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ATOMIC BEAM MEASUREMENT OF THE POTASSIUM 39-41-42 ISOTOPE SHIFT*

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December 1969

The isotope shifts of ^{41}K and 12.4 hour ^{42}K relative to ^{39}K were studied in the D_1 line ($4^2P_{1/2} \xrightarrow{7699\ \text{Å}} 4^2S_{1/2}$) by the atomic beam method and found to be + 7.4 ± 0.3 and + 16 ± 4 respectively, in units of $10^{-3}cm^{-1}$.

INTRODUCTION

The isotope shifts of ^{41}K and 12.4 hour ^{42}K relative to ^{39}K were studied in the D_1 line (7699 Å). An important preliminary to this experiment, the measurement of the Stark shift in the D_1 line of ^{39}K was reported previously.[1] The measurements were made by the atomic beam method in which electric fields are used to tune the hyperfine absorption lines of beam atoms (^{41}K or ^{42}K) into coincidence with the emission lines of the lamp (^{39}K). The resulting resonance absorption leads to a spin-flip which alters the trajectories of beam atoms causing them to focus at the detector. The relevent energy level diagrams and the possible overlaps or coincidence for the ^{39}K - ^{41}K and ^{39}K - ^{42}K systems are shown in Fig. 1. The atomic beam apparatus was tuned to pass only atoms with $m_J = -1/2$ for ^{41}K and $m_J = +1/2$ for ^{42}K ($\mu_I < 0$) so that most of the beam atoms are in the lower hyperfine state and we neglect the upper hyperfine state for simplicity.

EXPERIMENT

A schematic of the apparatus is shown in Fig. 2. A similar experimental arrangement was previously used to study isotope shifts in cesium and rubidium.[2,3] The dense beam of potassium which is interposed between the lamp and C-region acts as a hyperfine filter, removing the hyperfine components of the lamp line. Thus the light emerging from the absorption beam has a spectral distribution showing intensity minima at the centers of the hyperfine lines. The width of the intensity minima is determined by the collimation of the absorption beam and was about 200 MHz in the present experiment. The use of a hyperfine filter is crucial since the isotope shift is determined from the Stark shift and the latter is calibrated on the ground state hyperfine structure ($\Delta\nu_{hf}(4^2S_{1/2})$ = 462 MHz) which must be present in the exciting light. Since the hyperfine structure is not resolved in the ^{39}K lamp line a hyperfine filter is essential. Figure 3 shows graphically the signal formed when the absorption lines of ^{41}K are scanned by an electric field across a ^{39}K lamp line.[4]

POTASSIUM 39-41

Figure 4(a) shows the result of Stark scanning the $^{39}K(99.97\%)$ lamp line with a $^{39}K(99.97\%)$ atomic beam when an absorption beam of naturally occuring potassium is used. Such data is used to calibrate the Stark shift in terms of the applied voltages. In Fig. 4(b) are shown the results of Stark scanning the ^{39}K lamp line with a $^{41}K(99.18\%)$ atomic beam, with and without the potassium absorption beam. The sharp dip near zero electric field in the case of no absorption, Fig. 4(b), is due to the fact that the transition frequency of ^{41}K is higher than ^{39}K (see Figs. 1 and 3). The difference between the position of the intensity minimum in 4(a) and 4(b) determines the isotope shift

after allowance has been made for the different hyperfine splittings of the two isotopes. We find for the $^{41-39}K$ isotope shift 7.4 ± 0.3 mK (1 mk = $10^{-3}cm^{-1}$). This result is in agreement with an earlier spectroscopic measurement by Jackson and Kuhn who found 7.6 ± 0.5 mK for the isotope shift.[5]

POTASSIUM 39-42

^{42}K was produced by the reaction $^{41}K(n,\gamma)^{42}K$. The target sample consisted of one gram KCl encapsulated in quartz under a helium atmosphere (100 mm of Hg). The sample was irradiated for 24 hours at the G.E. Reactor facility at velocities which provide a neutron flux of $\approx 2 \times 10^{14}/cm^2$-sec. In natural abundance potassium consists of $^{41}K(6.88\%)$, $^{39}K(93.1\%)$ and $^{40}K(0.01\%)$. The neutron capture cross-section of ^{39}K in twice as large as that of ^{41}K so that considerably more ^{40}K is formed in the irradiation than ^{42}K; however, the specific activity of ^{40}K is insignificant by comparison with ^{42}K. Approximately 2.5 curies of ^{42}K were produced in each sample. In a typical experimental run 100 - 200 mg of KCl were consumed. The potassium was collected at the detector on a quartz surface for five minutes at each value of the applied voltage. The amount collected (signal) was measured through the β^- activity. Typical results for ^{42}K are shown in Fig. 5. We find for the $^{39-42}K$ isotope shift 16 ± 4 mK.

