

Experiments with cold hydrogen atoms

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This review examines the numerous studies performed in recent years on atomic processes involving "cold" hydrogen atoms in the gas phase and at a surface. The term "cold" atom denotes the range of relative collision energies $E < 10$ meV (correspondingly, "ultracold" atoms have $E \lesssim 1$ meV). This corresponds to the temperature range of tens (or units) of kelvins. Three main fields of study in which extensive experimental programs have been realized are treated: the study of collision processes involving hydrogen atoms, which are of astrophysical interest; the study of elastic atom-molecule scattering at ultralow energies; and studies on the problem of condensed hydrogen. The fundamental technical means of realization and the results obtained from the studies are discussed.

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1. INTRODUCTION

This review examines the numerous recent studies of atomic processes involving "cold" hydrogen atoms in the gas phase and at a surface.

The term "cold" atom denotes the range of relative collision energies $E \sim 10$ meV (correspondingly, "ultracold" atoms have $E < 1$ meV). This corresponds to the temperature range of tens (or units) of kelvins.

Both the very motivation of the planning of these experiments, i.e., the reasons for the rise of this new branch of the physics of atomic collisions, and the distinctive technique of realization and the results of the experimental studies of interactions at ultralow energies are of interest. One of the goals of the treatment below is an attempt to attract attention to this vigorously growing new field of studies of the physics of atomic collisions.

Why precisely have hydrogen atoms been singled out in the problematics of ultralow-energy atomic processes? In a certain sense, this reflects the singling out of H atoms in nature: on the one hand, hydrogen absolutely predominates in the abundance of the elements in the universe and H atoms play the determining role in the astrophysical processes in the cold interstellar gas. On the other hand, hydrogen atoms are the lightest atomic particles, so that their behavior should

most clearly manifest specific quantum effects. And while these well-known features had previously attracted only academic interest, today, for example, a need has arisen for quantitative interpretation of the powerful flux of observational data from radioastronomy in the centimeter and millimeter ranges, while the progress of experimental technique has rendered practical the problem of designing extensive laboratory studies of processes involving hydrogen atoms.

We shall first examine the three main fields of study in which the most extensive experimental programs have been realized: the study of collision processes involving hydrogen atoms, which are of astrophysical interest; the study of atom-molecule scattering at ultralow energies; and the study of the problem of condensed hydrogen. Then we shall discuss the fundamental technical means of realizing them and the results obtained.

2. PROCESSES INVOLVING "COLD" HYDROGEN ATOMS

One of the most remarkable facts discovered by radioastronomy in the past decade, which has drawn attention to atomic processes at low energies, is the existence in the dense interstellar clouds (ISCs) of a large amount of various molecules.^{1,2} This variety is illustrated by Table I, and the way in which it arises has been

TABLE I.

Inorganic		Organic
H ₂ , OH, SiO, SiC, SiS, SiN, NO, NS, SO, SiO ⁺	Diatomic	CH, CH ⁺ , CN, CO, CS,
H ₂ O, N ₂ H ⁺ , H ₂ S, SO ₂ , HDO, HSiN, HNO	Triatomic	C ₂ H, HCN, HNCHCO ⁺ , HCO, OCS
NH ₃	Tetratomic	H ₂ CO, HNCO, H ₂ CS, C ₃ N, HNCS
	Pentatomic	H ₂ CHN, H ₂ NCN, H ₂ C ₂ O, C ₄ H, HCOOH, HC ₂ N
	Hexatomic	CH ₃ OH, CH ₃ CN, HCONH ₂ , CH ₃ SH
	Heptatomic	CH ₃ NH ₂ , CH ₃ C ₂ H, HC ₃ N, HCOCH ₃ , H ₂ CCHCN
	Octatomic	HCOOCH ₃
	Eneatomic	(CH ₃) ₂ O, C ₂ H ₅ OH, CH ₂ CH ₂ CN, HC ₂ N
	More complex	HC ₃ N

to a considerable extent enigmatic (has been—because possible mechanisms have now been sensed out). We see from Table I that hydrogen atoms are contained in the overwhelming majority of complex molecules. In this regard, the problem arises of quantitatively explaining the chemical evolution of an initially atomic cloud into a practically completely molecular cloud. The radio emission from dense clouds in the cm and mm range of wavelengths contains information not only on the chemical composition, but also on the thermal state of the gas; the occupancy of the molecular levels from which transitions occur to yield emission. Therefore, along with the problem of the chemical evolution, a distinctive inverse problem faces the physics of atomic collisions and physical kinetics: to reconstruct the pattern of the thermal state of the gas cloud from the spectral distribution of the received radiations.

Thus one can state that the need has arisen of studying the collisional processes of hydrogen atoms, as well as of other atoms and molecules, that lead on the one hand to the chemical bonding of the free atoms of the interstellar cloud into molecular compounds, and on the other hand, to the occupation of the molecular levels responsible for the observed radiation at the temperatures of 10–100 K characteristic of a dense cloud.

The “enigma” mentioned above of the mechanism of the chemical transformation of an interstellar cloud stems from the fact that the density of a typical cloud is $\sim 10^4$ cm⁻³. At such low densities, pair collisions occur with the characteristic time $\tau(2) = (n_H Q c)^{-1} \sim 10$ years (here n_H is the density, Q is the effective collision cross-section, and c is the mean thermal velocity). Such long times imply that the colliding atoms of the cloud will lie in the electronic ground state. Ternary collisions should be the main source of molecules, e.g., the simplest one: H₂. These occur with the characteristic time

$$\tau(3) \sim 10^{31} (n_H)^{-2} \text{ sec.}$$

At typical densities, this exceeds the lifetime of the universe. Since pair collisions of atoms cannot form H₂ molecules (photorecombination is forbidden by the rule of conservation of total spin), while ternary collisions practically do not occur, the enigma of recombination of H (and other) atoms to molecules can be solved if we recall another component of the cloud, the

interstellar dust. According to the existing views, the mass of the dust amounts to about 1% of the mass of the gas, while the volume density n_g is

$$n_g = 10^{-12} n_H.$$

The role of the interstellar dust in recombination reduces to the fact that the “lifetime” of the collisional system can be fantastically enhanced via adsorption in the collision of the three bodies (the dust particle and the two atoms), as compared with the times for homogeneous recombination. In the latter case, this time is determined by the time of flight through the interaction region $[(Q/\pi)^{1/2}/c \sim 10^{-12} \text{ sec}]$. In the case of recombination involving a dust particle, the lifetime (in seconds) of the atom adsorbed on the dust particle is given by the well-known Frenkel’ relationship:

$$\tau_a = 10^{-12} e^{\varepsilon_a/kT_g} \quad (1)$$

Here ε_a is the energy of adsorption, or the depth of the adsorption potential, and T_g is the temperature of the dust particle. The exponential factor is responsible for the prolongation of τ_a . Thus, recent measurements³ of the diffractive scattering of H atoms by a monocrystalline surface of graphite (graphite is viewed as one of the most suitable candidates for the material of the dust particles] yield $\varepsilon_a = 0.043$ meV.

Thus, for $T_g = 10$ K, we have $\varepsilon_a/kT_g = 50$, while the lifetime of an H atom captured on the surface proves to be $\tau_a \approx 4 \times 10^9$ sec. As long as this time greatly exceeds the mean time between successive collisions of atoms onto the dust particle [$\tau_g = (n_H \pi a^2 c)^{-1} \leq 10$ sec, where a is the radius of the dust particle], more than two hydrogen atoms will always be present on it. Migration of the adsorbed atoms over the surface of the dust particle makes possible⁴ a high probability that they will meet and recombine, while disposing of their excess energy into the dust particle, which is the third body. At present, this is precisely the approach that allows one satisfactorily to explain quantitatively the rate of the process of formation of H₂ molecules, which is the first stage of chemical evolution. The characteristic time of “conversion” of an atomic H-cloud into a molecular H₂-cloud is given by the simple relationship⁵

$$\tau_{\text{mol}} \approx 3 \cdot 10^9 n_H^{-1} \text{ (years)}. \quad (2)$$

Evidently this time is short for a typical cloud ($n_H = 10^4$ cm⁻³) on the scale of the total time of existence (until collapse) of the cloud.

