Cross section for electron exchange in collisions of deuterium atoms with hydrogen and helium

B. P. Ad'yasevich and V. G. Antonenko

I. V. Kurchatov Atomic Energy Institute

(Submitted August 6, 1974)
Zh. Eksp. Teor. Fiz. **68**, 889–893 (March 1975)

Estimates have been obtained for the cross section for electron exchange σ_{00} in collisions of fast deuterium atoms ($E_d \approx 100$ keV) with helium [$\sigma_{00} = (4.0 \pm 0.6) \times 10^{-16}$ cm^2 at $E_d = 160$ keV] and with hydrogen (1.7×10^{-16} cm$^2 > \sigma_{00} > 0.1 \times 10^{-16}$ cm^2 in the range of E_d from 90 to 300 keV). A method is suggested for determining the cross sections σ_{00} over a wide energy range by measurement of the depolarization of beams passing through gaseous targets.

1. INTRODUCTION

Electron exchange has been discussed theoretically and studied experimentally only for thermal energies of atomic collisions corresponding to the conditions of operation of masers working in transitions between hyperfine-structure states.[1] At higher energies this process has not been studied, but it may play an important role in depolarization of beams passing through a gas. The present work is devoted to determination of the cross sections for exchange of electrons from analysis of experimental data on depolarization of deuteron beams in helium[2] and in hydrogen[3] with account of electron exchange.

2. POLARIZATION LOSS IN THE TARGET

The state of polarization of a deuteron relative to a chosen axis is defined by two quantities: the vector polarization $P = \bar{\hat{S}}_z$ and the tensor polarization $T = \bar{\hat{S}}_{zz}$, where $\hat{S}_z$ and $\hat{S}_{zz} = 3\hat{S}_z^2 - 2$ are the deuteron spin operators. A polarized deuteron passing through a gas can capture an electron and form a deuterium atom. Here the deuteron spin will precess in the magnetic field of the electron bound with it.

Solving the problem of behavior of the deuterium atom in the absence of an external magnetic field in the usual way, we can determine the time dependences of P(t) and T(t):

$$P(t)/P(0) = {}^1/_9(7+2\cos 2\pi\nu_0 t) \equiv 1 - {}^4/_9 \sin^2 \pi\nu_0 t, \tag{1}$$

$$T(t)/T(0) = {}^1/_3(1+2\cos 2\pi\nu_0 t) \equiv 1 - {}^4/_3 \sin^2 \pi\nu_0 t, \tag{2}$$

where $\nu_0 = 327.4$ MHz is the frequency of fine-structure splitting of the deuterium atom, and P(0) and T(0) are the polarizations of the deuteron at the moment of formation of the atom.

After the ionization, the precession of the deuteron spin stops. This means that at the moment t_1 of the second capture of an electron the resultant precession begins with zero average values of the phases and leads to a set of new phases $2\pi\nu_0(t - t_1)$. Repeated precession after electron exchange also begins with zero average phase values, since it is assumed that in atomic collisions leading to exchange of electrons both with identical and with oppositely directed spins, any changes of phase are equally probable.

Thus, after the precession stops at time t as the result of ionization or electron exchange, the deuteron will have new populations of the spin states and, consequently, new values of tensor polarization. If we take into account that during the precession time t a deuteron with a velocity v_d travels a distance $x = v_d t$, then

$$T/T_0 = 1 - {}^4/_3 \sin^2(\pi\nu_0 x/v_d). \tag{3}$$

The segments x obey a Poisson distribution

$$w(x) = n(\sigma_{01}+\sigma_{00}) \exp\{-n(\sigma_{01}+\sigma_{00})x\}, \tag{4}$$

where n is the concentration of target particles, σ_{01} is the ionization cross section, and σ_{00} is the electron-exchange cross section. On averaging Eq. (3) over the distribution (4) we obtain the average relative tensor polarization after traversal of one such path:

$$\frac{T}{T_0} = 1 - \frac{2}{3}\frac{f^2}{1+f^2}, \quad f = \frac{2\pi\nu_0}{v_d n(\sigma_{01}+\sigma_{00})}. \tag{5}$$