DISCUSSION AND RESULTS

The $^{39-41}K$ isotope shift is based on 10 measurements of which Fig. 4 is a typical example. The line width in each case is 7 mK and the center of the line can be determined easily to ± 2 mK or better. Systematic effects due to isotopic impurity were investigated by making several measurements with a lamp containing potassium in natural abundance. These measurements yielded a

value for the isotope shift which is 0.2 mK higher and with the same accuracy as measurements made with the enriched ^{39}K lamp though this increase is within the experimental error it is shown in the Appendix that an isotopic impurity of ^{41}K produces a systematic error in the same direction as the isotope shift. We believe that the ^{41}K impurity in the absorption beam is by itself negligible because of the fact that the absorption line due to component b of Fig. 1(b) is well separated from the absorption line due to the unresolved triplet β, a, α. The accuracy of the $^{39\text{-}42}K$ isotope shift was limited by counting statistics.

The measurements are summarized below and compared with the normal mass effect (Bohr)

$$\delta(\Delta E_B) = \frac{\delta A}{1836\ \bar{A}^2}\, E$$

the specific mass effect, $\delta(\Delta E_M)$ (Ref. 6) and the field-effect isotope shift, assuming a uniform charge distribution model for the nucleus,

$$\delta(\Delta E_f) = \frac{2\pi \frac{a_0^3}{Z} |\psi(0)|^2}{\Gamma^2(2\sigma)} R_u^{2\sigma} \left(\frac{a+(1+\sigma)K(a)}{a+(1-\sigma)K(a)}\right) \frac{\delta R_u}{R_u} R_\infty \quad , \quad \text{(Ref. 7)}$$

where A is the mass number, δA the mass difference between a pair of isotopes, $\bar{A}$ the mean mass number for two isotopes, E the energy separation $4^2P_{1/2} - 4^2S_{1/2}$ in cm^{-1}, $\sigma = (1-\alpha^2Z^2)^{1/2}$, $R_u = 2.495 \times 10^{-3} A^{1/3} \left(\frac{a_0}{2Z}\right)$, $a = \alpha Z$, $K(a) = -\frac{2}{5} a(1+0.106\ a^2)$, R_∞ the Rydberg constant, α the fine structure constant, Z the atomic number and Γ the gamma function. $|\psi(0)|^2$ is determined from the hyperfine structure.

Comparison of Measured and Calculated Isotope Shifts

Isotopes	$\delta(\Delta E)_{ex}$	$\delta(\Delta E_B)$	$\delta(\Delta E_M)$	$\delta(\Delta E_f)$	$\delta(\Delta E)_{total}$
^{39}K	0	0	0	0	0
^{41}K	7.4 ± 0.3	8.9	-5.18	-1.2	2.5
^{42}K	16 ± 4	13.0		-1.8	

A considerable discrepancy exists between the measured $^{39-41}K$ isotope shift and calculated $\delta(\Delta E)_{total}$ however because of the great uncertainty in the value of the specific mass effect it is not possible to draw definite conclusions. It is clear that the calculations must be refined in order that meaningful comparison can be made with experiment. The experimental results can be improved considerably if necessary. For the stable isotope it should be possible to achieve an accuracy of ± 0.05 mK by increasing the collimation of the absorption beam and by a careful analysis of the line shape. For the radioactive isotope an improvement of the accuracy by a factor of 5 should be possible merely by improving statistics.

APPENDIX

The ^{41}K impurity shifts the transition frequencies a, b Fig. 1(b) to higher values. If these transitions are scanned with a pure ^{39}K beam the overlaps a - b occurs at a value of V^2 lower than in Fig. 4(a) by some small amount $\delta(V^2)$. Hence the Stark calibration constant $\Delta\nu_{hf}/V^2_{a-b}$ will be increased to

$$\frac{\Delta\nu_{hf}}{V^2_{a-b} - \delta(V^2)} \cong \frac{\Delta\nu_{hf}}{V^2_{a-b}} \left[1 + \frac{\delta(V^2)}{V^2_{a-b}} \right] .$$

On the other hand when a, b are scanned with a pure ^{41}K beam the overlap α - b occurs at a value of V^2 lower than in Fig. 4(b) by the same amount $\delta(V^2)$. Thus the Stark shift that must be induced in α in order to overlap b is

$$\frac{\Delta\nu_{hf}}{V^2_{a-b} - \delta(V^2)} \times \left(V^2_{\alpha-b} - \delta(V^2)\right) \cong \Delta\nu_{hf} \frac{V^2_{\alpha-b}}{V^2_{a-b}}$$

$$+ \Delta\nu_{hf} \left(\frac{V^2_{\alpha-b}}{V^2_{a-b}} - 1 \right) \frac{\delta(V^2)}{V^2_{a-b}} .$$

The second term on the right of the last expression would appear as an additional "isotope shift" and since $V^2_{\alpha-b} > V^2_{a-b}$ it would add to the real isotope shift.

FOOTNOTES AND REFERENCES

*Work performed under the auspices of the U.S. Atomic Energy Commission.

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2. Richard Marrus, Edmond C. Wang, and Joseph Yellin, Phys. Rev. 177, 122 (1969).

