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Neutron Resonance Spectroscopy. XIV. Potassium*

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Results are presented of high-resolution transmission measurements using pure natural K metal samples. The measured total σ vs E to 400 keV is given, and resonance parameter evaluations are given for 65 resonances below 200 keV. The isosopte assignments, $A = 39$ or 41, are mainly based on recent unpublished measurements of Good and Harvey at the Oak Ridge electron linear accelerator using separated K isotope samples. Values of level strengths, $ag\Gamma_n$, are mainly based on transmission dip area analysis, which with evidence from the resonance shape and peak cross sections permits assignment of l and J for most resonances, and A for many of the resonances not identified in the separated isotope measurements. We obtain for the s and p strength functions: $10^4 S_0 = (0.66^{+0.63}_{-0.30})$, $(0.78^{+1.03}_{-0.41})$, and $10^4 S_1 = (1.8^{+0.7}_{-0.5})$ and $(2.4^{+1.3}_{-0.8})$ for ^{39}K and ^{41}K, respectively.

I. INTRODUCTION

This paper reports the results of high-resolution time-of-flight (t.o.f.) neutron spectroscopy measurements of the total neutron cross section and resonance level parameters for natural potassium. The resonance parameter analysis extends to 200 keV, and the measured σ vs E is shown to 400 keV. It is the fourteenth of a series of papers[1-13] reporting the results of neutron resonance t.o.f. spectroscopy using the Columbia University Nevis synchrocyclotron. The data were obtained in a major cyclotron run using our 202.05-m detector. Preliminary analysis using an R-matrix approach for evaluating the resonance parameters were carried out at State University of New York at Albany by Singh as part of his Ph.D. thesis.[14,15] The data have subsequently been reanalyzed by Singh and others of the authors at Nevis using our more usual type resonance area analysis, which includes Doppler-effect corrections. A particular complication distinguishes this analysis from most of our earlier work on medium or heavy A nuclei for which many levels are present per keV, and analysis is limited to $E \lesssim 20$ keV. Above ~20 keV, where most of the energy region studied for K is located, it is much more difficult to make the necessary energy- and sample-dependent background (B.G.) subtractions (for our 202.05-m flight path detector) needed to obtain meaningful measured cross section (σ) and transmission (T) values vs neutron energy (E). The situation is discussed in more detail in Ref. 13 on sodium, and in Ref. 7.

Natural potassium consists mainly of ^{39}K (93.10%) and ^{41}K (6.88%), both having $I = \frac{3}{2}^+$, with ~0.01% ^{40}K which does not contribute to our measurements. The region $A \sim 40$ is at a minima of the s strength function, S_0, and a maximum of the p strength function, S_1. Of the 65 levels below 200 keV for which we have made resonance parameter assignments, 11 levels are considered to be $l = 0$, while 54 levels are considered to be $l = 1$.

At the time of our measurements, the available neutron spectroscopy information for K was all from pre-1960 studies, mainly those by Good, Neiler, and Gibbons at Oak Ridge National Laboratory[16] and Toller, Patterson, and Newson at Duke,[17] resulting in resonance energy assignments for 11 levels total for ^{39}K and ^{41}K to 110 keV, and total width (Γ) assignments for 5 levels for ^{39}K and 3 levels for ^{41}K. Recent unpublished measurements by Good and Harvey[18] using the Oak Ridge electron linear accelerator (ORELA) facility, with separated K isotopes in KCl samples, give isotope assignments to most resonances below 120 keV.

The assignment of A, l, J values to each resonance is complicated by the fact that one can have $J = 1$ or 2 for $l = 0$, and $J = 0$, 1, 2, or 3 for $l = 1$. This leads to possible (ag) values as shown in Table I, where a is the atomic abundance and $g = (2J+1)/2(2I+1)$ is the spin statistical weight factor. We are not able to make precise statements concerning each of the 12 statistical level populations (definite A, l, J) so our statistical conclusions are mainly for the separate weighted averages of $l = 0$ states and of the $l = 1$ states.

TABLE I. Choices for ag vs J for ^{39}K and ^{41}K in natural K.

