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PHYSICS

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Theoretical Investigation of ^{41}K States Behavior under Strong Magnetic Field and π Polarized Laser Field

(Submitted by corresponding member of NAR RA A. V. Papoyan 4/XI 2015)

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Introduction. The influence of magnetic field on the medium and particularly on the atomic transitions is of great importance for a wide range of applications, starting from magnetometry, spectroscopy, space research, medicine, etc.[1-3]. There is a range of studies concentrated on the investigation of weak magnetic field influence on atomic transitions [4]. However, the behavior of alkali atoms in strong magnetic fields has been under attention only recently. The increasing interest is due to the fact that the external magnetic field eases the study of atomic states structure and transitions, as it separates degenerate states well from each other making possible their experimental detection. Investigations on atomic states of ^{85}Rb, ^{87}Rb, ^{133}Cs and ^{39}K are already published in [5-9, 11]. However, there is not sufficient up to date data on ^{40}K and ^{41}K isotopes as they are of low densities in nature (6.3% and 0.01%, respectively). In the current paper we present for the first time our theoretical studies of the ^{41}K isotope D_1 and D_2 lines in the presence of external magnetic field while interacting with $\pi\left(B\|E\right)$ polarized laser field.

The essence. To understand the behavior of the alkali atoms, let us see what is happening to the quantum numbers. The splitting of atomic levels in weak magnetic fields is described by the total angular momentum $F = J + I$ of the atom and its projection m_F, where $J = L + S$ is the total angular momentum of electrons and I is the nuclear spin. In the Hyperfine Paschen-Back (HPB) regime J and I become decoupled and the splitting of the atomic levels is described by their projections m_J and m_I. For alkali metals the HPB regime takes place at fields $B \gg B_0 = A_{hfs} / \mu_B$, where A_{hfs} is the ground-state hyperfine coupling coefficient (magnetic dipole constant) and μ_B is the Bohr magneton. For ^{41}K isotope it is easy to calculate $B_0 = 90$ G. The relevant atomic configuration is presented in Figure 1 in the basis of J and I quantum numbers for D_1 and D_2 lines. Below we show that at strong external magnetic fields initially strong transitions weaken, instead, transitions that were negligibly weak (or even initially forbidden) become stronger and visible. The latter ones we call initially forbidden further allowed (IFFA) transitions, labeled as 3 and 11 in Figure 1. The arrows there show the transitions that remain at strong magnetic fields. Numbers in rectangles correspond to these transitions. Also, corresponding transitions in the F, m_F basis are shown for D_1 and D_2 lines in Table 1 and Table 2 respectively.

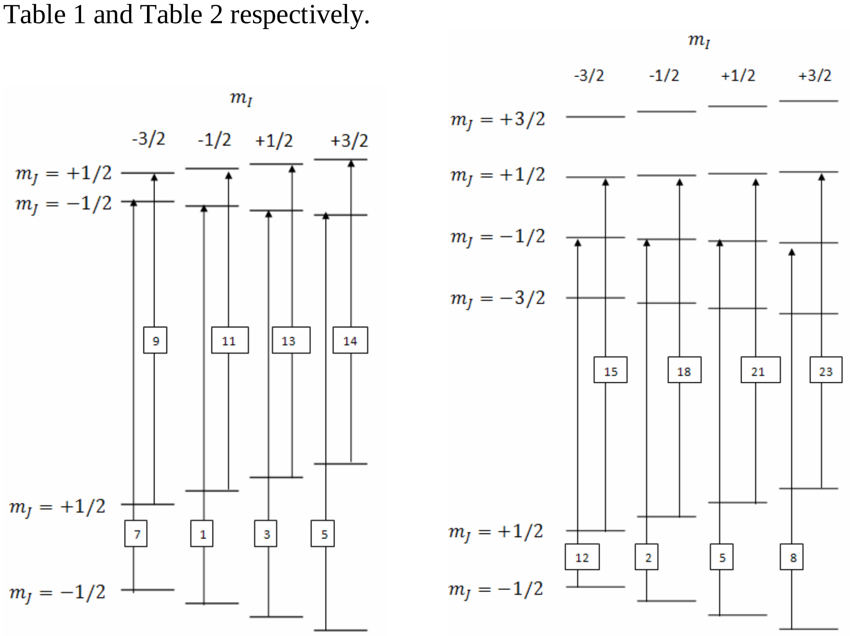

Fig. 1. Relevant atomic levels and transitions in the basis of the quantum numbers m_J and m_I . The left configuration corresponds to the D_1 line, the right one to the D_2 line. The numbers on the transitions correspond to the transitions that remain in strong magnetic fields (when $B \geq 90$ G).

