overlapping transitions. Measurements on these heavier molecules are of interest for purposes of comparison with theoretical values calculated using perturbed Hartree-Fock techniques.[18]

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[1]W. Kołos and L. Wolniewicz, J. Chem. Phys. 46, 1426 (1967).

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[5]Deuterium was studied rather than hydrogen because the signal-to-noise ratio for D_2 is significantly better than for H_2 in the apparatus used; this is due to the large background of singly ionized particles of mass 2 amu in the electron-bombardment detector.

[6]The plates and spacers were fabricated by the A. D. Jones Company of Burlington, Mass.

[7]N. F. Ramsey, Phys. Rev. 85, 60 (1952).

[8]The terms in the Hamiltonian which describe the interaction of the molecule with the external electric field are independent of nuclear spin. In this sense there is no "direct interaction" between $\vec{E}$ and the nuclear spin; however, there is a direct interaction between $\vec{E}$ and the molecular rotation, so that an indirect coupling between $\vec{E}$ and $\vec{I}$ exists at weak and intermediate magnetic fields due to the direct coupling between nuclear spin and rotational motion.

[9]The linewidth (full width at half-intensity) of this transition is on the order of 10 kHz and is in good agreement with the value calculated on the basis of the uncertainty principle.

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[11]Should such a shift exist, it could be due to terms proportional to odd powers of E appearing in the molecular Hamiltonian, or to a systematic effect such as a motional H field.

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DELAYED NEUTRONS FROM NEUTRON-IRRADIATED LiF CONTAINING COLOR CENTERS*

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It is shown that the neutron-electron interaction is orders of magnitude too small to allow neutrons to be bound to electron-excess color centers in alkali-halide crystals, as was indicated experimentally by Grant and Cobble.

In a recent Letter,[1] Grant and Cobble presented evidence that LiF crystals containing electron-excess color centers had the ability at 4°K to retain reutrons for ~40 sec. They concluded that a neutron-electron bound state existed. In this Letter, we calculate the neutron-electron interaction and find that this interaction is orders of magnitude too weak to lead to binding.

We first obtain a lower limit on the hypothetical neutron-electron binding energy, based on Grant and Cobble's data. They expose their LiF crystal to 4.8×10^8 thermal neutrons, and find that ~2 appear later. If we assume that only neutrons whose kinetic energy is less than the binding energy will be trapped, neglect any other fates for the incident neutrons (e.g., $Li^6+n\rightarrow Li^7$), assume a Maxwellian distribution for the incident neutrons, and assume that all trapped neutrons are detected, we find that the binding energy must be at least 4.4×10^{-5} eV.

We also estimate, using the uncertainty principle, the kinetic energy of a neutron confined to one atomic volume (e.g., an F center). We obtain $\sim10^{-4}$ eV.

Thus, an attractive interaction, if it is to bind the neutron to a trapped electron, must be at least $\sim 10^{-4}$ eV and of somewhat long range. We consider two types of interaction: (a) neutron-spin–electron-spin and (b) spin-independent forces. In both cases, we assume a Born-Oppenheimer approximation[2] for the electron and neutron; that is, we calculate the electron energy as a function of neutron position, and use the resulting function as a potential energy for the neutron.

The spin-spin interaction arises from the contact potential, as first derived by Fermi.[3] For the neutron-electron interaction the ground state of the electron will be depressed by the term

$$\mathcal{E}_g(R) = \frac{-8}{3}\frac{e\hbar}{2mc}1.913\frac{e\hbar}{2M_Nc}\pi\psi^2(R),$$

where M_N is the neutron mass, $\psi(R)$ is the electron wave function, and R is the position of the neutron. We consider an F center, with a function of the form[4]

$$\psi(R) = \left(\frac{\alpha^3}{7\pi}\right)^{1/2}(1+\alpha R)e^{-\alpha R}.$$

We choose $\alpha = 0.56a_0^{-1}$, a value appropriate to the F center in NaCl[5]; in LiF α would be slightly larger, but not sufficiently so to matter very much. Putting in numbers for the various quantities, we obtain

$$\mathcal{E}_g(R) = -2.5\times 10^{-8}(1+\alpha R)^2 e^{-2\alpha R}\ \text{eV}.$$

We immediately notice that the maximum value of $|\mathcal{E}_g|$ is orders of magnitude smaller than we argued earlier would be required. Nevertheless, we attempted to solve numerically the Schrödinger equation[6] for a neutron moving in this potential. We could not obtain a bound state. Further investigation of this equation by means of a variational method indicates that the interaction would have to be 4 to 6 orders of magnitude larger for a bound state to occur.

We have also considered other neutron-spin–electron-orbit and spin-spin interactions, which would be appropriate to an electronic state with $l \neq 0$, and to the s state when the neutron is off center. These interactions, however, seem to be of the same order of magnitude as the contact interaction, and therefore they apparently will not produce binding either.

Regarding spin-independent interactions, we investigated two: the induced polarization of the neutron, and the narrow, deep potential well used to fit neutron-electron scattering data. A potential well[7] of depth 4340 eV, radius 2.82×10^{-13} cm leads to a maximum interaction of neutron and F center $\sim 10^{-11}$ eV. Using a neutron polarizability[8] of $\sim 3.7\times 10^{-42}$ cm^3, the interaction with an electron $1a_0$ away is $\sim 10^{-16}$ eV. Clearly, both of these are much too small to produce binding.

