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# ATOMIC CASCADE IN KAONIC HYDROGEN AND DEUTERIUM

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Abstract

The atomic cascade in kaonic hydrogen and deuterium has been studied in the extended standard cascade model. We discuss predictions of $K$ x–ray yields in relation to experimental data and the prospects for future experiments.

## 1 Introduction

Kaonic hydrogen and deuterium are initially formed in highly excited states. The formation is followed by the so–called atomic cascade where the exotic atoms deexcite to lower levels through various processes (radiative, Stark, Auger, and Coulomb transitions) until nuclear absorption or kaon decay takes place. The atomic cascade in kaonic hydrogen and deuterium was studied in refs. [1, 2]. In the present work, the $K$ x–ray yields has been calculated in the extended standard cascade model [3, 4] which is based on improved results for the collisional processes.

The predictions for the x–ray yields depend on the three (poorly known) strong interaction parameters: the $1s$ shift ($\Delta E_{1s}^{\mathrm{had}}$), the $1s$ width ($\Gamma_{1s}^{\mathrm{had}}$), and the $2p$ width ($\Gamma_{2p}^{\mathrm{had}}$).

## 2 Kaonic hydrogen

We have chosen the strong interaction parameters

$$\Delta E_{1s}^{\mathrm{had}} = 193\ \mathrm{eV\ (repulsive)}, \quad \Gamma_{\mathrm{1s}}^{\mathrm{had}} = 249\ \mathrm{eV}, \quad \Gamma_{\mathrm{2p}}^{\mathrm{had}} = 0.3\ \mathrm{meV} \qquad (1)$$

for the cascade calculations. For $\Delta E_{1s}^{\mathrm{had}}$ and $\Gamma_{1s}^{\mathrm{had}}$ this corresponds to the central values obtained recently by the DEAR Collaboration [5]. The value for the $2p$ width was chosen for the best agreement with the measured yields [6].

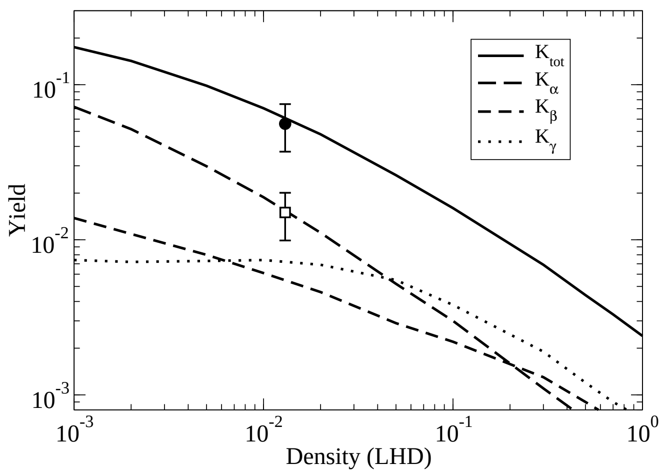


Figure 1: *The density dependence of the K x–ray yields in kaonic hydrogen. The experimental data for the $K_{\mathrm{tot}}$ and $K_\alpha$ yields are from ref.* [6].

Figure 1 shows the density dependence of the x–ray yields. The yields decrease strongly with the density as Stark transitions feed the $s$ and $p$ states, from which nuclear absorption takes place, faster.

The experimental data on x–ray yields suggest a $2p$ strong interaction width in the range $0.0 - 0.6$ meV. Besides the x–ray yields from KEK [6] at 0.013 LHD (liquid hydrogen density) shown in fig. 1, the DEAR Collaboration has presented preliminary results at 0.031 LHD [7]: $K_\alpha = 1 - 3\%$ and $K_\alpha \sim K_\beta \sim K_{>\gamma} > K_\gamma$. Table 1 and 2 shows the predicted $K$ yields for $\Gamma_{2p}^{\rm had} = 0.0$, 0.3, 0.6 meV.