3. T. H. Duong, R. Marrus, and J. Yellin, Phys. Letters 27B, 565 (1968).

4. An electrodless discharge lmap made of Corning 1720 glass was used.

5. D. A. Jackson and H. Kuhn, Proc. Roy. Soc. A165, 303 (1938).

6. J. Bauche, private communication. This value was obtained by a non-relativistic Hartree-Fock calculation.

7. A. R. Bodmer, Nucl. Phys. 9, 371 (1958/59).

FIGURE CAPTIONS

Fig. 1(a). Possible resonances for the ^{39}K - ^{41}K and ^{39}K - ^{42}K systems.

Fig. 1(b). Hyperfine structure of the 7699 Å line of ^{39}K, ^{41}K, and ^{42}K. The numbers are in MHz and the theoretical intensities are shown on the side of each component.

Fig. 2. Schematic of the experiment to measure the potassium isotope shifts.

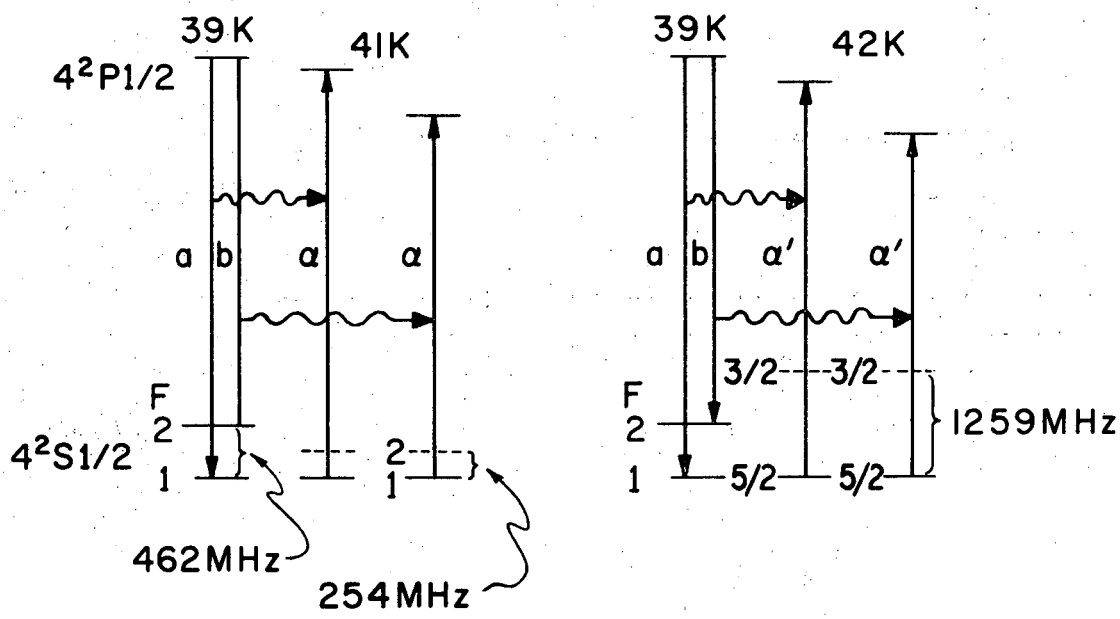
Fig. 3. Graphical representation of how a signal is formed when a ^{41}K beam scans a ^{39}K lamp.

Fig. 4(a). Signal observed when a ^{39}K lamp filtered by a potassium absorption beam is scanned by a ^{39}K atomic beam. The D_2 line is removed by an interference filter.

Fig. 4(b). Signal observed when a ^{39}K lamp is scanned by a ^{41}K atomic beam. The D_2 line is removed by an interference filter.