The simple estimates that I have given illustrate the application of the overall schema of the adsorption mechanism to the case of H atoms. Evidently the predictive effectiveness of this schema will be determined by the concrete values of such decisive parameters as:

- the probability of capture of an atomic particle into the adsorption potential,
- the energy of adsorption on dust particles of various compositions,
- the nature of the distribution of the released energy of recombination (in the case of the H₂ molecule, $\Delta E \approx 4.5$ eV).

The need for reliable information about these characteristics creates a powerful stimulus for the development of studies of collisions at low energies. In addition to the problems of the chemical transformation of the cloud, there is considerable interest in estimates of collisional excitation (deactivation) by hydrogen atoms of the molecular degrees of freedom for the partners listed in Table I.

The key information in this type of estimates is a knowledge of the potential-energy surfaces of the interaction. Thus studies of scattering in the low-energy prove to be a second field of active interest. The attention of many research groups is currently focused on it.

To summarize what I have said, I might note that the potentiality of a quantitative description of the kinetics of collisional (chemical and physical) transformations in an interstellar cloud (ISC) will permit one both to determine the age and to establish the internal structure of an evolving cloud from observations of the relative content of different molecules and the spatial distribution of the emission intensity.

The cited studies of elastic scattering at low energies are also of independent interest, since the energy region ≤ 10 meV is the region where resonance-scattering effects are manifested.

The theory of resonance scattering has been treated in detail in Ref. 6 (see also the references in Ref. 7). Here it is pertinent to discuss only the qualitative features of scattering at low energies and the requirements imposed on experiments aimed at detecting resonance effects in elastic molecular scattering.

The scattering of slow particles⁶ in an attractive field in the case in which the discrete spectrum of negative energy levels (*s*-states) is characterized by the presence of a shallow level ($w < 0$) has a singularity when the energy of the particle being scattered is close to the energy of the level, i.e., at resonance.

This singularity amounts to a considerable increase in the effective or the total scattering cross-section. If $w > 0$, then the level will be quasidiscrete, since the centrifugal barrier in the effective potential ($V_{\text{eff}} = V(r) + [\hbar^2 l(l+1)/2\mu r^2]$) makes the probability small for a particle having the resonance energy to leave this state to go to infinity.

Correspondingly, the lifetime τ of this state is long. This implies the formation in a resonance collision of a metastable composite system having a τ that exceeds the characteristic time of flight of the interaction region.

Resonances in the energy-dependence of the elastic scattering cross-section are sometimes called profile (shape) resonances, because their properties are determined by the profile or shape of the potential, and are sometimes called orbiting resonances by analogy with the classical capture into quasistationary orbits.⁸ Figure 1 gives a qualitative picture of the effects of resonance scattering for the effective interaction potentials corresponding to different values of *l*. A Len-

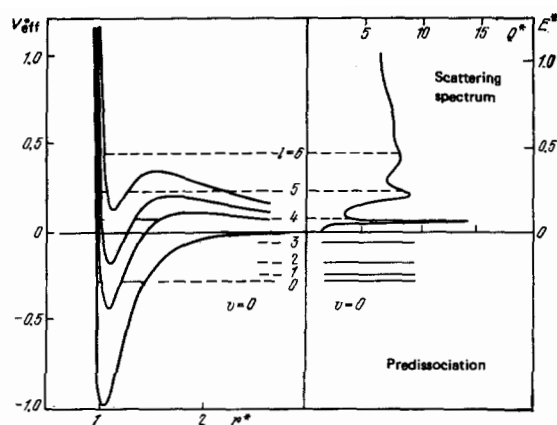


FIG. 1. Qualitative diagram of the appearance of resonances in the total molecular-scattering cross-section for the case of an interaction potential $V(r)$ having a single vibrational level ($v=0$). The dotted lines show the position of the vibrational level in the effective potentials V_{eff}^* corresponding to the different values of l from $l=0$ to $l=6$. The effective potentials for $l=1-3$ are not shown, and the existence of a (discrete) level is detected by spectroscopic observations (predissociation spectrum). The right-hand side of the diagram illustrates the organic connection between optical spectroscopy and collision spectroscopy; the reduced coordinates are used: $E^* = E/\epsilon$, $V_{\text{eff}}^* = V_{\text{eff}}/\epsilon$, $r^* = r/r_m$, $Q^* = Q\pi r_m^2$.

nard-Jones-type potential has one vibrational level ($v=0$). As we see from Fig. 1, a level having $l > 4$ lies in the continuous spectrum (i.e., it is virtual), while it is quasidiscrete for $l \leq 4$. The effective potentials for $l=1-3$ are not shown, and the existence of a (discrete) level is revealed by spectroscopic observations (predissociation spectrum). The right-hand side of Fig. 1 illustrates the organic relationship between optical spectroscopy and collision spectroscopy.

Since the total elastic scattering cross-section is described by the well-known relationship⁶

$$Q = \frac{4\pi}{k_0} \sum (2l+1) \sin^2 \eta_l, \quad (3)$$

the number of terms of the summation contributing appreciably to the cross-section must be small in order that the resonance structure of the $Q(E)$ relationship may be revealed. For an interaction described by a Lennard-Jones-type potential, the maximum value of the orbital quantum number l_{max} that contributes to the summation can be estimated from the relationship $l_{\text{max}} \approx 3k_0 r_m$. Consequently, the only way of truncating the summation is to decrease the value of the wave number k_0 ($= \mu g/\hbar$). Hence we can easily see that, for a low relative energy E ($= \mu g^2/2$), the greatest effect of decreasing k_0 is attained for hydrogen atoms. The requirement on the profile of the potential works in the same direction. For a spherically symmetric potential $V(r)$, the effective centrifugal potential $V_{\text{eff}} (= V(r) + [\hbar^2 l(l+1)/2\mu r^2])$ will not have a minimum at large l . Thus it will not have ground states responsible for scattering resonances. For the Lennard-Jones potential, the "disappearance" of the minimum occurs⁹ at $E > 0.8 \epsilon$. Hence, for typical weakly bound van der Waals systems with a depth of the potential well $\epsilon/k \sim 10-100$ K, we arrive at the restriction on the quantity $E/k \leq 8-80$

K. We can draw another practical conclusion from studying Fig. 1: the resonance structures are very narrow on the energy or velocity scale, and to reveal them requires a high energy (or velocity) resolution of the experiment. At relative energies below the resonance energy, another series of specific scattering features occurs. This is the "zero-point energy" resonance. The He-He system has shown a macroscopic manifestation of this in experiments on the shaping of a beam of He atoms during gasdynamic efflux into a vacuum.¹⁰ A gap is observed at low energies in the energy-dependence of the scattering cross-section analogous in nature to the Ramsauer-Townsend effect. This feature has been directly observed in the systems H-He¹¹ and He-He.¹² Finally, structures can arise in the region $E > 0.8 \varepsilon$ that involve the so-called Feshbach resonances.¹³