There is another phenomenon that has been observed, while investigating alkali atoms D_1 line behavior in the π polarized laser radiation field. There are transitions that are not changing their probabilities and maintain transition shift slopes, which we call guiding transitions (GT). The two GTs, labeled as 7 and 14 in Figure 1, maintain their probabilities and shift slopes in a very large range of external magnetic field (from 0 G to ~ 250 kG). The upper limitation is due to the fine structure constant α .

The model. The theoretical model is based on the Hamiltonian for the D line of alkali atoms for any static magnetic field [10]. The diagonal terms of the Hamiltonian have the form

$$\langle F, m_F | H |, F, m_F \rangle = E_0(F) - \mu_B g_F m_F B_z \quad (1)$$

Table 1

D_1 line ($\left|J=1/2\right\rangle \rightarrow \left|J'=1/2\right\rangle$), labels for π transitions corresponding to the labels in the rectangles in Fig. 1

$\left\|F=1, m_F\right\rangle \rightarrow \left\|F', m_{F'}=m_F\right\rangle$					
$m_F \rightarrow$	-2	-1	0	+1	+2
$F'=2$		**2**	**4**	**6**	
$F'=1$		**1**	**3**	**5**	
$\left\|F=2, m_F\right\rangle \rightarrow \left\|F', m_{F'}=m_F\right\rangle$					
$m_F \rightarrow$	-2	-1	0	+1	+2
$F'=2$	**7**	**9**	**11**	**13**	**14**
$F'=1$		**8**	**10**	**12**	

Table 2

D_2 line ($\left|J=1/2\right\rangle \rightarrow \left|J'=3/2\right\rangle$), labels for π transitions corresponding to the labels in the rectangles in Fig. 1

$\left\|F=1, m_F\right\rangle \rightarrow \left\|F', m_{F'}=m_F\right\rangle$							
$m_F \rightarrow$	-3	-2	-1	0	+1	+2	+3
$F'=3$			**3**	**7**	**10**		
$F'=2$			**2**	**6**	**9**		
$F'=1$			**1**	**5**	**8**		
$F'=0$				**4**			
$\left\|F=2, m_F\right\rangle \rightarrow \left\|F', m_{F'}=m_F\right\rangle$							
$m_F \rightarrow$	-3	-2	-1	0	+1	+2	+3
$F'=3$		**12**	**15**	**19**	**22**	**24**	
$F'=2$		**11**	**14**	**18**	**21**	**23**	
$F'=1$			**13**	**17**	**20**		
$F'=0$				**16**			

where $E_0(F)$ is the atomic energy in the absence of magnetic field B_z, g_F is the corresponding Landé factor. The off-diagonal matrix elements may be non-zero only between $\Delta F = \pm 1, \Delta m_F = 0$.

$$\langle F-1, m_F |H|, F, m_F \rangle = -\frac{\mu_B}{2}(g_J - g_I) B_z \left(\frac{\left[(J+I+1)^2 - F^2 \right]\left[F^2 - (J-I)^2 \right]}{F} \right)^{1/2} \cdot$$

$$\cdot \left(\frac{F^2 - m_F^2}{F(2F+1)(2F-1)} \right)^{1/2} \quad (2)$$

We use the eigenvalues to calculate the energy levels of the excited and the ground states and the state vectors are expressed in terms of the unperturbed atomic state vectors

$$\left| \psi(F_e, m_e) \right\rangle = \sum_{F'_e} C_{F_e F'_e} \left| F'_e, m_e \right\rangle \quad (3)$$

and

$$\left| \psi(F_g, m_g) \right\rangle = \sum_{F'_g} C_{F_g F'_g} \left| F'_g, m_g \right\rangle \quad (4)$$

where the sums are only over the state vectors having the same m_F since the perturbation introduced by the magnetic field couples only sublevels with $\Delta m_F = 0$.