Table 1: *The predicted K x–ray yields (%) in kaonic hydrogen at 0.013 LHD for different values of the* $2p$ *strong interaction width.*

| $\Gamma_{2p}^{\rm had}$ | $K_\alpha$ | $K_\beta$ | $K_\gamma$ | $K_{>\gamma}$ |
|---|---|---|---|---|
| 0.0 meV | 4.19 | 1.41 | 1.47 | 4.81 |
| 0.3 meV | 1.61 | 0.59 | 0.69 | 3.64 |
| 0.6 meV | 0.94 | 0.35 | 0.42 | 2.94 |

Table 2: *The predicted K x–ray yields (%) in kaonic hydrogen at 0.031 LHD for different values of the* $2p$ *strong interaction width.*

| $\Gamma_{2p}^{\rm had}$ | $K_\alpha$ | $K_\beta$ | $K_\gamma$ | $K_{>\gamma}$ |
|---|---|---|---|---|
| 0.0 meV | 2.11 | 0.89 | 1.19 | 2.67 |
| 0.3 meV | 0.81 | 0.36 | 0.66 | 2.10 |
| 0.6 meV | 0.50 | 0.22 | 0.45 | 1.87 |

It would be interesting if the relatively high $K_\beta$ yield observed by the DEAR Collaboration could be confirmed in future experiments because it could indicate that there is a large thermalized fraction of kaonic hydrogen atoms at $n = 3$. The reason is that the $3p - 3d$ energy difference of 0.18 eV makes Stark transitions irreversible at low energies as only $3d \to 3p$ is allowed energetically. This leads to an overpopulation of the $3p$ state and an increased $K_\beta$ yield. A similar phenomenon is observed in pionic helium [8].

## 3 Kaonic deuterium

The SIDDHARTA Collaboration plans to measure the $1s$ strong interaction width in kaonic deuterium for the first time [9]. The feasibility of this experiment depends on the x–ray yields being high enough: a $K$ yield of 1% or more at 20 bar would be encouraging [10]. Cascade model predictions of the absolute x–ray yields are, therefore, important.

Though the strong interaction parameters have not been measured, predictions based on model estimates and phenomenological fits are possible. We will use the values

$$\Delta E_{1s} = 0.5 \text{ keV}, \quad \Gamma_{1s}^{\text{had}} = 1 \text{ keV}, \quad \Gamma_{2p}^{\text{had}} = 1 \text{ meV} \tag{2}$$

as a standard. The $1s$ parameters are based on a study of low–energy $(N\bar{K}, \Lambda\pi)$ and $(N\bar{K}, \Sigma\pi)$ data [11]. Predictions of the $2p$ width vary considerably: from 0.014 meV [11] to 25 meV [1]. Figure 2 shows the density dependence of the x–ray yields in kaonic deuterium. Compared to the yields in kaonic hydrogen they are lower but qualitatively similar.