In nuclear physics a mechanism of interaction of particles is well known that involves the short-term capture of the bombarding particle owing to transfer of the energy of the particle to target. The corresponding resonances, for which Feshbach has given a quantum-mechanical treatment, arise in molecular scattering in the case in which the relative collision energy coincides with the energy of a bound state in which the scattering molecule is excited to the nearest rotational state. These resonances, which can also arise in heavy ($\mu > 1$) systems, are characterized by a very small energy width. Owing to the smallness of the rotational quanta, they can lie unresolvably close to one another in terms of the currently existing experimental means. In this case, instead of marked peaks, only a small perturbation of the monotonic trend will exist in the energy-dependence of the cross-sections. Signs of such perturbations have perhaps been observed in experiments (see Ref. 7) on the scattering of H atoms by molecules. The practical interest in the study of resonance scattering involves the following. As is well known, the usual profile of the van der Waals interaction potential of atoms in s -states results from the competition of the contributions of the long-range (attractive) and short-range (repulsive) forces.¹³ In a good approximation at large interatomic distances, the long-range forces are described by the expansion

$$V_I = -\frac{c_6}{r^6} - \frac{c_8}{r^8} - \frac{c_{10}}{r^{10}}. \quad (4)$$

The coefficients here can be calculated reliably by theory, and are expressed in terms of the polarizability and the higher electric moments for the individual atoms. The short-range exchange forces arise upon approach to distances at which the electron clouds of the partners overlap appreciably. They can be satisfactorily be described by the Born-Mayer exponential potential or by a potential that includes a quadratic (r^2) term in the exponential. The fundamental problem is how far inside the potential well the attractive dispersion branch, given by the series of (4), can be "extended" when its course is appreciably perturbed by repulsive forces.

Since the theoretical calculations of the energy are extremely difficult and insufficiently accurate in the region where the minimum lies at intermediate dis-

tances, we should rather expect an answer to this question from experiment, which currently possesses sufficient sensitivity and accuracy. It is precisely studies of elastic scattering in the region of low and ultralow energies, in particular, measurements of the energy-dependence of the total cross-sections, that will enable us to answer this question. The sensitivity of these measurements arises from the fact that the region of low energies is the region of resonance scattering.⁶ Figure 2 illustrates this sensitivity with the example of the dependence of the total cross-section Q on the relative energy E of collisions for the system H-CO₂ as calculated for a central potential in two approximations V_I and V_{II} having the same depth ε and position r_m of the minimum, but differing in the long-range region:

$$V_I = \varepsilon \left[\left(\frac{r_m}{r} \right)^{12} - 2 \left(\frac{r_m}{r} \right)^6 \right], \quad (5)$$

$$V_{II} = \varepsilon \left[\left(1 + \frac{c_6^*}{3} \right) \left(\frac{r_m}{r} \right)^{12} - 2 \left(1 - \frac{c_6^*}{3} \right) \left(\frac{r_m}{r} \right)^6 - c_8^* \left(\frac{r_m}{r} \right)^8 \right].$$

As we see from Fig. 2, the variations, which have highly specific forms (with narrow excursions, or resonances caused by the quantum nature of the interaction of the colliding particles), actually exhibit position shifts and changes accessible to measurement in the amplitudes of the extrema for the two potentials V_I and V_{II} .

The problem of the production of H₂ molecules in an ISC has been one of the first stimuli to the development of the studies being discussed. However, no less a stimulus today is the inverse problem of obtaining a gas made of hydrogen atoms that is stable with respect to recombination—the problem of "synthesis" of the macroquantities of this new substance. This substance is of interest as a new object of quantum macrophysics and as an unusually effective fuel having the highest energy content per unit mass (as compared with ordinary chemicals).

A neutral hydrogen atom, which has the electron spin $S = 1/2$ and the nuclear spin $I = 1/2$ ($F = I + S = 0$ or 1) is a boson, analogous to a helium atom.⁶ According to the known rules for constructing molecular terms, two H atoms in the 1^2s -state will interact according to two

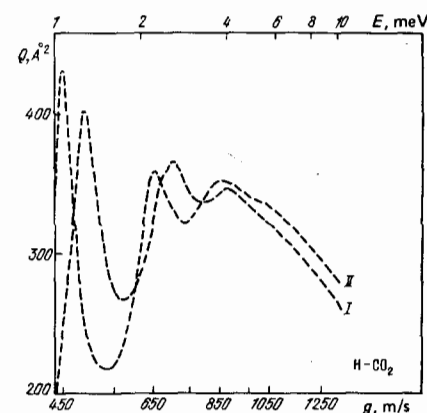


FIG. 2. Energy dependence of the total scattering cross-section of the H-CO₂ system in the resonance region, as calculated by using the potentials V_I and V_{II} differing slightly in form.

terms that correspond to the different total spins of the system: $X^1\Sigma_g^+$ and $b^3\Sigma_u^+$. The first of these corresponds to a bound state with a depth of the potential minimum $\epsilon/k \approx 52,000$ K and an equilibrium distance $r_e = 0.74$ Å, while the second corresponds to a weakly bound state having a depth of the van der Waals minimum $\epsilon/k = 6.4$ K. Thus, if we "close" the recombination channel for which the collisional system of two H atoms would have a total spin of zero, then a gas made of hydrogen atoms cannot convert to a molecular gas. In principle, one can conceive of effecting such a "closing of the channel" by sorting, or polarization of the electron spins. The question arises of what properties the hypothetical gas of polarized hydrogen atoms (denoted as H \uparrow) will possess.

First, the small masses of the H atoms and the values of ϵ have the result that the motion of the polarized atoms remains so energetic, even at absolute zero, that they remain in the gaseous phase.

The molecular theory of liquids deals with the dimensionless de Boer parameter η , which characterizes the behavior of the system as the thermodynamic parameters are varied:

$$\eta = \frac{h}{m\sigma^3\epsilon}$$

Here σ is a characteristic dimension defined by the condition $V(\sigma) = 0$ (the parameter B , which is closely related in meaning, or the reduced capacity of the potential well, is: $B = (1/\eta)(r_m/\sigma)^2$; it is employed in the theory of molecular collisions for characterizing the number of vibrational levels contained in a potential well¹⁵). The critical value of the de Boer parameter $\eta_{cr} = 0.45$ determines the boundary for phase transitions for systems consisting of boson particles (such as hydrogen atoms; for fermions $\eta_{cr} = 0.27$). A liquid and a gas phase cannot coexist for systems having $\eta > \eta_{cr}$. Correspondingly, if $\eta > \eta_{cr}$, a gas of polarized H \uparrow atoms cannot be liquefied at any temperatures whatever. The known results of the quantum-mechanical calculations of the terms of H₂ molecules of Kolos and Wolniewicz have been used in Ref. 16 to approximate the $b^3\Sigma_u^+$ term with a Lennard-Jones-type potential function. The obtained values $\epsilon/k = 6.46$ K and $r_m = 3.69$ Å enable one to determine the values of the de Boer parameter for the different isotopes of hydrogen: $\eta = 0.55$ for H \uparrow , $\eta_D = 0.27$ for D \uparrow , and $\eta_T = 0.18$ for T \uparrow .

Thus we see that an H \uparrow gas lies outside the region of allowed phase transitions (correspondingly a gas of D \uparrow fermions proves to be at the edge of stability with respect to liquid-gas transitions, since $\eta_D \approx \eta_{cr}$). The stated fact proves to be one of the decisive factors in the sharpening of interest in the problem of stabilizing gases of H \uparrow (and D \uparrow), since the possibility is opened up of direct study of their quantum properties, in particular, effects involving the Bose-Einstein (BE) condensation, and superfluidity.