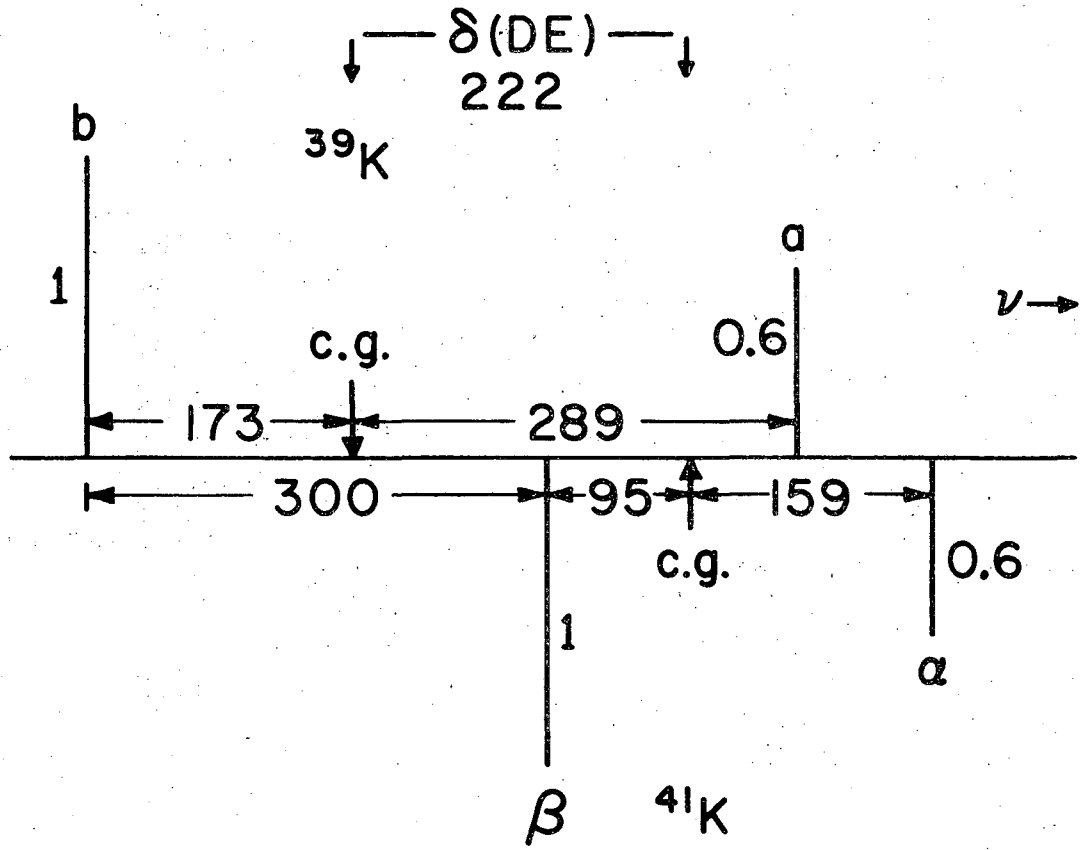
Fig. 4(c). Signal observed when a ^{39}K lamp filtered by a potassium absorption beam is scanned by a ^{41}K atomic beam. The D_2 line is removed by an interference filger.

Fig. 5. Signal observed when a ^{39}K lamp filtered by a potassium absorption beam is scanned by a ^{42}K atomic beam.



XBL 6912-6360

Fig. 1(a)



XBL 6912-6361

Fig. 1(b) (first part)

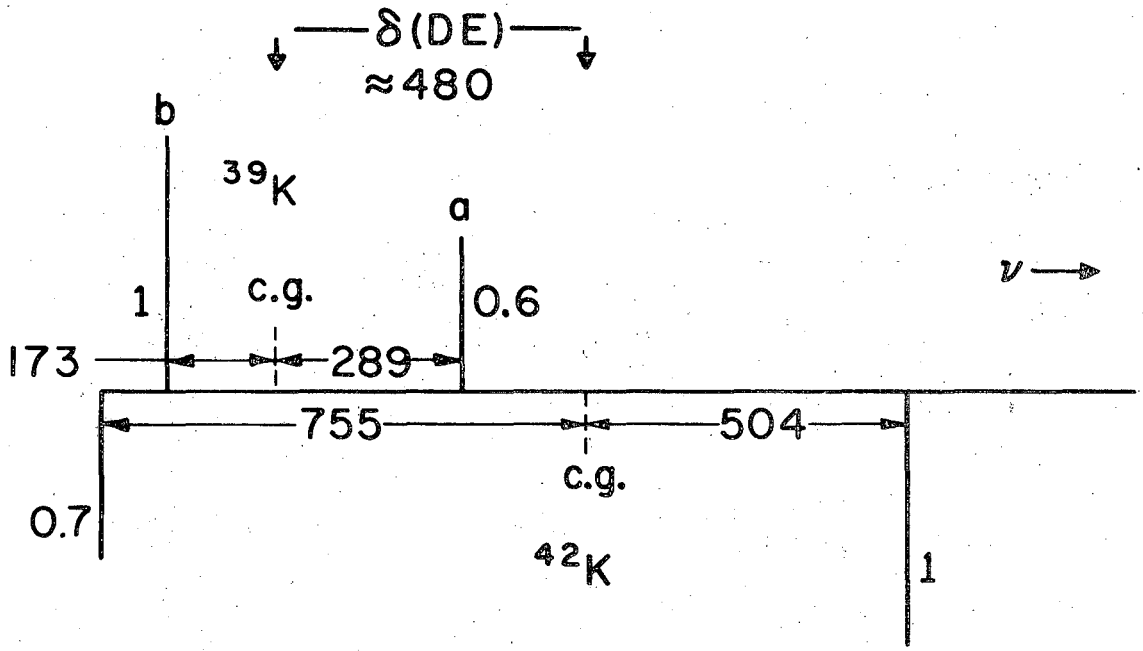


Fig. 1(b) (second part)