We see that from a theoretical point of view, the evidence seems strong that a neutron cannot be trapped by an electron in an ionic crystal. How, then, can one explain the results of Grant and Cobble? In the absence of a knowledge of the details of their experiment, we cannot; certainly the logic of their experiment is very tight. There do appear to be some chemical changes in their samples between 4°K, room temperature, and after heating; at least there are differences in their observed β-γ counts in channels 80-90 and 60-70 between these cases. However, their experiment with a sheet of cadmium would seem to rule out a radioactive-species effect in the neutron region except by some very tenuous reasoning.

Since this paper was originally prepared, a Letter by Krohn et al.[9] appeared, in which an experiment similar to Grant and Cobble's was performed, with negative results. The result of Krohn et al. is consistent with our calculations.

Since electron-excess color centers in LiF have not been widely studied,[10] and since Li^6 readily undergoes the (n, α) reaction with tritium produced, it would seem worthwhile to repeat these experiments on a more standard alkali halide such as KCl.

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KINEMATIC CORRECTIONS TO ATOMIC BEAM EXPERIMENTS*

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We have calculated and measured the effective velocity distribution for metastable hydrogen atoms produced in a typical beam apparatus. The distribution is characterized by $U^n \exp(-U^2)$, where $n \simeq 4$ rather than $n = 2$. We discuss modifications of velocity-dependent corrections to beams measurements of the Lamb shift in the first excited state of atomic hydrogen.

In many beam experiments with light atoms or molecules, a ground-state particle I is excited to a metastable state I^* by electron impact, as in Fig. 1. A well-collimated I beam from an oven at temperature T is incident at $\angle\varphi$ on a beam of electrons at energy $\mathcal{E}+\Delta\mathcal{E}$, where $\mathcal{E}$ is the $I \rightarrow I^*$ excitation threshold and $\Delta\mathcal{E}$ is a small excess energy. Afterwards, an I^* beam exits at $\angle\psi$; it is collimated into an interval $\Delta\psi$ by output slits, and then falls onto a detector. A simple calculation,[1] assuming a $U^3\exp(-U^2)$ I-beam velocity distribution [$U = V/\alpha$, where V is the atom velocity and $\alpha = (2kT/M)^{1/2}$ is the thermal velocity], shows that the most probable recoil angle $(\varphi+\psi) \simeq r/\sqrt{2}$, where $r = (m\mathcal{E}/MkT)^{1/2}$. This angle is about 7° for H at 2500°K.

We find that a combination of effects due to recoil and collimation of the I^* beam substantially affects the resultant velocity distribution which is usually assumed to be $U^n \exp(-U^2)$, with $n = 2$.[2] Instead, under typical conditions, $n \simeq 4$ is a better description, and the actual distribution has upper and lower cutoff velocities which are quite sensitive to apparatus parameters. Consequently, all such experiments which depend on the assumed distribution should be checked for systematic errors. Here, we briefly describe the calculation and experiment which show these effects. We then discuss corrections to the experiments which have measured $\mathcal{S}(\mathrm{H}, n = 2)$, the Lamb shift in the $n = 2$ state of atomic hydrogen.

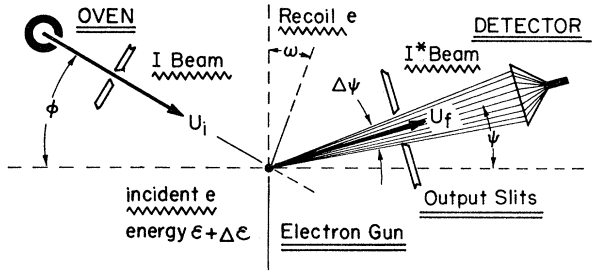

FIG. 1. Experimental schematic. A beam of ground-state particles I effuses from an oven and is incident at $\angle\varphi$ on a beam of electrons. The electron impact excites metastable I^* particles which exit toward a detector in the shape of a "cone" $(\psi, \Delta\psi)$. Generally, the angles φ and ψ are adjusted so as to provide a maximum I^* signal.

By solving the momentum- and energy-conservation equations for the situation in Fig. 1, we can relate the initial and final atom velocities. Since the experiments are usually done near threshold, where $\kappa = \Delta\mathcal{E}/\mathcal{E} \ll 1$, an approximation to $O(\kappa)$ is sufficient. We neglect transverse recoil,[3] and assume the recoil electrons are isotropically distributed.[4] Noting that the detected I^* atoms have velocities $U \sim 1$, we find that to sufficient approximation (a few percent), the initial and final velocities are equal. Next, momentum conservation gives the velocity U scattering at specific angles (φ, ψ) as

$$U = \overline{U} - \Delta U \cos(\omega + \psi),$$

where

$$\overline{U} = R\cos\psi/\sin(\varphi+\psi), \quad \Delta U = \lambda\overline{U}/\cos\psi,$$

with

$$R = r(1+\kappa)^{1/2}, \quad \lambda = [\kappa/(1+\kappa)]^{1/2}. \tag{1}$$

As the electron recoil angle ω traces out $0 \leq \omega \leq 2\pi$, the velocity U at (φ, ψ) traces out $\overline{U} - \Delta U \leq U \leq \overline{U} + \Delta U$. At threshold, $\lambda = 0$, the only velocity detected is $\overline{U}$ itself. If φ and ψ are adjusted to a maximum I^* signal alignment condition (MI^*SAC), as is usual, then $\overline{U} \simeq \sqrt{2}$. This is considerably faster than the most probable velocity