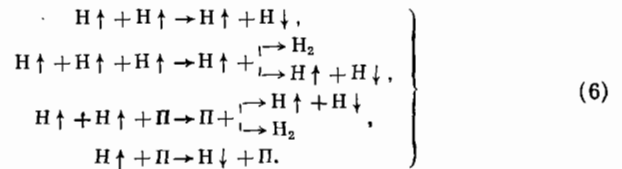
Second, a gas of polarized H \uparrow atoms is the best approximation to the model of an ideal Bose gas. We can easily see this from the fact that the Bose-Einstein condensation for a temperature of 0.2 K sets in at a density of 4×10^{19} cm⁻³. As we can easily see, at this

density the mean interatomic distance is about 30 Å. Evidently, the interatomic interaction forces for the given values of ϵ and r_m can be considered negligible to a good approximation. For helium, the classical object of quantum microphysics (having the corresponding value $\eta_{He} = 0.1815$), the liquefaction of the gas with falling temperature sets in long before the temperature of BE condensation is reached. Consequently the mean interatomic distance in liquid helium turns out to be an order of magnitude smaller than for H \uparrow atoms. Therefore the manifestation of BE condensation at the transition point to the superfluid state of helium is complicated by the strong perturbation arising from the intermolecular interactions. Now this process of BE condensation of an H \uparrow gas, which has not been observed and which has existed in the "pure form" only in theory, can become accessible to direct experimental studies. An increase in the pressure (density of H \uparrow) causes the system to convert at $p \sim 50$ atm ($V \sim 65$ cm³/mole) to the solid state of a quantum crystal. This state remains nonmetallic up to a pressure of the order of a megabar.¹⁶

The first study discussing the properties of a gas of polarized atoms dates to 1959,¹⁷ but it passed almost unnoted. In the 70's, a second wave of theoretical studies arose, now supported by the efforts of numerous experimental laboratories (see Refs. 18 and 19). The advances in this field have recently been summarized at a special International Conference at Aussois, France^{17, 19}.

Now let us examine briefly the stability of an H \uparrow gas to recombination, while deferring the methods of obtaining it to later discussion. In line with the treatment below, we note that one can conveniently polarize H atoms in such a way (Fig. 3) that they lie in the lowest energy state (i.w., with a value of the projection of the spin $M_s = -1/2$, or in the "spin-down" state). Figure 3 implies that this state is actually split in two, and correspondingly, a quantum gas of polarized atoms turns out to have two components. The main processes that destroy the recombination stability of a gas of such atoms are the endothermic processes of electron spin reversal (Fig. 3), both in the volume and at the surfaces of the vessel holding the hypothetical H \uparrow gas.

One can describe²⁰ the stated processes by symbolic relationships (the symbol Π denotes a surface):



For processes in the gas phase, a simple way to suppress the channel of endothermic spin-reversal reactions and to prevent the breakdown of the system involves a decrease in the relative energies of the colli-

¹⁷The proceedings of the conference have been published in a special issue of "Journal de Physique" [Vol. 41, Colloq. C7, supplement to No. 7 (1980)].

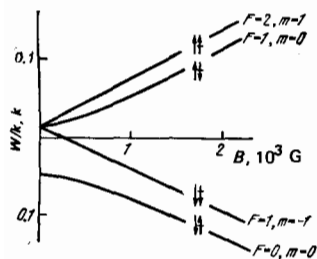


FIG. 3. Diagram of the hyperfine energy levels of a hydrogen atom in a magnetic field. \uparrow —electron spin, \uparrow —nuclear spin.

sions—or of the temperature.

Since the activation barrier of the process of collisional spin reversal is the Zeeman splitting $\mu_B H$ (see Fig. 3) of the states having different polarizations in the magnetic field, the rate constant of the spin-reversal reaction will be determined by the factor $\mu_B H/kT$ that enters into the Arrhenius exponential. Therefore, an increase in the magnetic field, which increases the splitting (Fig. 3) of the states, and a decrease in the temperature can practically completely suppress the endothermic channel of collisional spin reversal. Thus, when $H = 10^5$ G (10 T) and $T = 0.1$ K [$(H/T) = 10^6$], we have the exponent $\mu_B H/kT = 134$, while the exponential function is $\approx 10^{-58}$. This implies complete suppression of the breakdown process. An increase in the temperature to 1 K at the same H is accompanied by an increase in the rate by a factor of $\sim 10^{52}$.

Analogous arguments hold for collisions with a surface. Nevertheless the situation in this case is complicated by the fact that the adsorption energy ϵ_a can prove to be an additional source of the energy needed for overcoming the activation barrier. Evidently a choice of a nonparamagnetic coating material of the walls having an adsorption energy $\epsilon_a/k \ll \mu_B H$ will allow one to avoid the stated difficulty. The application of a surface coating of superfluid helium on the wall has been discussed in this connection. As was shown in Ref. 21, the binding energy for H atoms at the film $\epsilon_a/k = 0.1$ K (actually there is an estimate that exceeds this by a factor of five). An application of surface layers of frozen noble gases is also possible, although, as compared with a superfluid film, their employment has the defect that it doesn't guarantee complete coverage of the inner surfaces and it doesn't permit continuous renewal of the surface covering.

The discussion of the problem of the recombinational stability of gaseous polarized hydrogen and the optimistic prognoses of the possible prolonged confinement of the gaseous system should be supplemented by mentioning the problem of stability of a condensed phase.^{22,23} At high densities the simple estimates given above prove insufficient. The most general treatment of the problem of the stability of polarized crystals, i.e., crystals made of atoms with parallel electron spins, and estimates of the lifetimes for different decay channels has been given²² for the example of hydrogen-like atoms of the alkali metals. To obtain a condensed phase of polarized hydrogen is the problem offering further promise, and we shall not discuss here the existing estimates of the characteristic times. In the same fashion, one can realize an experiment to study and stabilize a gas of polarized hydrogen atoms

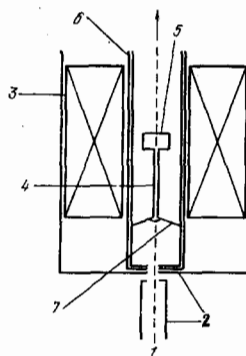


FIG. 4. Diagram explaining the idea of an experiment²⁵ to store polarized hydrogen atoms. 1—atom source, 2—cooling apparatus at liquid-helium temperature $T \sim 4$ K, 3—solenoid of a superconductive magnet, 4—capillary, 5—storage cell, 6—cryostat at $T \sim 0.1$ K, 7—cooling wall (to $T \sim 0.1$ K).

(we shall not treat here the methods of storing and stabilizing atomic hydrogen in solid matrices²⁴). One can understand the fundamental ideals of the methods being employed for creating the gas from the diagram²⁵ shown in Fig. 4.

A flux of hydrogen atoms from the source (1) enters the channel (2), which is cooled to liquid-helium temperature. Upon accommodating to the walls of the channel, the H atoms lose kinetic energy. The beam of cold hydrogen atoms emerging from the exit aperture is directed into a region of strong magnetic field gradient ($H \leq 10^5$ G) generated by a superconductive solenoid (3), which sorts the atoms in terms of the projections of the electron spin. The half of the atoms having the needed polarization is accelerated by the field ($\mu_B H > kT$) and can enter the capillary (4) leading to the accumulation cell (5); the other half with the unwanted orientation is decelerated by the magnetic field and is repelled by it in the opposite direction. The walls of the capillary and the storage chamber itself are maintained at a temperature as low as 0.1 K. Thus the accelerated atoms having the needed polarization can lose their excess energy upon accommodating at the wall. Atoms are collected in the storage cell, which lies in a region of uniform field for which the stabilization condition $H/T \sim 10^6$ holds. The continuous supply of atoms having the needed polarization enables one to store the atoms whenever the gas is stable with respect to recombinational decay. This scheme realizes an idea resembling the confinement of a plasma in a magnetic bottle (see Ref. 18). However, in addition to creating a magnetic stopper, the strong field here plays the additional role of a stabilizer against recombination. The density of the stored gas can be limited by the relationship between the kinetic and magnetic pressures ($H^2/8\pi \geq nkT$); however, for $H = 10^5$ G and $T = 0.1$ K, the pressures will be comparable at a density that exceeds the critical density for Bose-Einstein condensation ($\sim 10^{19}$ cm⁻³) by several orders of magnitude. Thus, when the power of the atom source suffices, the only factor restricting the attainable density will be the recombinational stability of the polarized gas.