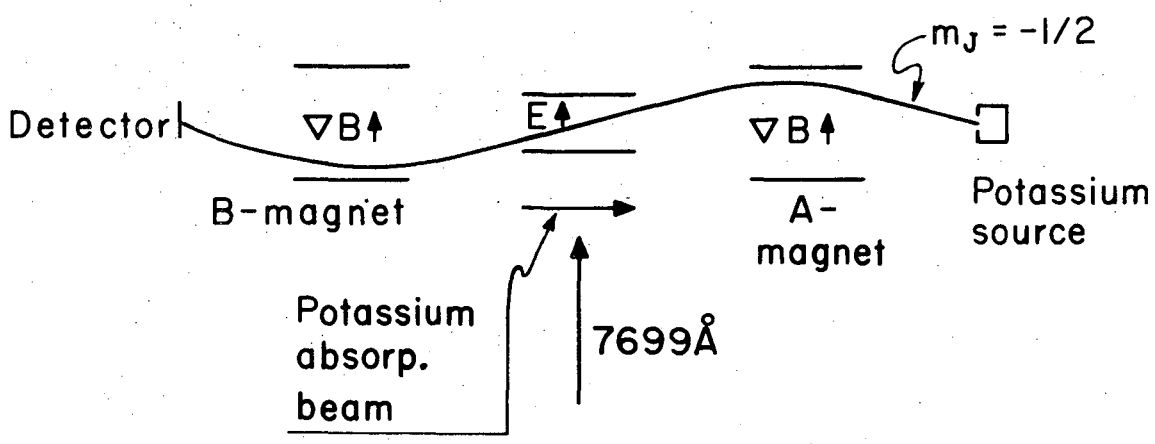
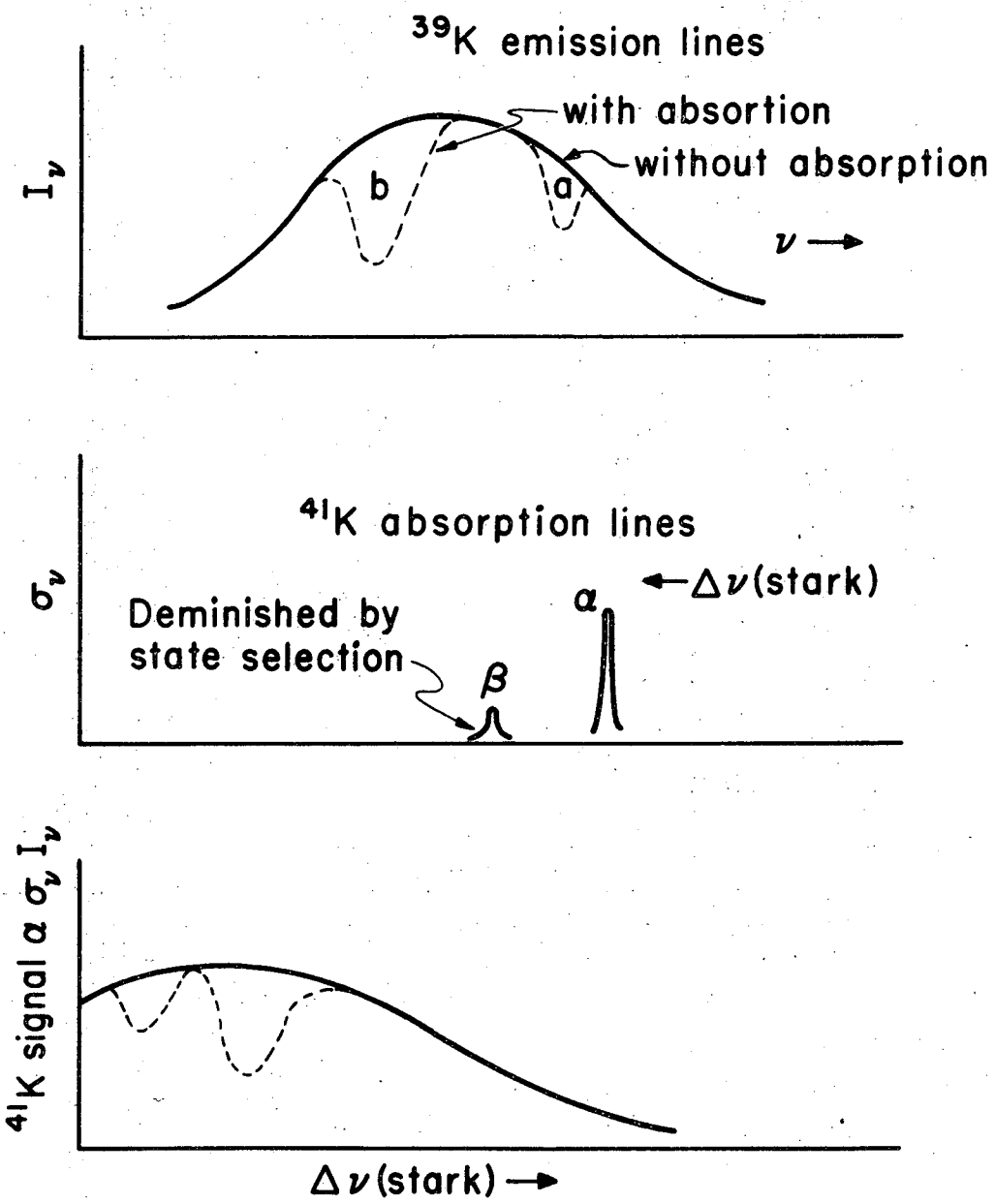