If the beam traverses in the gas a distance l, then the average number M of captures and exchanges is

$$M = nl\sigma_{10}(\sigma_{01}+\sigma_{00})/(\sigma_{01}+\sigma_{10}), \tag{6}$$

where σ_{10} is the electron-capture cross section. In the case of a path l sufficiently small that we can neglect the loss of energy of the beam in the gas and sufficiently large that the law of large numbers is satisfied for M ($M > 4$), the relative tensor polarization at the end of the path l is

$$\frac{T}{T_0} = \left(1 - \frac{2}{3}\frac{f^2}{1+f^2}\right)^M. \tag{7}$$

3. ALLOWANCE FOR DEPOLARIZATION AS THE RESULT OF OPTICAL TRANSITIONS

In the case of a large total path in the gas, as an illustration, under the conditions of ref. 3, it is necessary to take into account depolarization as the result of formation of an excited state of the atom either in capture of an electron by the deuteron or in collision of the deuterium atom with atoms of the target and a subsequent optical transition to the ground state.

The number of such events per unit pathlength is $\alpha(q_1 + q_2)$, where

$$q_1 = \frac{n\sigma_{00^*}\sigma_{10}}{\sigma_{01}+\sigma_{10}}, \quad q_2 = \frac{n\sigma_{10^*}\sigma_{01}}{\sigma_{01}+\sigma_{10}}, \tag{8}$$

$$\alpha = 1/[1+n(\sigma_{0^*1}+\sigma_{0^*1^-})v_d\tau];$$

here σ_{00^*} is the cross section for excitation of the atom, σ_{10^*} is the cross section for formation of an excited atom in electron capture, σ_{0^*1} is the cross section for ionization from the excited state, and $\sigma_{0^*1^-}$ is the cross section for formation from the excited state of a negative complex in a bound or unbound state. As was shown in the work of Hughes and Kisner,[4] the latter two cross sections correspond to the two main processes competing with removal of excitation by an optical transition. The quantity α corresponds to the probability of an optical transition from an excited state having a lifetime τ in the presence of processes destroying this state in atomic collisions. The quantity q_1 corresponds to the number of excitations of the atom per unit path in the gas, and q_2 corresponds to the number of formations of excited atoms in electron capture in the same pathlength. It is easy to show that for deuterons with energy of the order of 100 keV traversing in hydrogen a total path less than 10 cm, it is necessary to take into account only excitation of 2P states. The contribution of the remaining states is substantially less as the result of the smaller cross sections and larger lifetimes.

To evaluate the corrections for optical depolarization under the experimental conditions of ref. 3, we used the data of Hughes and Kisner on $\sigma_{0^*1} + \sigma_{0^*1^-}$ (ref. 4). The cross section σ_{0^*1} was determined according to the work of Bates and Walker[5] with use of Brode's data on the total cross section for scattering of electrons in hydrogen,[6] and the cross sections σ_{01} and σ_{10} were taken from the work of Stier and Barnett.[7] In accordance with the data of Birely and McNeal,[8] the cross section σ_{10^*} was set equal to $0.04\sigma_{10}$ and the values of the cross section σ_{00^*} were found by extrapolation to higher energies. We have listed below the estimates of the numbers of 2P → 1S optical transitions in the deuterium atom, αq_1 and αq_2, in a pathlength of 1 cm in hydrogen with a concentration of $7 \times 10^{17}\,\text{cm}^{-3}$ as a function of the energy E_d for the experimental conditions of ref. 3:

E_d, kev:	88	110	129	172	203	226	300
αq_1:	0.0093	0.0084	0.0068	0.0040	0.0029	0.0024	0.0009
αq_2:	0.0135	0.0089	0.0059	0.0029	0.0017	0.0010	0.0003

It is evident that for a sufficiently long pathlength in the gas (≈10 cm), optical transitions occur in an appreciable fraction of the atoms. With increase of the energy the number of optical transitions decreases substantially.