3. EXPERIMENTAL STUDIES EMPLOYING COLD HYDROGEN ATOMS

a) Preparation of cold hydrogen atoms

Since hydrogen exists only in the molecular form under normal conditions, evidently the preparation of

atoms must involve breaking the molecular bond. Dissociative sources of atomic particles have been employed for a long time in laboratory practice,²⁶ but they have the characteristic that the mean energy of the exiting atoms exceeds the energy at room temperature. Dissociation in an electrodeless HF or UHF discharge is the most convenient and widely employed method for preparing atoms. The creation of a beam of cold atoms with a discharge source can be done either by considerably lowering the temperature of the walls of the discharge tube, or by introducing the flux of hot atoms from a discharge tube into a special cooling volume, where the temperature of the walls can be varied within the needed temperature range. Figure 5 shows a diagram of a hydrogen-atom source with an UHF discharge in a tube immersed in liquid nitrogen, i.e., at a wall temperature of 78 K.²⁷ A direct study of the atom-velocity spectra by the time-of-flight method enables one to establish the effective temperature of the atoms emerging from the discharge tube; the measurements²⁷ showed that it corresponds to $T_H \sim 90$ K. However, this value seems to be the practical limit for the described direct method of obtaining cold atoms, since the use of other refrigerants (besides liquid nitrogen) will be unacceptable in terms of the expenditure of refrigerant (the power up to 100 W released in the discharge will be spent in evaporating the refrigerant).

Another way to obtain beams of cold atoms free from this restriction is illustrated in Fig. 6. It is based on extracting the atoms from the "hot" HF-discharge source (with an effective temperature ~ 400 K), and then directing them into a cooling chamber, the exit of which is the slit of an effusion source.²⁸ In this case the characteristic temperature of the atoms will be determined by the degree of accommodation to the walls and by the temperature of the walls of the chamber.

Direct time-of-flight measurements²⁸ have shown that, when one uses liquid nitrogen, the mean energy of the atoms is actually close to the temperature of the walls and corresponds to $T_H \sim 90$ K. However, an attempt to lower the mean energy of the atoms to the corresponding temperature 20.4 K of liquid hydrogen did not yield the expected effect. The relative departure of the mean energy of the atoms from the value corresponding to the temperature of the walls increased in comparison with liquid-nitrogen cooling, and the intensity of the

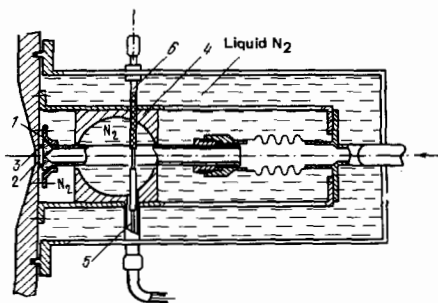


FIG. 5. Diagram of a source of cold hydrogen atoms employing an UHF discharge at liquid-nitrogen temperature. 1—discharge tube, 2—exit nozzle, 3—seal, 4—resonator, 5—power-supply cable, 6—adjustment shaft.

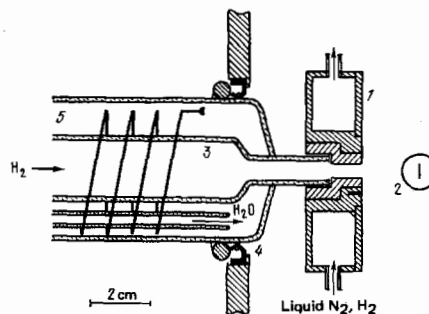


FIG. 6. Diagram of a hydrogen-atom source²⁸ using a HF discharge and cooling of the atoms in a special chamber having a temperature determined by the supplied refrigerant (liquid N_2 , H_2 , etc.). 1—Dewar of the cooling chamber, 2—exit slit, 3—water-cooled discharge tube, 4—vacuum seal, 5—HF coil.

atom beam emerging from the chamber fell sharply. Such effects can be naturally explained by recombination of the atoms at the walls of the chamber, and the second method may seem to possess a limiting attainable lowering of the temperature of the atoms. Since the lifetime τ_a of an atomic particle captured on a surface is determined by the quantity $\exp(e_a/kT)$, evidently a lowering of the wall temperature of the cooling chamber alone cannot yield a positive result. Here one must choose a coating material for the inner walls that will ensure brevity of stay of atoms on them.

Evidently, with a lifetime τ_a on the surface, the degree of occupation of the latter by adsorbed atoms will be determined by the quantity $nc\tau_a/4$. Increasing τ_a will increase the number of particles on the surface that are capable of the above-treated recombination with loss of the excess energy to the wall, which serves as the third body. The inclusion of this mechanism of surface loss of atoms explains the negative result of Ref. 28. Thus the development of a source of cold and ultracold hydrogen atoms requires optimization of the refrigeration system with account taken of the competing effects of accommodation (complete, with capture of the particles) and surface recombination of the captured particles. Owing to the smallness of the rate constant of triple recombination ($k_3 \sim 10^{-32}$ cm⁶/s at room temperature; recent measurements¹⁹ of this constant at temperatures down to ~ 1 K have shown that the constant varies very weakly with temperature), and with reasonable dimensions of the atom channel joining the discharge tube to the cooling chamber, volume recombination will not compete in practice with surface recombination up to densities $n \sim 10^{15}$ cm⁻³. As we have said, the best material for the surface coating is a film of superfluid helium. However, a broad spectrum of temperatures is possible over the length of the atom channel from liquid helium to above room temperature, and the evaporation of the liquid helium near the source will lead to an unacceptable expenditure of it, and to a vapor pressure in the region where the film breaks down. An optimal variant proves to be two-stage cooling, first to ~ 10 K, and then to liquid-helium temperatures and below. At temperatures ≥ 10 K, satisfactory coatings are layers of molecular hydrogen or of the

noble gases frozen onto the surface. In practice the use of H_2 is even preferable, since feeding molecular hydrogen into the source with the discharge turned off enables one to carry out a preliminary treatment of the surface of the atom channel. Since the degree of dissociation in the electrodeless discharge does not reach 100%, in the undissociated molecules will regenerate the coating in the subsequent operation of the source. All these considerations have been taken into account²⁹ in building a cold-atom source. Figure 7 illustrates the apparatus and requires little explanation. The flux of atoms from the UHF discharge tube 1 (Fig. 7), which is water-cooled, is introduced through a Teflon tube into the vacuum volume of the apparatus. The Teflon tube is connected a butt joint to a quartz tube, the end of which is cemented in to ensure thermal contact of the channel with the cooling chamber 3, which is connected with a heat conductor to a liquid-helium cryostat. The length of the transport atom channel 2 (see Fig. 7) was about 20 cm (ϕ 5mm). An apparatus 4 for time-of-flight measurements is set up after the cooling chamber, the temperature of which could be lowered only to ~ 7.7 K owing to losses. Its detector is based on the quadrupole mass spectrometer 5. The output signal of the detector is applied to the detection system 6 (with a control PDP-type minicomputer), which enables the recording and processing of the measurements. The measurements of the time-of-flight spectra of the atoms leaving the cooling chamber showed with good accuracy that they correspond to a Maxwell distribution at a temperature (~ 8.5 K) close to the temperature of the walls. The losses of atoms in the atom channel and in the cooling chamber proved small: thus, the flux measured at 8.5 K was $q_{8.5} \approx 2 \times 10^{16}$ at $\cdot s^{-1} = 0.3 q_K$, where q_K is the flux at room temperature. The density of cold atoms in the flux reached 3×10^{13} cm^{-3} . These results removed doubts of the possibility of attaining intense beams of low-temperature hydrogen atoms. Before this it had been feared that the release of the recombination energy could in principle hinder not only the cooling but also the establishment generally of equilibrium of the atoms at the temperature of the cooling surface.

b) Study of the elastic scattering of hydrogen atoms at low energies

Studies of resonance scattering of cold hydrogen atoms have been performed for collisions with atomic (noble-gas atoms, mercury) and molecular targets (N_2 , CO , O_2 , CO_2 , C_2H_4 , etc.) at relative energies E in the range from 30 to 1 meV. The usual method of monokinizing the primary beam of light particles is to employ a mechanical velocity selector,³⁰ while the reduction of the relative energies and of the collision energies is attained by employing as the target a secondary beam that intersects the primary beam at an acute angle (the scheme of overtaking or convergent beams).