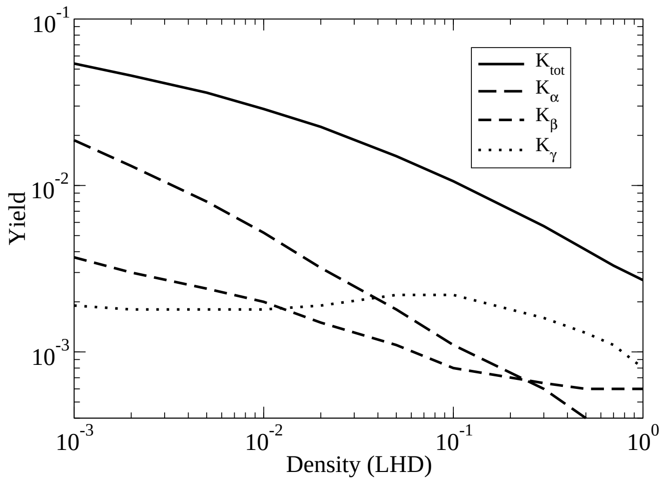


Figure 2: *The density dependence of the K x–ray yields in kaonic deuterium.*

Table 3, 4, and 5 show the dependence of the $K_{\text{tot}}$ and $K_{\alpha}$ yields at 0.026 LHD on each of the three strong interaction parameters. The $2p$ width is the most important for the proposed measurement of the $1s$ strong interaction shift and width because it could reduce the $K_{\alpha}$ yield far below 1%. A possible scenario is that the $K_{\alpha}$ line is too weak for a precise determination of $\Delta E_{1s}^{\text{had}}$ and $\Gamma_{1s}^{\text{had}}$ and that high statistics is obtained only for the $K$–complex (consisting of the overlapping lines of the higher transitions). In this case reliable cascade model predictions of the relative yields are crucial for the analysis of the spectrum.

Table 3: *The predicted* $K_{\text{tot}}$ *and* $K_\alpha$ *x–ray yields (%) in kaonic deuterium at 0.026 LHD for different values of the* $1s$ *shift (in keV).*

| | $\Delta E_{1s}$ | | | | |
|---|---|---|---|---|---|
| | 0.1 | 0.2 | 0.5 | 1.0 | 1.5 |
| $K_{\text{tot}}$ | 1.61 | 1.66 | 2.00 | 2.91 | 3.70 |
| $K_\alpha$ | 0.23 | 0.23 | 0.26 | 0.41 | 0.52 |

Table 4: *The predicted* $K_{\text{tot}}$ *and* $K_\alpha$ *x–ray yields (%) in kaonic deuterium at 0.026 LHD for different values of the* $1s$ *strong interaction width (in keV).*

| | $\Gamma_{1s}^{\text{had}}$ | | | | | |
|---|---|---|---|---|---|---|
| | 0.1 | 0.2 | 0.5 | 1.0 | 1.5 | 2.0 |
| $K_{\text{tot}}$ | 4.51 | 3.51 | 2.40 | 2.00 | 1.98 | 2.04 |
| $K_\alpha$ | 0.63 | 0.48 | 0.34 | 0.26 | 0.27 | 0.28 |

Table 5: *The predicted* $K_{\text{tot}}$ *and* $K_\alpha$ *x–ray yields (%) in kaonic deuterium at 0.026 LHD for different values of the* $2p$ *strong interaction width (in meV).*

| | $\Gamma_{2p}^{\text{had}}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.0 | 0.2 | 0.5 | 1.0 | 2.0 | 5.0 | 10.0 |
| $K_{\text{tot}}$ | 6.05 | 3.95 | 2.76 | 2.00 | 1.28 | 0.69 | 0.45 |
| $K_\alpha$ | 1.91 | 0.98 | 0.50 | 0.26 | 0.12 | 0.04 | 0.02 |
| $K_\alpha/K_{\text{tot}}$ | 0.315 | 0.248 | 0.182 | 0.132 | 0.095 | 0.056 | 0.041 |

## 4 Conclusion

The x–ray yields in kaonic hydrogen and deuterium have been calculated in the extended standard cascade model. The predicted $K$ yields depend strongly on the (poorly known) $2p$ strong interaction widths so measurements of x–ray spectra can be used to determine them.

A comparison of cascade model predictions in kaonic hydrogen with existing data from KEK [6] and preliminary data from the DEAR Collaboration [7] restricts the $2p$ strong interaction width to the range $0.0 - 0.6$ meV.

For the proposed x–ray measurement by the SIDDHARTA Collaboration in kaonic deuterium, the poor knowledge of the strong interaction parameters makes three scenarios possible: (1) the $K_\alpha$ yield is high enough for a determination of the $1s$ shift and width. (2) The $K_\alpha$ yield is too low but the $K$–complex can be used in combination with reliable cascade model predictions. (3) If $\Gamma_{2p}^{\rm had} \gg 1$ meV the proposed experiment may not be feasible because the total $K$ yield is too small.

## 5 Acknowledgments

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