The energy shifts calculated by Eqs. (1-4) are presented in Figure 2. As we see, starting from relatively not strong magnetic fields (compared to Rb [5-7] and Cs [8, 11]), at around 300 G and 400 G for D_1 and D_2 lines, respectively, this dependence becomes linear. The mentioned difference (300 G and 400 G) is caused by the presence of electric quadrupole constant (B_{hfs}) in $P_{3/2}$ states, which is absent for $J = 1/2$ states. Note, that the calculations show that this linearity goes up to 250 kG, however, this is not presented here in order to have a better view on the transition shifts behavior. The dashed lines in the figures represent the transitions, whose probabilities tend to zero and they are not visible in the experiments under strong magnetic fields. The solid lines are those transitions whose probabilities are not negligible and they can be seen in the experiments. As mentioned above, the definition of the numbers with the corresponding transitions in the F, m_F basis is shown for D_1 and D_2 lines in Table 1 and Table 2, respectively. It is worth to mention, that in our previous experiment performed using nanocells [11], one can determine the 41K transitions in the atomic absorption spectrum [9], which, however, are much weaker compared to the ^{39}K atomic transitions, as the density of the former is much smaller than that of ^{39}K.

The intensities of the transitions are calculated and presented in Figure 3. As it is well seen for the D_1 (the left figure) and D_2 (the right figure) lines the transitions that were strong in the presence of the weak magnetic field ($B < 80$

G for D_1 line and $B < 10$ G for D_2 line, i.e. dashed lines), become negligibly small at $B > 300$ G and $B > 400$ G, respectively, therefore they are no more visible in the experiments, while IFFA as well as less probable transitions become dominant.

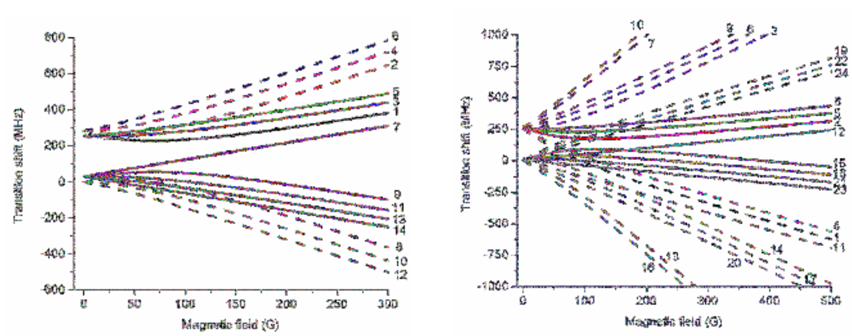

Fig. 2. Magnetic field dependence of the energy shifts of the ^{41}K isotope D_1 (left) and D_2 (right) lines. The solid lines describe the transitions which exist in HPB regime, while dashed lines describe transitions whose probabilities tend to zero in HPB regime. The zeros are *F=2*, m_F*=-1 to* $F'=1$, $m_{F'}$*=-1*.

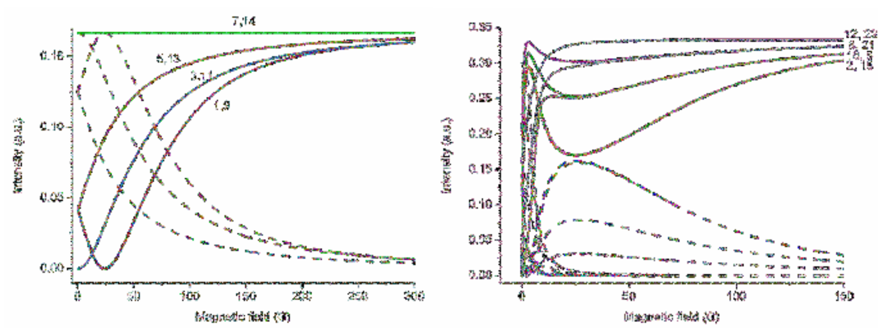

Fig. 3. Transition intensities dependence on magnetic field for D_1 (left) and D_2 (right) transitions of ^{41}K isotope.