The time-of-flight method of atom velocity selection was employed in Ref. 31 for monokinizing the scattered particles. One of the research groups (see references in Ref. 32) monokinizes the primary and secondary beams by employing the known effects (see Ref.

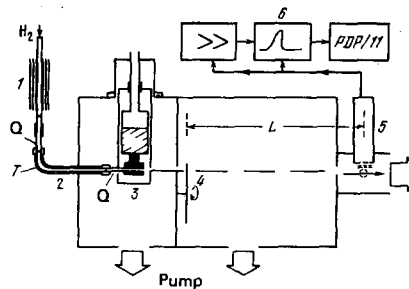


FIG. 7. Diagram of an apparatus²⁹ for preparation and time-of-flight analysis of the velocities of H atoms cooled in a chamber using liquid helium. 1—water-cooled H_2 -dissociator, 2—atom channel (Q—quartz, T—teflon), 3—cooling chamber and Dewar, 4—chopper disk for time-of-flight measurements, 5—quadrupole mass spectrometer for detecting atoms, 6—recording system.

33) of gasdynamic efflux into a vacuum with attainment of high final values of the Mach number (the ratio of the directed and thermal velocities in the beam, $M \sim 10$). Here the relative energies are altered by varying the temperature of the receiver (from liquid-helium to room temperature). Figure 8 shows typical results of measuring the energy-dependence of the total cross-section of the system H-Xe. We see well marked resonance peaks that correspond to quantum numbers of the angular momentum $l=5, 6$, and 7. Table II includes the values found in these measurements of the parameters of the type V_{II} potential, which reduces to the ordinary Lennard-Jones V_I potential when $c_8^* = 0$. For mercury hydride H-Hg, the potential that matches the experimental relationship is characterized by a deep well typical of a chemical bond, while its long-range branch for $r > 3.06$ Å can be characterized by a modified Lennard-Jones potential with $r_m = 3.06$ Å, $\epsilon = 1.44$ meV.³⁴ The chemical-type interaction stems from the intersection of the $^2\Sigma_+$ terms of the system, which correlate with the 1S ground state and the 3P excited state of the mercury atom. The existence of this intersection strongly perturbs the long-range branch, so that a pure dispersion interaction occurs only at $r > 10$ Å. Owing to this feature, the H-Hg system proved not very convenient for analyzing the interaction potential in the

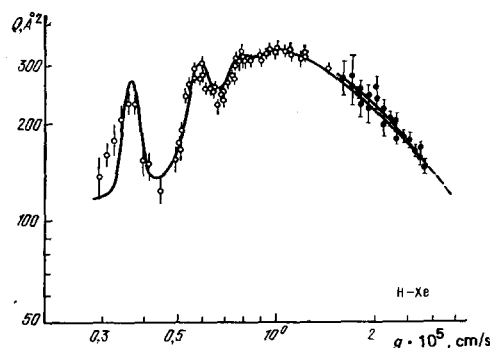


FIG. 8. Typical experimental energy-dependence of the total elastic scattering cross-section for H-Xe in the resonance region.²⁸ The vertical bars are the errors of the individual measurements, and the solid line is the best fit of a calculated dependence employing a V_I -type potential.

TABLE II. Values of the parameters (ϵ , τ_m , c_g^*) of the V_{11} potential found from measurements of the resonance dependence of the total cross-sections on the relative energy.

System	ϵ , MeV	τ_m , Å	c_g^*	Reference
H-He	0.46	3.72	0	11
H-Kr	5.9	3.57	0	11
H-Xe	7.08	3.82	0	11
H-Hg*)	14.4	3.06	—	34
H-N ₂	3.72	3.7	0	11
H-CO	4.88	3.31	0	11
H-O ₂	4.54	3.75	0	11
H-CO ₂	6.54	3.62	0.6	11
H-HCl	6.33	3.67	0.5	11
H-HBr	7.7	3.60	0	11
H-HI	9.3	3.68	0.2	11
H-C ₂ H ₄	6.30	4.00	0	11
H-C ₂ H ₂	6.40	3.93	0	11
H-CF ₄ *)	5.3	3.5	—	11
H ₂ -Kr	7.19	3.72	0	11
H ₂ -Xe	8.12	3.93	0	11

Note. A modified V_7 potential was employed.

region of characteristic van der Waals distances. The experimental energy dependences of the total cross-sections for a set of systems including the molecular partners CO₂, SF₆, HBr, HI, etc. have detected traces of additional structures in the region $E > 0.8 \epsilon$. Since an ordinary resonance with a quasidecrete level in this energy region is impossible, arguments have been adduced to explain the observations on the possible manifestation here of resonances with rotational levels, or Feshbach resonances. There is as yet no convincing evidence favoring the unequivocality of such an interpretation of these structures, since the molecules are treated in the point approximation in the corresponding calculations of $Q(E)$. Only after the role of the anisotropy of the actual interaction has been established can one decide reliably on the nature of the features that have been found. A highly effective means for studying the collisional changes in the spin state of hydrogen atoms has proved to be the method of the hydrogen maser (HM) and its modifications.³⁵⁻³⁷ The set of studies performed in the Institute of Chemical Physics of the Academy of Sciences of the USSR (see the references in Ref. 35) has convincingly shown that measurements of the width and shift of the HM lines and also of the relaxation times offer broad possibilities of determining both the lifetimes of the short-lived collision complexes and the effective cross-sections for breakdown of the spin state and depolarization of hydrogen atoms in various gases. These measurements have been performed at temperatures close to room temperature, and an extension of them to the low-temperature region seems highly interesting.

c) Studies of the interaction of cold hydrogen atoms with a surface

Study of collision processes at a surface are of evident interest, both in connection with the problem of interstellar chemistry, and in connection with the discussed problem of stabilizing atomic hydrogen, since the transport and storage of atoms is necessarily performed in closed channels with a predominance of surface over volume collisions. These studies have led to the employment of both the molecular-beam method and the "bulb" method traditional in chemical kinetics. For the latter, it has proved highly effective to com-

bine it with the HM technique.³⁶ This combination has enabled the development of a convenient method for measuring the lifetimes of hydrogen atoms at the wall. In Ref. 36, the resonator bulb was placed in a cryostat containing liquid helium, while the inner walls were coated by admitting molecular hydrogen to form monomolecular layers of a cryodeposit. A flux of hydrogen atoms was admitted into a resonator prepared in this way (without selection with respect to spin state). Measurement of the delay of the response signal with respect to the pulse exciting the resonator enables one to determine the lifetime of the H atoms at a wall covered with a frozen layer of H₂ molecules. Under the assumption (which was not tested in the cited study) that the atomic gas is in equilibrium with the wall, the measurements imply that the mean lifetime of H atoms captured in the adsorption potential for $T \sim 4$ K is $\tau_a \sim 30$ ns; the temperature-dependence of τ_a allows one to estimate the value of $\epsilon_a/k = 9 \pm 2$ K.

