=54.5 \times 10^{-29}\ \text{m}^3$ [14]. If rubidium atom is nonpolar atom (d=0), when T=523 K, and $n=2.32 \times 10^{23}\ \text{m}^{-3}$, the susceptibility $\chi_e=n\alpha \leq 1.26 \times 10^{-4}$, the capacitance is C=56.007 pF. Obviously, the polarizability and capacitance are inconsistent with the experimental results. This experiment further proved that rubidium atom is a polar atom.

Experiment 4: Accurate measurement of the capacitances of Cs and Hg vapor at different density

A cylindrical capacitor fills with Cs vapor and surplus liquid Cs

T (K)	513	523	533	543	553	563	573	583
P (Pa)	7.79	12.35	19.57	28.28	42.8	64.7	93.6	135.3
n ($10^{21}\ \text{m}^{-3}$)	1.1	1.71	2.66	3.77	5.6	8.32	11.8	16.8
C (pF)	406	480	572	667	765	868	972	1084
χ_e	5.88	7.13	8.69	10.3	11.9	13.7	15.4	17.4

Table 1: The electric susceptibility of sodium vapor at different density (C_{10}=59 pF).

T (K)	533	537	541	545	549	553	557	561
P (Pa)	503.5	580.8	668.4	767.7	880.2	1006.7	1149.5	1310.2
n ($10^{21}\ \text{m}^{-3}$)	6.84	7.83	8.94	10.2	11.6	13.2	14.9	16.9
C (pF)	3430	3880	4340	4770	5180	5660	6130	6680
χ_e	64.9	73.6	82.5	90.7	98.6	107.8	116.8	127.5

Table 2: The electric susceptibility of potassium vapor at different density (C_{20}=52 pF).

T (K)	523	525	527	529	531	533	535
P (Pa)	1677.5	1793	1915.4	2045	2182.7	2328.4	2482.5
n ($10^{21}\ \text{m}^{-3}$)	2.32	2.47	2.63	2.8	2.97	3.16	3.36
C (pF)	9430	9670	10230	10870	11500	12170	12880
χ_e	167.4	171.7	181.7	193.1	204.3	216.3	229

Table 3: The electric susceptibility of rubidium vapor at different density (C_{30}=56 pF).

material, and another capacitor fills with Hg vapor and surplus liquid Hg material (Figure 5). Cesium and mercury material are about 10 grams respectively. The vacuum capacitance of Cs vapor is C_{40}=54 pF and the vacuum capacitance of Hg vapor is C_{50}=51.8 pF. After fill with Cs or Hg materials, the capacitances become C_{41}=107.8 pF (for Cs vapor) and C_{51}=52.1 pF (for Hg vapor) respectively. It is easy to find mercury material with higher purity than alkali material. Note that the saturated vapor pressure of Cs atoms is $P=10^{6.949-3833.7/T}$ psi (473 K ≤ T ≤ 623 K) [21]. We put the two capacitors into the stove, and measure their capacitances and density at different temperatures. Our experiments showed that the capacitances of Cs vapor increased sharply with the increase of temperature, but the capacitance of Hg vapor, C_{61}=52.1 pF, remains constant at different temperatures, and $\chi_e \approx 0.006$. Table 4 gives a complete experimental data of cesium. The experimental results are shown in Figure 4.

The formula of saturated pressure of mercury vapor is $P=10^{7.752-3065.9/T}$ mmHg (673 K ≤ T ≤ 1573 K). Because the temperature (673 K) exceeds the furnace temperature, we use the experimental values of saturated vapor pressure of mercury [21]. Table 5 gives a complete experimental data of mercury vapor.

Atomic polarizability of mercury is $\alpha=(9/2)\,4\pi R^3=19.8 \times 10^{-29}$ m^3, where $R=1.52 \times 10^{-10}$ m is the radius of Hg atom, 9/2 is the correction of quantum mechanics [14]. When T=497 K, and $n=6.819 \times 10^{23}$ m^{-3}, the theoretical value of the susceptibility is only $\chi_e=n\alpha=1.35 \times 10^{-4}$, the theoretical value of the capacitance is only C=51.807 pF. Tables 4 and 5 formed a sharp contrast because Cs atom is polar atom but Hg atom is non-polar.

Discussion

A. The measurement of the PDM of alkali atom (uses cesium as an example)

Experiments to search for PDM of atoms began half a century ago. In all experiments, they measured the spin resonance frequency ν of individual atom by $h\nu=2\mu B \pm 2dE$, where h is Planck's constant, μ and d is magnetic and electric dipole moments [17]. In fact, despite the relentless search for a non-zero PDM of an atom for more than 50 years, no conclusive results have been obtained so far. A representative result as follows: d(Hg)=[0.49 ± 1.29 (stat) ± 0.76 (syst)] × 10^{-29}e.cm (in 2009). Note that the statistical error (1.29 × 10^{-29}e.cm) is bigger than the measured value (0.49 × 10^{-29}e.cm) over 2.6 times besides the systematic error (0.76 × 10^{-29}e.cm)! The fact shows that the measurement of atomic PDM is an extremely difficult problem. The existing formula is not successful, because it measured the microscopic quantity d by using another microscopic quantity ν.