$m_J = -1/2$
Detector
∇B
E
∇B
B-magnet
A-magnet
Potassium source
Potassium absorp. beam
7699Å
XBL6912-6363

Fig. 2



XBL6912-6364

Fig. 3

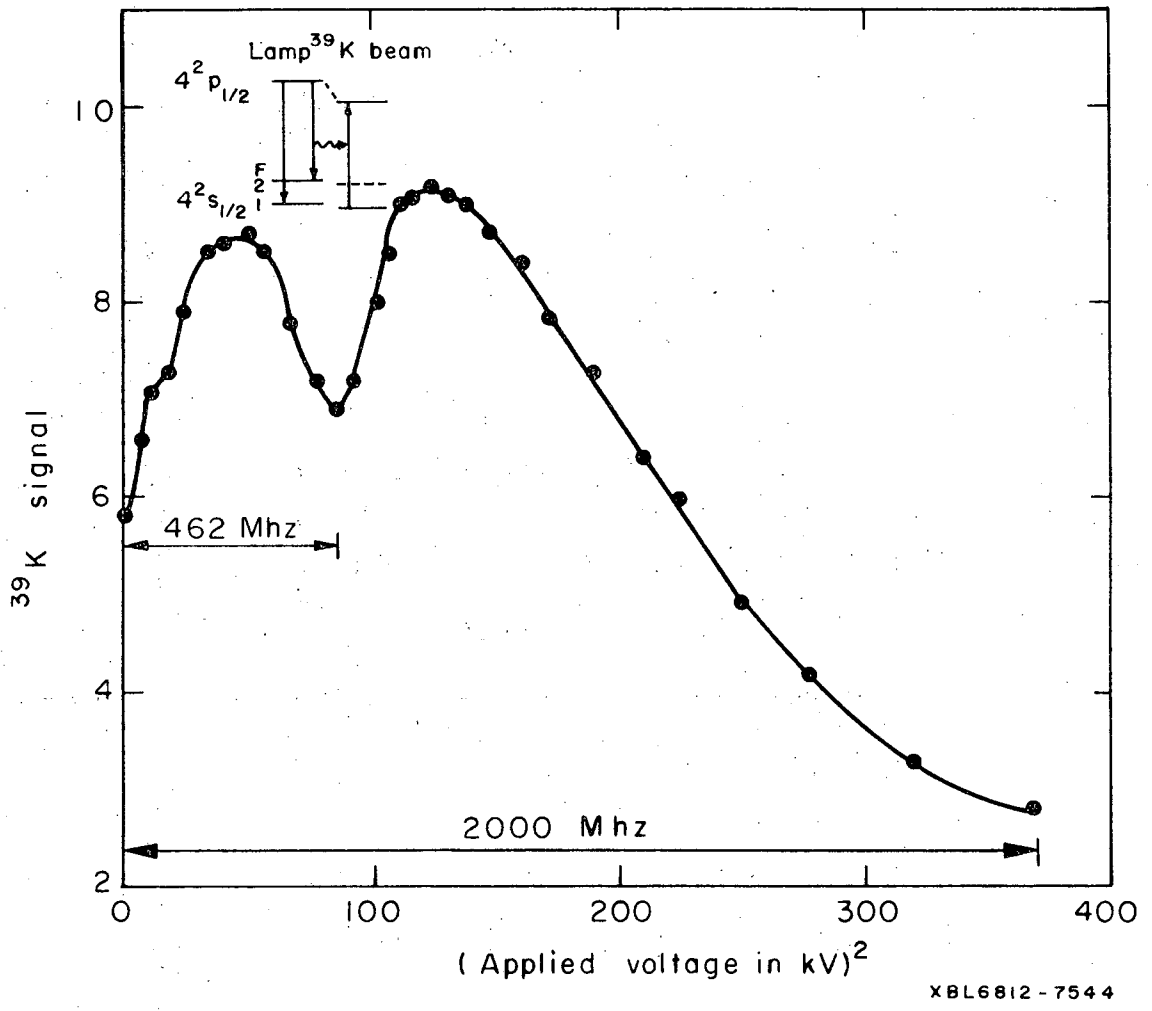
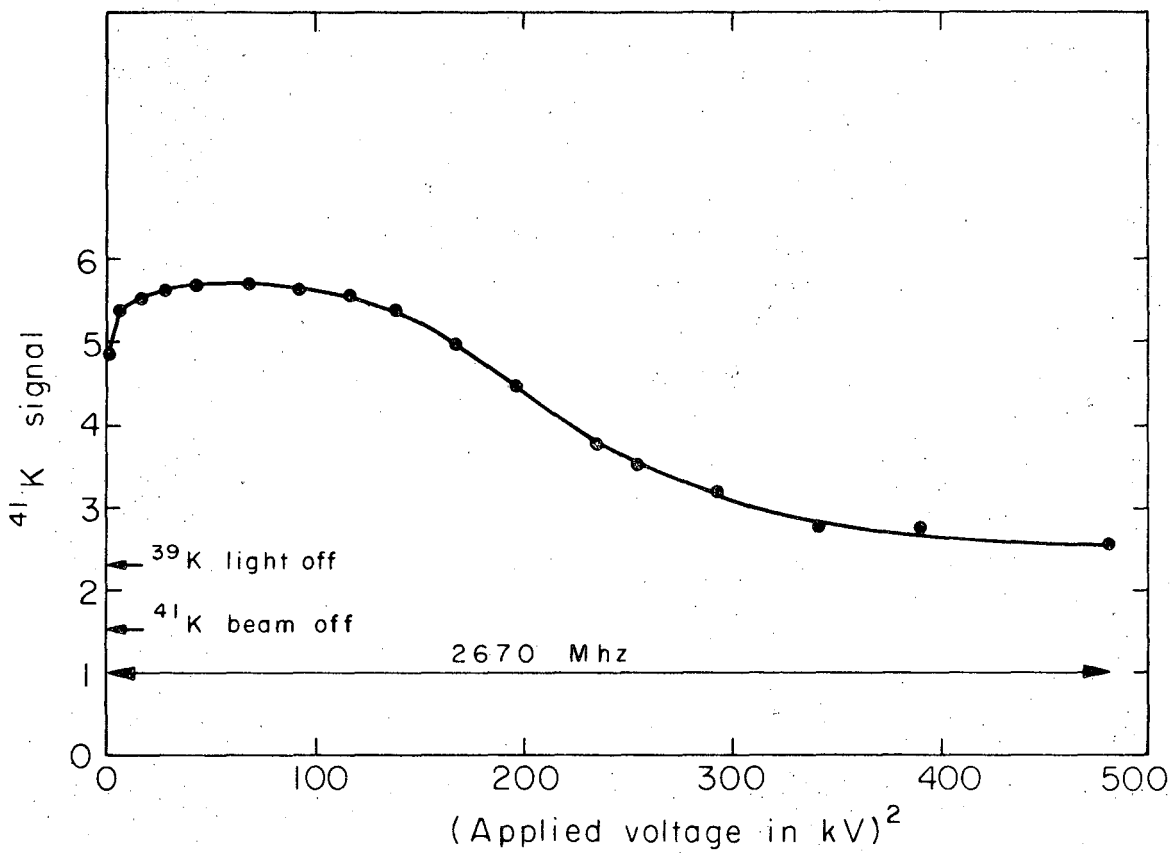
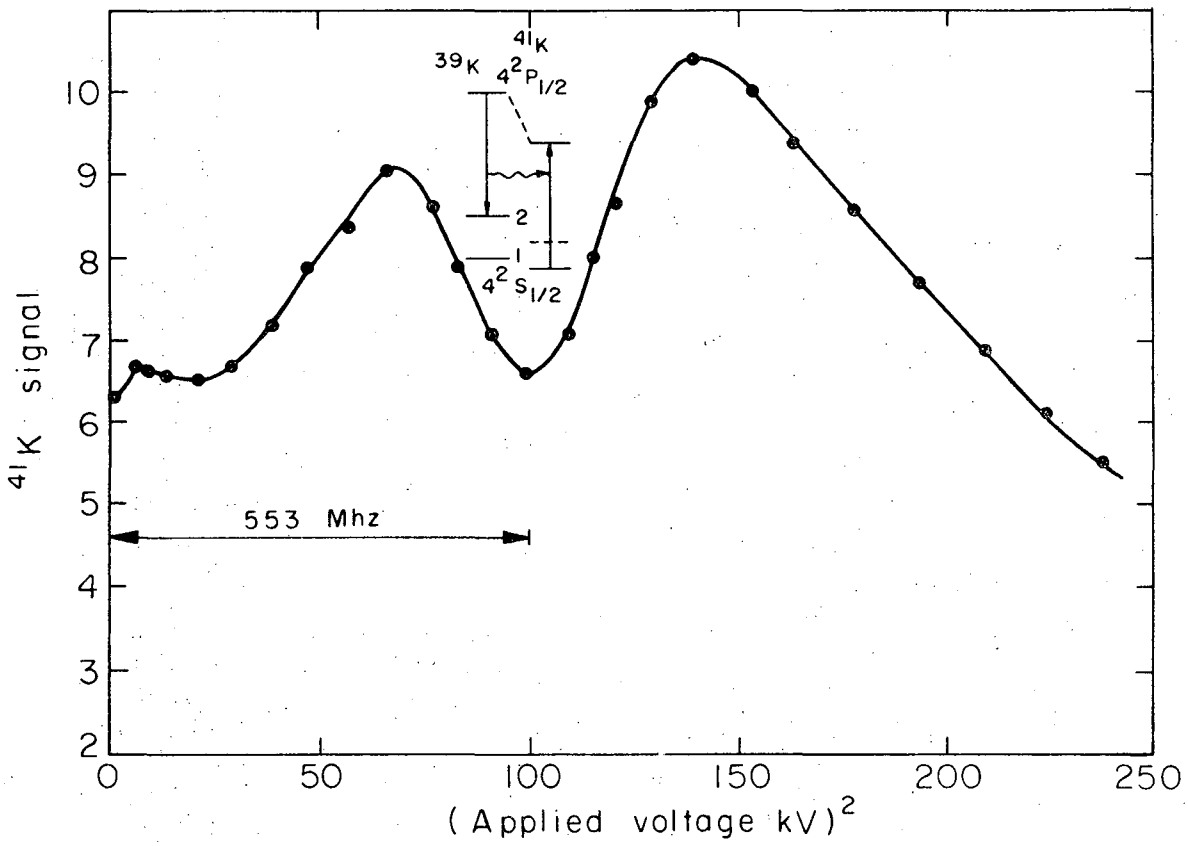

