RESIDUAL IONIZATION OF A GAS EXPANDING IN VACUUM

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In many processes, rapid heating of a substance to a high temperature, on the order of several tens of thousands of degrees, produces a gas cloud which then scatters in vacuum.*

During the stage of sufficiently large expansion, the scattering of the gas occurs with an almost constant average velocity, u, corresponding to the total conversion of the initial internal energy ϵ_0 into kinetic energy, ($u = \sqrt{2\epsilon_0}$ if the process is adiabatic). The dimensions of the cloud are in this case on the order of $r = ut$ and the mean density (the number of atoms per cubic centimeter) is

$$n = n_0 (r_0 / r)^3 = n_0 (t_0 / t), \quad t_0 = r_0 / u, \tag{1}$$

where n_0 and r_0 are the initial density and dimension of the heated body. The gas cools adiabatically

$$T = (Ae^{S/R})^{\gamma-1} n^{\gamma-1} \sim t^{-3(\gamma-1)}. \tag{2}$$

Here γ is the adiabatic exponent, S the specific entropy, and A is a constant determined from the known equations of statistical mechanics.

At high temperature the gas is strongly ionized. In thermodynamic equilibrium, the degree of ionization would rapidly tend to zero upon cooling. Actually, however, if the expansion obeys Eq. (1), the number of particle collisions, even after an infinite time interval, is limited and the recombination is never completed at $t \to \infty$ $(T \to 0)$: a so-called "quenching" occurs (unlike the plane case, when $n \sim 1/t$, see reference 2).

To estimate the residual ionization, let us consider the kinetic equations (for simplicity we restrict ourselves to the case of a monatomic gas made up of atoms of a single element, incapable of producing negative ions). If x is the actual degree of ionization, x_{eq} the equilibrium degree of ionization, and $\alpha(x, n, T)$ is the coefficient of recombination, then the kinetic equation can be written in the following form, which will be found convenient later on:

$$dx / dt = \alpha n [x_{eq}^2 - x^2], \tag{3}$$

where the quantity $\alpha n x_{eq}^2$ represents the rate of ionization, transformed with the aid of the principle of detailed balance, and $\alpha n x^2$ is the recombination rate. Using Saha's equation for $x_{eq} \ll 1$ we get

$$\begin{aligned} x_{eq}^2 &= 2 (g_+ / g_0) (2\pi m_e kT / h^2)^{3/2} n^{-1} e^{-I/kT} \\ &= B (T^{3/2} / n) e^{-I/kT} \end{aligned} \tag{4}$$

Let the ionization at first, at high temperatures, be almost in equilibrium and let it "follow" the cooling: $x \approx x_{eq}(t)$, $x^2 - x_{eq}^2 \approx x_{eq}^2$. Quenching begins when the difference between the recombination and ionization rates increases to a value on the order of the rates themselves. This instant t_1 and the corresponding quantities T_1, n_1, and $x_1 \approx x_{eq1}$ can be estimated by inserting into (3) $dx/dt = dx_{eq}/dt$ and putting $x^2 - x_{eq}^2 \approx x_{eq}^2$. We obtain an approximate equation which is solved together with (1) and (2):

$$\alpha_1 n_1 x_{eq1} t_1 = {}^3/_2 (\gamma - 1) I / kT_1. \tag{5}$$

The recombination consists of photorecombination and recombination in triple collisions with participation of electrons.† Expressing the coefficient of the latter with the aid of the principle of detailed balance we obtain

$$\alpha = \bar{v}_e \sigma_{ph} + x (n \bar{v}_e \sigma_e / BT^{3/2}) I / kT, \tag{6}$$

where $\bar{v}_e$ is the velocity of the electrons, $\sigma_{ph} = \text{const}/T$ is the cross section for photorecombination, and σ_e is the average cross section for ionization by electrons of energies greater than I.

Starting with the instant t_1, it is possible to neglect in Eq. (3) the rate of ionization, i.e., the term proportional to x_{eq}^2. If we put approximately $\gamma = 5/3$ $(T \sim n^{2/3} \sim t^{-2})$, which does not lead to a large error, the integration reduces to elementary quadrature.

The expressions are particularly simple if one of the recombination mechanisms predominates. Thus, if the quenching begins early, at relatively large densities and at high ionization (the initial dimension r_0 and the time scale t_0 are small), the recombination proceeds principally via triple collisions and the residual ionization is $x_\infty \approx x_1 (kT_1/2I)^{1/2}$. In the case of large time scales, to the contrary, the quasi-equilibrium stage is drawn out, and the principal role is played in the quenching region by photorecombination: $x_\infty \approx x_1 (kT/I)$.