To calculate the polarization of deuterons stopped after removal of the 2P-state excitation by an optical transition to the 1S state, we first determined the populations of the hyperfine components of the $2P_{1/2}$ and $2P_{3/2}$ states for given initial polarizations P_{0^*} and T_{0^*}, and then with allowance for the relative intensities of optical transitions to the levels of the hyperfine components of the $1S_{1/2}$ state we determined the populations of these hyperfine components. It was established that the residual polarization depends on the means of formation of the excited atoms. In the case of electron capture

$$P_1^*=0.47P_0^*, \quad T_1^*=0.10T_0^*.$$

In the case of excitation of the atom from the ground state the values of vector and tensor polarization are somewhat smaller:

$$P_2^*=0.34P_0^*, \quad T_2^*=0.03T_0^*.$$

Thus, the experimentally observed relative tensor polarization $(T/T_0)_{\text{exp}}$ is determined by the expression

$$\left(\frac{T}{T_0}\right)_{\text{exp}}=\frac{T}{T_0}\exp\left\{-\left[\left(1-\frac{T_1^*}{T_0^*}\right)\alpha q_1+\left(1-\frac{T_2^*}{T_0^*}\right)\alpha q_2\right]l\right\}, \tag{9}$$

where T/T_0 is the relative tensor polarization due only to precession of the deuteron spin. Under the experimental conditions of ref. 3 the exponential correction factor in Eq. (9) is close to unity and the minimal value 0.8 is achieved only for the lowest energies.

4. ESTIMATE OF CROSS SECTIONS FOR ELECTRON EXCHANGE

Lindstrom, Garret, and von Möllendorf[2] measured the relative tensor polarization of deuterons with energy 160 keV which had passed through 0.55 cm in helium at a pressure from 1 to 20 mm Hg. Under these conditions it is possible to use Eq. (7) for calculation of the depolarization. In Fig. 1 we have shown curve 1 for which $\sigma_{00} = 0$, and curve 2 for which the electron-exchange cross section $\sigma_{00} = 4.0 \times 10^{-16}\,\text{cm}^2$ gives the best agreement with the experimental data. The error in determination of the cross section is $\Delta\sigma_{00} = \pm 0.6 \times 10^{-16}\,\text{cm}^2$.

Under the experimental conditions of ref. 3 the loss of energy of the deuterons on slowing down in the gas was as high as 60 keV, and use of Eq. (7) to determine the relative tensor polarization of the deuterons is unsuitable. Therefore, as in ref. 3, the corresponding calculations were carried out by computer with the Monte Carlo method but with inclusion of the electron-exchange cross section, whose value was chosen such that the experimental data, corrected by Eq. (9) for depolarization as the result of optical transitions, agreed with theory. The values of σ_{00} obtained for eight deuteron-energy values are given in Table II, from which it is evident that in order of magnitude the exchange cross section σ_{00} is comparable[7] with the cross sections σ_{01} and σ_{10}. The errors in determination of the values of σ_{00} are mainly due to errors in measurement of $(T/T_0)_{\text{exp}}$ in ref. 3. The errors indicated in Fig. 2 in determination of the velocity are due to the finite thickness of the target.

5. CONCLUSIONS AND DISCUSSION OF RESULTS

The analysis carried out shows that drawing on the electron-exchange mechanism permits explanation of the discrepancy between the experimental data on deu-