This result shows the possibility and expedience of performing analogous measurements with freezing of other typical interstellar molecules on the wall (e.g., water, ammonia, formaldehyde, etc.). This will enable one to establish the efficiency of the process of condensation of molecules in clouds onto particles of interstellar dust and to obtain reliable indications on the plausibility of hypotheses on the existence of molecular (sometimes even polymeric³⁸) coatings made of these particles. For example, the measured time $\tau_a = 30$ ns allows one to rule out the existence of an adsorbed layer of H₂ molecules on the dust particles of an ISC. This is because, since $\tau_a \ll \tau_g$, the appearance of such a layer completely rules out the mechanism of surface recombination of atoms, while leaving the channels for "loss" of H₂ molecules as before. Therefore the attainment of a high stationary concentration of H₂ molecules in an interstellar cloud becomes impossible. Studies of the effects of interaction of a beam of hydrogen atoms with a surface can yield direct information on the laws of recombination on the surface. One can easily satisfy the relationship $\tau_a > \tau_g$ critical under cosmic conditions, since in a laboratory experiment τ_g is controlled by the intensity of the incident beam. Thus, when $\tau_a \sim 10^{-8}$ sec, the mean flux density of the atoms in the beam must amount to $J \geq 10^{14}$ cm⁻²/sec, which is attainable. All the published results of experimental study of surface-recombination effects have been obtained by using an integral-type bolometric detector, which yields no information at the level of the elementary event, as is usual in beam experiments. In Ref. 39 a beam of polarized hydrogen atoms bombarded an Ar-H₂ condensate produced by preliminary freezing of the gas onto the sensitive surface of a silicon bolometer. The aim of the investigation was to study the possibility of capture of H atoms by the weak adsorption potential and of stabilizing the captured atoms at $T \sim 4$ K in the form of a "two-dimensional gas". The bolometric detector had a threshold sensitivity corresponding to the heat effect from a beam of intensity 10^8 sec⁻¹. The measurements revealed that the coefficient of thermal accommodation of hydrogen atoms depends strongly on their kinetic energy, and increases as the latter declines. This re-

sult is important in connection with the problem of cooling atomic fluxes. The measurements established that the bombardment of the surface by a beam ($J=10^{14}$ cm $^{-2}$ /sec) of polarized atoms is accompanied by depolarization of the atoms on the surface and their subsequent recombination. As I have stated above, one of the conditions for stabilization is that the collision energy should be small in comparison with the magnitude of the splitting. In the experiment being discussed, a sextupole polarizing magnet sorted the atoms of the beam in terms of the greatest energy of the hyperfine state. Therefore no activation rule forbidding recombination existed. Characteristically, according to the measurements the released heat of recombination is practically not transferred to the atoms of the surface, but is borne away by the H₂ molecule being desorbed. This observation agrees with the results of a theoretical analysis of the process of surface recombination,^{40,41} which showed that practically all the recombination energy must be included in the vibrational excitation of the H₂ molecule ($\nu=14$). The exit of the recombined atoms in the form of a strongly vibrationally excited ($\nu=14$) H₂ molecule will constitute a serious methodological problem for direct detection of the products of recombination. Evidently the use of electron-impact ionization for detection will destroy the weakly bound molecule, and other detection methods are needed. Here the possibility of laser detection may be of considerable interest⁴² (in particular, two-photon excitation⁴³).

In Ref. 44, which was devoted to studying processes of capture, accommodation, and recombination of H atoms on low-temperature substrates (~4 K), a quadrupole mass spectrometer was employed for analyzing the particles leaving the surface, in addition to a bolometric detector. These measurements were able to establish the strong dependence of the studied interaction characteristics on θ , which is the degree of occupation of the surface with adsorbed H₂ (or D₂) molecules. Thus, the attachment coefficient of H atoms at a surface covered by a layer of D₂ varied from 0.65 ± 0.15 for $\theta_{D_2} \sim 6$ to 0.11 ± 0.05 for an atomically clean surface with $\theta_{D_2} = 0$. Under these conditions the probability of recombination varied from 0.03 ± 0.015 to 0.09 ± 0.03 , while passing through a maximum of 0.12 ± 0.05 at $\theta_{D_2} \sim 1$. The dependences of the attachment and accommodation coefficients on the degree of occupancy of the surface of the bolometer were also established for bombardment with hydrogen molecules. These measurements with hydrogen atoms and molecules were performed with beams of relatively high energies (close to the energies at room temperature). Therefore a reliable extrapolation of the data obtained into the region of intermediate temperatures 10–100 K will require additional measurements.

d) Experiments on stabilization and storage of polarized hydrogen

After the convincing demonstration of the possible generation of intense fluxes of cold hydrogen atoms, one could suppose that there should be no hindrance to an attempt to store a gas of polarized H \uparrow atoms that is

stable with respect to recombination. A recent communication⁴⁵ has reported the successful stabilization of an H \uparrow gas with a density of 10^{15} cm $^{-3}$ for several hours at $T \sim 1$ K in a strong magnetic field. The lack of a detailed description does not allow us to decide yet on the actual achievements, and in this regard the results of Ref. 46 are more interesting. These experiments on the storage and stabilization of an H \uparrow gas were performed in the apparatus⁴⁶ shown schematically in Fig. 9.

The storage of polarized hydrogen is carried out in a copper cell of volume $V \sim 1$ cm 3 (1 in Fig. 9) placed at the center of a superconducting magnet (see Fig. 2) with a field B up to 11 T.

The field gradient sorts the supplied atoms, admitting into the cell the atoms having the desired spin projection and retarding those with the undesired spin. The temperature of the cell is maintained at the level $T \approx 0.27$ K by using a separate ^3He cryostat (3) with sorption pumping. Here the inner walls are covered with a film of superfluid ^4He (the vapor pressure in the cell P_{He} is $\sim 10^{-7}$ Torr). A specific feature of the scheme applied in Ref. 46 is the employment of a closed channel for atom transport that is combined with the regenerator (4) of the film of superfluid ^4He . The regenerator is maintained at a temperature $T \approx 0.48$ K with its own ^3He cryostat (5); it plays the role of a condenser for the vapors from the film, which breaks down via evaporation near the main atom cooler (7). The film of superfluid ^4He rises from the regenerator into the storage cell, covers the connecting channel, the walls of the cell, and the carbon bolometer thermometers (6) located inside. The film falling toward the atom cooler gradually evaporates owing to the temperature gradient. The counterflow of ^4He vapor that arises is liquefied in the condenser of the regenerator to carry out a continuous renewal of the film. On the other hand, this rising (see Fig. 9) flux of ^4He atoms acts as the "jet" of a sort of diffusion micropump. The jet exerts an extra pumping action on the H atoms, and increases their flow toward the region of the magnetic field gradient, while

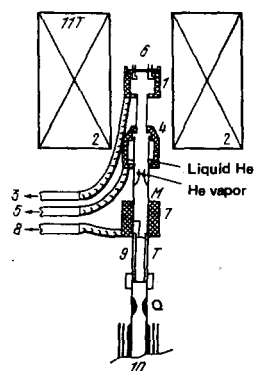


FIG. 9. Schematic diagram of the apparatus employed⁴⁶ for experiments on storing and studying the stabilization of a gas of polarized hydrogen atoms. 1—storage cell, 2—superconducting magnet, 3— ^3He cryostat with sorption pumping, 4—regenerator for the film of superfluid helium, 5— ^3He cryostat cooling the film regenerator, 6—bolometers for measuring the recombination effect in the gas of H atoms, 7—cooling chamber for H atoms, 8—cryostat, 9—atom channel (Q—quartz, T—teflon, M—metal), 10—H-atom source.