The reason for having only 8 transitions for D_1 and 8 transitions for D_2 lines for π polarized laser field is that in rather strong ($B \gg B_0$) external magnetic fields F is no longer a “good” quantum number. The “good” quantum numbers become I and J (with their projections). GT appears because of the atomic states coupling (in an external magnetic field). Only the states which satisfy $\Delta F = \pm 1, \Delta m_F = 0$ selection rules are coupled. Coupling is the superposition of the quantum states. Since the quantization axis is the external magnetic field, only $\Delta m_F = 0$ states can be coupled (as was mentioned above). Not to have the same states ΔF should be ± 1 and not zero (Table 3). The GTs exist exceptionally between two uncoupled states. Hence, for ^{41}K and for π $(B \| E)$ polarization radiant field GTs are $S_{1/2}(F=2, m_F=-2) \rightarrow$ $\rightarrow P_{1/2}(F'=2, m_{F'}=-2)$ and $S_{1/2}(F=2, m_F=+2) \rightarrow P_{1/2}(F'=2, m_{F'}=+2)$ transitions.

Table 3
Atomic states. UC-uncoupled states, C-coupled states

$m_F \rightarrow$	-2	-1	0	+1	+2
$S_{1/2}$ states					
$F=2$	**UC**	C	C	C	**UC**
$F=1$		C	C	C	
$P_{1/2}$ states					
$F=2$	**UC**	C	C	C	**UC**
$F=1$		C	C	C	

$m_F \rightarrow$	-3	-2	-1	0	+1	+2	+3
$P_{3/2}$ states							
$F=3$	**UC**	C	C	C	C	C	**UC**
$F=2$		C	C	C	C	C	
$F=1$			C	C	C		
$F=0$				C			

As a last step, we have calculated the spectra of ^{41}K D_1 and D_2 lines for $B = 0G, B = 200G$, $B = 400G$ and $B = 0G, B = 250G$, $B = 500G$ magnetic fields, respectively.

The components coming from $F_g = 1$ are in black and the components coming from $F_g = 2$ are in blue. The components' full width at half maximum is $w_{FWHM} = 50$ MHz. The cumulative curves for different increasing magnetic fields are respectively in cyan, red and yellow. We claim that it is exactly what will be seen while performing experiments with the ^{41}K isotope. Particularly, using the nano-cell with the thickness L= λ/2 (λ = 770 nm) and filled with the ^{41}K, in the way as it was experimentally realized for the ^{39}K atoms [9].

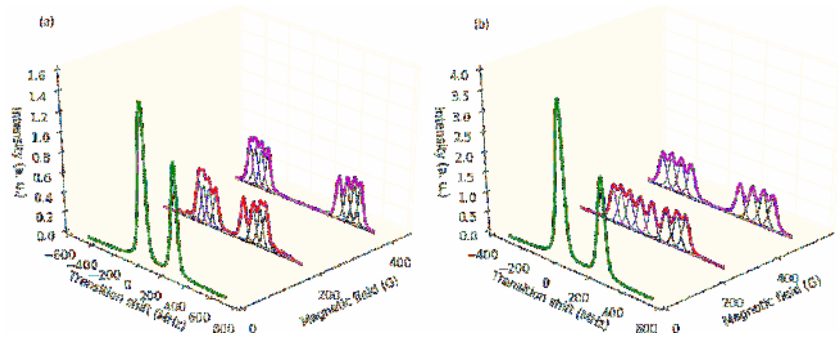

Fig. 4. Spectra of ^{41}K (a) D_1 line; (b) D_2 line for $B = 0G, B = 200G$ and $B = 400G$ magnetic fields. The zeros are F=2, m_F=-1 to F'=1, m_F=-1.

Conclusion. We have theoretically studied the behavior of ^{41}K D_1 and D_2 lines for π polarized resonant light in the presence of strong magnetic field. We have shown that for this case in D_1 line there are two guiding transitions that maintain their probabilities and frequency slopes. Particularly, we explain the reason of GT existence, we observe reduction of Zeeman transitions and difference of two D lines behavior in HPB regime. Finally, we present the theoretical 3D spectra for D lines for different magnetic fields. It should be noted that a complete HPB regime for relatively low magnetic fields *B*~ 400 G has been demonstrated, while this value of magnetic field is the smallest for all alkaline metals.