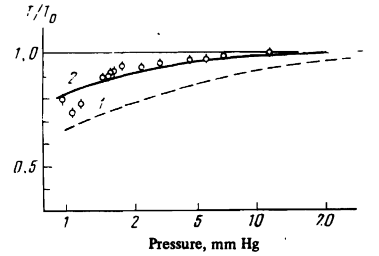

FIG. 1

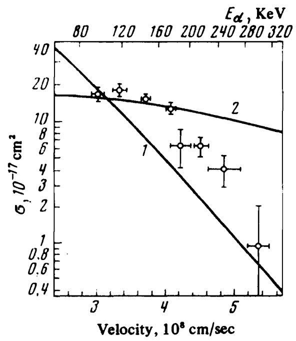

FIG. 2

FIG. 1. Tensor polarization of a beam of deuterons which has traversed a path of 0.55 cm in helium, as a function of the gas pressure in the target: ○—results of Lindstrom et al. (ref. 2); curve 1—calculations with $\sigma_{00} = 0$ from ref. 3; curve 2—calculation with Eq. (11) with $\sigma_{00} = 4.0 \times 10^{-16}\,\text{cm}^2$.

FIG. 2. Cross sections for processes occurring in atomic collisions of deuterium atoms in hydrogen, as a function of the deuteron velocity: curve 1—electron-capture cross section σ_{10} from the data of Stier and Barnett (ref. 7); curve 2—ionization cross section σ_{01} from the data of Stier and Barnett (ref. 7); points—estimate of the cross sections for electron exchange σ_{00} from the data of ref. 3.

teron polarization on passing through a gas[2,3] and the theoretical calculations.

The values of the electron-exchange cross section σ_{00} obtained as the result of analysis of the experimental data of the studies cited for collisions of fast deuterium atoms with the particles of gaseous targets must be considered as preliminary. This is due to the fact that those studies[2,3] were not designed especially to determine these cross sections, and their experimental conditions are far from optimal for determination of σ_{00} with high accuracy. Unfortunately the question of the magnitude of the cross section σ_{00} at energies above 1 eV has not been discussed in the theory. Measurement of the loss of polarization of a beam of deuterons in passing through gaseous targets is still the only method of determining this cross section. The cross section σ_{00} is the sum of the cross sections for exchange of electrons with identical and oppositely directed spins, since in view of the assumption of zero average phase values the deuteron spin precession does not depend on the preservation or change of the electron spin. In the case of hydrogen and helium targets, the latter process is accomplished only in excitation of hydrogen and helium.

It should be noted that the energy interval can be extended substantially toward lower energies down to several hundred or several tens of electron volts. In this case the polarized deuteron beam having the necessary energy should be passed through an appropriate gaseous target, after which the remaining charged component of the beam should be accelerated to an energy of 80—100 keV for the purpose of measuring the residual tensor polarization in the reaction $H^3(\vec{d}, n)He^4$.

It should be noted, however, that the method proposed can be used only to determine the cross section σ_{00} for deuterium. In principle it is possible to produce sources of other polarized ions, but nevertheless no simple methods of determining the polarizations of these ions are known.

In conclusion we take pleasure in expressing our gratitude to V. M. Galitskiĭ, who called our attention to the role of electron exchange in depolarization of deuterons on passage through a gas and who make a number of valuable remarks in discussion of the results obtained, and to D. P. Grechukhin for assistance in evaluating the effect of optical transitions on the depolarization.

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[1] B. M. Smirnov, Atomnye stolknoveniya i élementarnye protsessy v plazme (Atomic Collisions and Elementary Processes in Plasma), Atomizdat, 1968, p. 86.
[2] W. W. Lindstrom, R. Garrett, and U. von Möllendorff, Nucl. Instr. and Meth. 93, 385 (1971).
[3] B. Ad'yasevich and V. G. Antonenko, Zh. Eksp. Teor. Fiz. 66, 1911 (1974) [Sov. Phys.-JETP 39, 940 (1974)].
[4] R. H. Hughes and H. Kisner, Phys. Rev. A5, 2107 (1972).
[5] D. R. Bates and J. C. G. Walker, Planetary and Space Sci. 14, 1367 (1966).
[6] R. B. Brode, Rev. Mod. Phys. 5, 257 (1933).
[7] P. M. Stier and C. F. Barnett, Phys. Rev. 103, 896 (1956).
[8] J. H. Bierely and R. J. McNeal, Phys. Rev. A5, 692 (1972).

Translated by C. S. Robinson
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