However, it is easy to measure the average kinetic energy of gas molecules with temperature: $E_k=3kT/2$. Similarly, it is easy to measure atomic PDM by the change of the capacitance. In order to measure the PDM of an atom, we transform the eqn. (4). From $\chi_e=nd\,L(a)/\varepsilon_0 E$, note that E=V/H and $\varepsilon_0=C_0H/S$, we obtain:

$$C - C_0=\eta\, L(a)/a \qquad (11)$$

where $\eta=Snd^2/kTH$ is the capacitance constant.

From eqn. (5), we obtain the measurement formula of PDM:

$$d=(C - C_0)V/L(a)n\,S \qquad (12)$$

Note that $L(a)=[(e^a+e^{-a})/(e^a - e^{-a})] - 1/a$, and a=d E/kT, since $L(a)$ contains unknown quantity d, no one can separate the variables from this equation to obtain the unknown quantity d, which is a famous math problem that has puzzled scientists for more than hundred years. In order to calculate the function $L(a)$ when the atomic dipole moment is unknown, the capacitance of alkali vapor at different voltages is measured.

Take cesium as an example to show how to measure $L(a)$ (T=353K, C_0=66 pF, H=6.8 mm), the measurement was started in 0.01 V. When $V_1 \le 0.3$ V, C_1=130.0 pF is approximately constant; when V_2=350 V, $C_2=68.0$ pF $\approx C_0$ approaches saturation [15]. From eqn. (11), when V_1=0.3 V, $a<<1$, $L(a) \approx a/3$, we obtain $\eta=3(C_1-C_0)$=192 pF. When V_2=350 V, $a>>1$, $L(a) \approx 1-1/a$, we obtain $a_2=\eta L(a_2)/C_2 - C_0$=95, $L(a_2)$=0.9895. Now calculate the value of $L(a)$ in the preliminary experiment, since a=dE/kT=dV/kTH, and $a_0/a_2=V_0TH/T_0H_0V_2$, so a_0=0.1722 and $L(a_0)$=0.05729. Note that we deduced eqn. (11) from the parallel-plate capacitor formula $\varepsilon_0=C_0\,H/S$, so the cylindrical capacitor must be regarded as an equivalent parallel-plate capacitor with the plate area $S=C_0H/\varepsilon_0$.

B. The measurement of the gas density

Since the atomic dipole moment is the same in the two capacitor, from eqn. (11) we obtain the gas density of arbitrary vapor pressure (Figure 6):

$$n=(C - C_0)\,V\,L(a)\,S_0\,n_0/(C' - C'_0)V_0\,L(a_0)\,S \qquad (13)$$

For example, the density of Cs gas in Figure 6 is $n=5.65 \times 10^{14}$ cm^{-3}, where $C'-C'_0$=5086 pF, V_0=1.2 V, the equivalent plate area $S_0=5.86 \times 10^{-2}$ m^2, $n_0=7.37 \times 10^{16}$ cm^{-3}, $C-C_0$=2 pF, V=350 V, $L(a)=L(a_2)$=0.9895 and the equivalent plate area $S=C_0H/\varepsilon_0=5.07 \times 10^{-2}$ m^2 [14]. If alkali atom has a non-zero PDM, why it does not violate the time reversal symmetry? If alkali atom has a large PDM, why its linear Stark effect has not been observed? What is the true meaning of the Boltzmann constant? Their answers can be found [15,16,19].

T (K)	473	477	481	485	489	493	497
P (Pa)	481.3	562.8	656.4	762.9	886.1	1026	1184
n (10^{21} m^{-3})	0.737	0.854	0.988	1.139	1.312	1.507	1.725
C (pF)	5140	5460	5930	6380	6930	7880	8960
χ_e	94.2	100.1	108.8	117.1	127.3	144.9	164.9

Table 4: The electric susceptibility of cesium vapor at different density (C_{40}=54 pF).

T (K)	473	477	481	485	489	493	497
P (Pa)	2304	2700	3096	3492	3888	4283	4679
n (10^{21} m^{-3})	3.528	4.1	4.662	5.215	5.758	6.292	6.819
C (pF)	52.1	52.1	52.1	52.1	52.1	52.1	52.1
χ_e	0.006	0.006	0.006	0.006	0.006	0.006	0.006

Table 5: The electric susceptibility of mercury vapor at different density (C_{50}=51.8 pF).

In summary, our research showed that atoms can be divided into three categories: polar, non-polar and hydrogen atom. The alkali atoms are polar atoms because their capacitance is related to temperature and density. All kinds of atoms are non-polar atoms except for alkali and hydrogen atoms, because their capacitance is independent of temperature and density. Hydrogen atom is distinct from all others. The ground state hydrogen is nonpolar atom but its excited state is polar atom, for example, the first excited state in hydrogen has non-zero PDM: $d_H=3ea_0$. On the other hand, quantum computers are necessary because the potential of contemporary computers is almost exhausted. Many world-class companies are working on quantum computers that are millions of times more powerful than ordinary computers. Now scientists generally assume that polar molecules may be used as candidate materials for quantum computers. In the future, polar atoms will replace polar molecules as candidate materials, because of its very smaller moment of inertia.

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