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Theoretical Investigation of ^{41}K States Behavior under Strong Magnetic Field and π Polarized Laser Field

Theoretically research of the behavior of ^{41}K D_1 and D_2 lines for π polarized resonant light is conducted in the presence of strong magnetic field when the total electronic angular momentum J and nuclear spin I are decoupled. We show that in the case of linear polarization and for D_1 line there are two transitions, so called guiding transitions (GT) that maintain their probabilities and frequency slopes. In Hyperfine Paschen-Back (HPB) regime other transitions are coming together to those GTs, making 2 groups (4 in each). Each transition in the group has the same frequency slope and probability as the GT in their group. It is demonstrated that from 12 (D_1) and 20 (D_2) initially allowed Zeeman transitions (taking into account the selection rules) at low B-

field, only 8 transitions in each D line remain in absorption spectra at $B > 200G$. A complete HPB regime for relatively low magnetic fields $B \sim 200G$ has been observed. This value is the smallest for all alkaline metals.

Ա.Ե. Տոնոյան

^{41}K ատոմի վիճակների վարքի տեսական հետազոտությունը ուժեղ մագնիսական և π բևեռացմամբ լազերային դաշտում

Տեսականորեն ուսումնասիրվել է ^{41}K D_1 և D_2 գծերի վարքը π բևեռացված ռեզոնանսային դաշտում՝ ուժեղ մագնիսական դաշտի առկայությամբ, երբ գումարային էլեկտրոնային անկյունային J մոմենտը և միջուկային I սպինը տարանջատված են: Ցույց է տրվել, որ գծային բևեռացված լույսի դեպքում D_1 գծում կան երկու անցումներ, այսպես կոչված ուղեկցող անցումներ (ՈՒԱ), որոնք մագնիսական դաշտում պահպանում են իրենց հավանականություններն ու հաճախային շեղման թեքությունները: Գերնուրբ Պաշեն-Բակի ռեժիմում (ԳՊԲ) մյուս անցումները միավորվում են այդ ՈՒԱների շուրջ՝ առաջացնելով չորսական անցումներով երկու խումբ: Յուրաքանչյուր խմբի ամեն անցում ձգտում է իր խմբի ՈՒԱի հաճախային շեղման թեքությանն ու հավանականությանը: Ցույց է տրվել, որ թույլ մագնիսական դաշտերում ջոկման կանոններով պայմանավորված ի սկզբանե թույլատրված 12 (D_1) և 20 (D_2) Զեեմանյան անցումներից, կլանման սպեկտրում, 200 Գ դաշտում, յուրաքանչյուր D գծում մնում են 8 անցումներ: Դիտվել է կատարյալ ԳՊԲ երևույթ, հարաբերական թույլ՝ 400 Գ, արտաքին դաշտում: Դաշտի այս արժեքը ամենափոքրն է բոլոր ալկալի մետաղների համար:

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Теоретическое исследование поведения ^{41}K атомов в π-поляризованном лазерном излучении в присутствии сильного магнитного поля

Проведено теоретическое исследование поведения атомов ^{41}K для D_1 и D_2 линий в случае π-поляризованного лазерного излучения в присутствии сильного магнитного поля, в случае, когда происходит разрыв связи между полным угловым моментом электрона J и магнитным моментом ядра I. Показано, что для D_1 линии и линейно-поляризованного излучения имеются направляющие атомные переходы (НП), которые сохраняют вероятности и величины производных частотных сдвигов по магнитному полю. В режиме Пашена – Бака на сверхтонкой структуре (ПБС) другие атомные переходы группируются с этими НП, образуя 2 группы (по 4 перехода в каждой). Каждый переход в группе имеет такую же вероятность и частотный наклон, как НП в своей группе. Показано, что из 12 (для D_1) и 20 (для D_2) разрешенных по правилам отбора для слабых магнитных полей, при B>200 Гс остаются только по 8 атомных переходов. Полный режим ПБС наблюдается для сравнитеьлно малых магнитных полей B~400 Гс. Эта величина наименьшая для всех щелочных металлов.

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