By way of an example we list the calculated residual ionization of iron vapor, from initially heated solid iron of normal density, at $T_0 = 116{,}000°$.‡ An estimate of the energy and entropy, with allowance for the electronic specific heat, yields $\epsilon_0 = 72$ ev/atom, $S = 61$ cal/mole-degree, $u = 15.5$ km/sec. If the initial radius is $r_0 = 10$ m (large iron meteorite), then $x_1 = 4.2 \times 10^{-3}$, $T_1 = 4550°$, $n_1 = 1.4 \times 10^{17}$ cm^{-3}, and $x_\infty = 2.1 \times 10^{-4}$. If $r_0 = 1$ cm, which is closer to the laboratory scale, then $x_1 = 0.58$, $T_1 = 9300°$, $n_1 = 6.6 \times 10^{17}$ cm^{-3}, $r_1 = 50$ cm, and $x_\infty = 0.13$.

The smaller the mass of the evaporated substance and the greater the initial heating, the greater the residual ionization.

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[*] For example, when high-energy meteorites strike the surface of a planet that has no atmosphere, during explosions of wire by electric currents in evacuated apparatus, during evaporation of anode points in pulsed X-ray tubes,[1] etc.

[†] Triple collisions in which heavy particles participate are important only if $x \lesssim 10^{-4}$ and do not play any role under our conditions.

[‡] In view of the absence of experimental data we assume the following likely values for the cross sections:

$$\sigma_e = 3 \cdot 10^{-17} \text{ cm}^2, \ \sigma_{\text{ph}} = 2 \cdot 10^{-21} T^{-1} \text{ cm}^2 \text{ (T is in ev).}$$

[1] V. A. Tsukerman and M. A. Manakova, J. Tech. Phys. (U.S.S.R.) **27**, 391 (1957), Soviet Phys.–Tech. Phys. **2**, 353 (1957).

[2] Ya. B. Zel'dovich and Yu. P. Raĭzer, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 1402 (1958), Soviet Phys. JETP **8**, 980 (1959).

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MEASUREMENTS OF NUCLEAR MAGNETIC MOMENTS IN THE ALKALI EARTHS BY MOLECULAR BEAM MAGNETIC RESONANCE

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THE molecular beam magnetic resonance method (MBMR) has a number of advantages as compared with other methods of measuring nuclear magnetic moments in those cases in which the molecular beam consists of atoms in the S_0 state. The interaction of such atoms with an external magnetic field depends solely on the orientation of the nuclear magnetic moment. The magnetic resonance spectrum consists of one line and the shape of the line is not distorted by other interactions. Moreover, the position of the resonance is not subject to chemical shifts. Thus, the diamagnetic correction, which has been calculated accurately only for atomic and molecular hydrogen,[1] can be examined carefully.

The MBMR method (using atoms in the S_0 state) has been used to measure the magnetic moments of Ba^{135} and Ba^{137},[2] Ne^{21},[3] and Sr^{87}.[4] The application of this technique to other nuclei has been limited by the possibility of producing and detecting the appropriate atomic beams. It has been found possible to carry out these measurements in atomic beams of all the alkali earth metals using apparatus developed for this purpose.[5] This apparatus has been described by us earlier.[4]

Atomic beams of strontium, barium, and magnesium have been obtained by heating these metals (natural isotopic composition) in an oven source. A calcium atomic beam with sufficient intensity for detection of the Ca^{43} isotope was obtained by heating a mixture of CaO with 6% of the Ca^{43} isotope and mischmetal. The atomic beam was detected by a mass-spectrometer detector, using surface ionization of the atoms on tungsten, cleansed by oxygen under the optium conditions for each element.[5] The detectable intensities of narrow beams (I), the corresponding source temperatures (t), and the surface ionization coefficients (β) for the optimum detection conditions are given in Table I.

TABLE I

Isotope	t, °C	I, counts/sec	β
Mg^{25}	600	200	$2 \cdot 10^{-4}$
Ca^{43}	1070	300	0.02
Sr^{87}	750	10^4	0.2
Ba^{135}	800	500	0.6
Ba^{137}		850	

The measurements, carried out by the techniques which have been described,[5] were made at fixed field. The field was measured by the magnetic resonance of protons in water and the magnetic resonance of the Sr^{87} in the atomic beam; in the latter case the source was loaded with the necessary amount of metallic strontium in addition to the material being investigated. The values of the magnetic moment μ (with the diamagnetic correction) thus obtained are given in nuclear magnetons in Table II. In these calculations the magnetic moment of the proton has been taken as 2.79275[6] while the magnetic moment of Sr^{87}