reducing the effective temperature of the hydrogen atoms by H-He collisions. Moreover, the pressure of the ^4He vapor from the evaporated film brings about an additional sealing of the exit channel of the storage cell (the mean free path in the regenerator zone amounts to $\lambda \approx 0.4$ mm for a cross-section A of the channel ≈ 1 cm 2). The sealing effect has a quite appreciable magnitude. Thus, according to direct measurements,⁴⁶ the time for effusional emptying of the cell ($\tau_e = 4V/Ac$) with the field turned off is increased by a factor of almost 80 by the damming effect. When the strong magnetic field is turned on, the emptying time will obviously be prolonged further. Under these conditions ($\mu_B H > kT$), only the atoms from the high-energy tail of the velocity distribution will prove capable of "escaping" the region having the field $B(z)$ inhomogeneous along the z axis ($v_{esc} = (2\mu_B B(z)/m)^{1/2}$). When $B = 7$ T, the emptying time is estimated to be $\tau_B = 110$ sec. An account taken of the sealing action of the ^4He vapors allows one to estimate the time of confinement τ_{con} of a gas of polarized H \uparrow atoms (80×110) as being $\tau_{con} \approx 2.5$ hrs.

The lower part of Fig. 9 shows the H-atom cooler 7 ($\phi = 4$ mm), which exists in thermal contact with the ^4He cryostat 8, and which is connected through the short teflon and quartz tube 9 to the discharge H-atom source 10.

The H-atom cooler amounts to a development of the apparatus shown in Fig. 7. However, in contrast, the inner walls of the copper cooler are simply coated with a frozen layer of molecular H_2 .

Thus the transport path for the cold atoms has a coating of H_2 condensate, which goes over into a film of superfluid helium. This brings about efficient accommodation and prevents the possibility of condensation of the H atoms themselves on the walls. The presence of H \uparrow atoms in the storage cell is detected with the bolometer, which is activated by slight heating to destroy the shielding film of superfluid ^4He on it. The activation denudes the surface on which rapid recombination occurs. The H atoms that have lost their polarization at the surface initiate a recombination avalanche or flash (with a characteristic time ~ 8 μsec), which gives rise to the heat release that is detected. The total amount of heat of recombination released at the walls of the cell is a measure of the density of the stored H \uparrow atoms.

The recombination process induced by the heating of the bolometer and the destruction of the ^4He film gives rise to a specific "jump" or step on the volt-ampere curve of the bolometer; the height of the step also characterizes the number of stored atoms. The appearance of this jump in the volt-ampere characteristic caused by the recombinational breakdown of the system allows one to determine the presence of H \uparrow atoms in the cell. The potentiality for stabilizing an H \uparrow gas (the lifetime) was easily established as follows: keeping the accumulation time the same (30 sec in Ref. 46), they determined the height of the recombination step when initiated after successively increasing (e.g., doubling) intervals of time. The characteristic time of decay of

the system will be determined by the instant of appreciable change in the height of the step on the volt-ampere characteristic. By using this method, the authors of Ref. 46 found no changes at $T = 0.27$ K and $B = 7$ T for times $\tau_{con} \leq 532$ sec (according to the later report¹⁹ the confinement time was increased to 2800 sec, which, incidentally, agrees well with the given estimate of the time for effusional decay).

A series of supplementary experiments, including the use of a second bolometer, showed convincingly that the observed effects are associated with the gas phase, rather than with atoms adsorbed on its surface. The confinement time attained by the group at MIT¹⁹ was more than an hour ($T = 0.1$ K, $B = 10$ T). Thus they demonstrated experimentally the possible prolonged existence of a gas of polarized H \uparrow atoms. A cautious estimate of the density of the gas of polarized H \uparrow atoms obtained in the experiments⁴⁶ corresponds to $n = 2 \times 10^{14}$ cm $^{-3}$ (according to Ref. 19, the new value of the density is $n = 10^{16}$ cm $^{-3}$). The group at MIT reports¹⁹ the confinement in a cell of volume 4 cm 3 of a gas with a density 5×10^{16} cm $^{-3}$. Although these values are lower by several orders of magnitude than the density required for experiments on BE condensation, there is today practically no doubt of the possible attainment of the required values. As for the duration of the confinement of the stabilized H \uparrow gas, here also there are grounds for expecting attainment of the required values. This is because the currently attained values have mainly been governed by the technical characteristics of the employed cryoapparatus, rather than by physical factors.

The prospect of studying Bose-Einstein condensation effects renders topical the problem of the experimental means for such observations. At first glance this problem might seem unexpected, since according to the generally adopted treatment (see Ref. 17), BE condensation occurs in momentum space, and need not have "spatial" manifestations.

The bolometric transducer for the recombination effect that has been discussed above is an integral one, and is unacceptable in these studies, simply by the criterion that it cannot perform measurements that do not destroy the object. However, in contrast with the classical BE condensation, BE condensation in the presence of a strong magnetic-field gradient is characterized by a number of features that provide the key to direct observations of its manifestations. The profile of the density distribution of the atoms in the region of the gradient becomes inhomogeneous, owing to the repulsive effect of the magnetic field. In a field having a gradient in the direction along the z axis that can be approximated in the interval from $z = 0$ to $z = z_m$ by the quadratic function $B(z) = B_0 [1 - (z/z_m)^2]$, as has been shown,⁴⁸ the energy spectrum of the possible states of the system is represented as a series of energy bands spaced about 4×10^{-8} K apart. The occupancy of the states accessible to the ensemble of stored H \uparrow atoms is governed by the Bose statistics. Consequently the density distribution of the atoms will depend on the total number of them. After the critical density n_{BE} has

been reached, the profile of the distribution along the z coordinate in the region of the field gradient begins to deform to form a clearly marked density peak in the region of maximum field (B_0). The curvature (d^2n/dz^2) of the distribution changes sign in the transition to BE condensation, while the $n(z)$ relationship becomes quadratic as $T \rightarrow 0$.

If we denote the density for $B = B_0$ as n_0 , and the density in the region of the gradient along the z axis as $n(z)$, then we can relate⁴⁸ these two quantities by introducing the compression coefficient $c(z)$ ($c(z) = \exp\{\mu_B[B_0 - B(z)]/kT\}$):

$$n_0 = c(z) n(z).$$

In view of the exponential relationship of $c(z)$ to T and B , under the conditions of the experiment⁴⁶ being discussed, we find that $c(z)$ can reach a value of 10^{15} ($B = 10$ T, $T = 0.1$ K). The deformation of the density profile caused by the Bose-Einstein condensation "translates" the experiment from momentum space into normal coordinate space. In principle, this deformation can easily be found, e.g., by transducers for the magnetization ($\sim n\mu_B$) having sufficient spatial resolution. It seems that a highly effective means for observing the kinetics of the BE condensation process might be the method of corpuscular diagnostics, i.e., illumination of the condensation zone with beams of neutral atoms. The employment of a ribbon-type atomic beam of energy 1 keV and low intensity for illuminating the zone of the magnetic field gradient and of a coordinate-sensitive detector based on microchannel plates (see the references in Refs. 30 and 48) can enable the continuous determination during the accumulation of the H \uparrow of the density profile with a resolution down to 10 μm .

4. CONCLUSION

The problem of interpreting the radio emissions of the interstellar medium in the mm and cm ranges and the problem of generating a stable gas of polarized hydrogen atoms at high density have attracted attention to the study of atomic processes involving cold hydrogen atoms. Extensive studies have begun on the resonance scattering of H atoms in various gases and at a surface, and the first substantial results have been obtained on the storage and stabilization of a gas of polarized H \uparrow atoms. Undoubtedly these vigorously developing studies will yield new information essential for astrophysics, atomic physics, and quantum macrophysics.

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