Lamp ^{39}K beam
$4^2P_{1/2}$
F
2
1
$4^2S_{1/2}$
462 Mhz
2000 Mhz
^{39}K signal
(Applied voltage in kV)^2
0
100
200
300
400
2
4
6
8
10
XBL6812-7544

Fig. 4(a)



XBL6812-7546

Fig. 4(c)



XBL 6812-7545

Fig. 4(b)

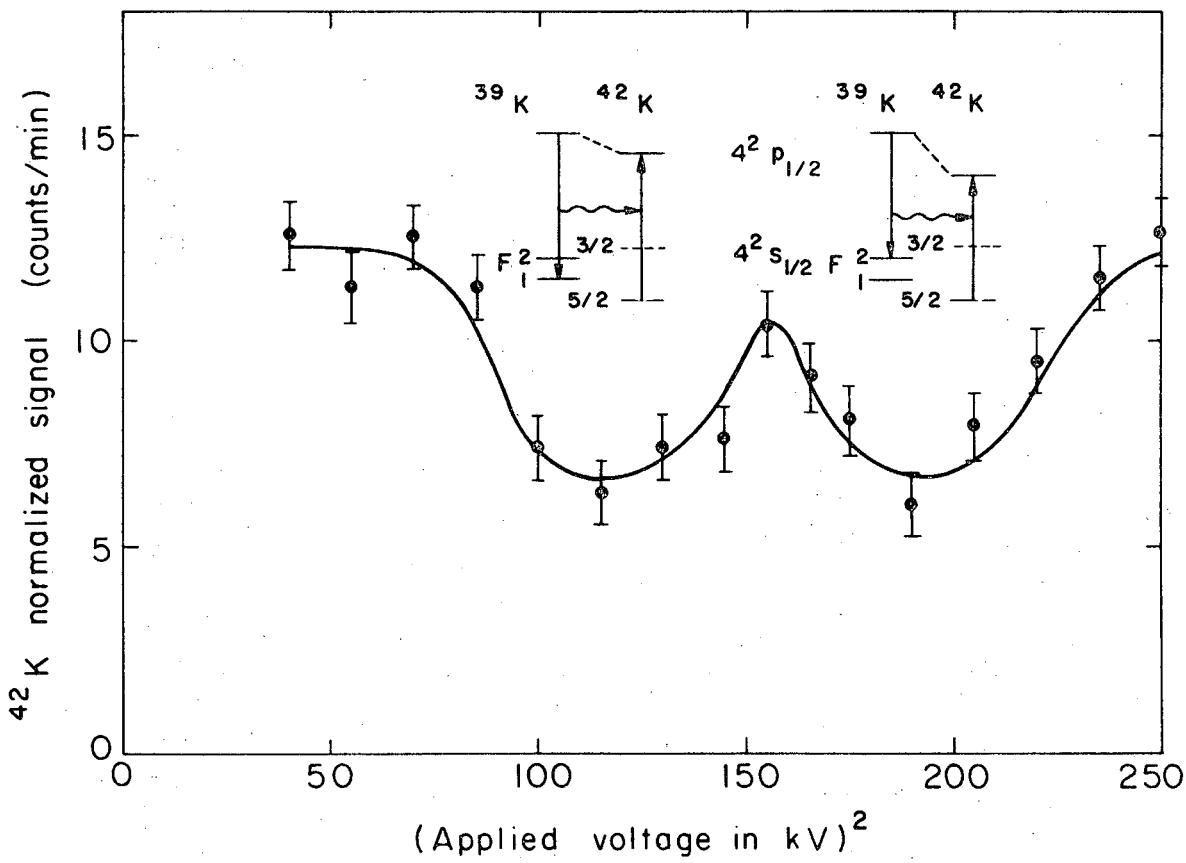

^{42}K normalized signal (counts/min)
15
10
5
0
0
50
100
150
200
250
(Applied voltage in kV)^2
^{39}K
^{42}K
$4^2P_{1/2}$
$4^2S_{1/2}$
F
2
1
3/2
5/2
^{39}K
^{42}K
F
2
1
3/2
5/2
XBL6812-7548

Fig. 5

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