^{39}K(93.1%), $I^\pi = (\frac{3}{2})^+$		^{41}K(6.88%), $I^\pi = (\frac{3}{2})^+$	
J	ag	J	ag
3	0.815	3	0.0602
2	0.582	2	0.0430
1	0.349	1	0.0258
0	0.116	0	0.0086

II. EXPERIMENTAL DETAILS

The measurements used our 202.05-m flat detector for transmission measurements. The detector consisted of a slab of ^{10}B viewed by a bank of NaI detectors. The t.o.f. count spectra were developed using an on-line EMR 6130 computer system with appropriate auxilliary circuitry which permitted us to treat 16 000 channels simultaneously with high-input counting rates. This system has been described in more detail previously.[8,10] The detector channel widths were 40 nsec above ~1300 eV, which includes most of the level structure studied.

The samples of K metal enclosed in polyethylene bags of ≈0.1-mm wall thickness had $(1/n) = 2.45$, 7.60, 25.9, 79.3, and 262 b/atom of natural K. They were prepared for use with a transmission collimator aperture ≈32 mm high by 127 mm wide. The thickest sample provided the main σ_t vs E information except in the resonance peaks, while the thinner samples helped to determine the behavior at the resonance peaks. The cyclotron operated at 70 bursts/sec. Totals of 400 000, 300 000, 300 000,

TABLE II. Resonance parameters for neutron levels in natural K to 200 keV. Isotope assignments, A, labeled with a, are from the separated isotope data of Good and Harvey (Ref. 18). b indicates the ^{41}K levels which were masked by overlapping stronger ^{39}K levels in our data. c denotes those ^{41}K weak levels unresolved in our data, but seen in the separated isotope data.

E_0 (keV)	A	l	J	$\frac{2732\,ag}{E_0}$ (in keV) (b/atom)	$ag\Gamma_n$ (eV)
1.1114 ± 0.0004	39 [a]	1			0.0068 ± 0.0005
2.0287 ± 0.0005	41 [a]	0	2	57.92	0.11 ± 0.02
3.2046 ± 0.0010	41 [a]	1			0.0081 ± 0.0010
3.2774 ± 0.0011	39 [a]	1			0.047 ± 0.007
4.012	41 [c]				
5.5363 ± 0.0045	41 [a]	0	1	12.73	2.6 ± 0.3
9.3780 ± 0.0095	39 [a]	0			25 ± 3
12.138 ± 0.008		1			0.083 ± 0.015
12.606 ± 0.008	39 [a]	1	1	75.66	0.61 ± 0.12
13.330 ± 0.010	41 [a]	1	(1)	5.286	0.20 ± 0.04
			(2)	8.811	
14.284 ± 0.010	39	1			0.38 ± 0.08
15.012 ± 0.010	41 [a]	1	1	4.696	0.16 ± 0.04
15.934 ± 0.011	39	1	(2)	99.79	0.79 ± 0.14
			(3)	139.7	
16.464 ± 0.012		1			0.08 ± 0.03
16.704 ± 0.025	41 [a]	0	(2)	7.035	6.0 ± 1.2
20.285 ± 0.016	41 [a]	1			1.0 ± 0.3
24.926 ± 0.022	41 [a]	1			3.7 ± 0.7
25.519 ± 0.023	39 [a]	0	1	37.39	49 ± 8
27.083 ± 0.025	41 [a]	1	(3)	6.074	0.63 ± 0.15
28.308	41 [c]				
32.19 ± 0.03	39 [a]	1	1	29.63	1.7 ± 0.4
33.30 ± 0.04	39 [a]	1	(1)	28.64	9.4 ± 2.0
37.49 ± 0.04	39 [a]	1	0	8.480	5.4 ± 1.1
38.56 ± 0.04	41 [a]	0	2	3.044	28 ± 5
42.35	41 [b]				
42.61 ± 0.05	39 [a]	0	2	37.31	300 ± 30
45.95 ± 0.06	39 [a]	1	1	20.76	24 ± 7
52.09 ± 0.07	39 [a]	1			7.4 ± 2.0
54.55 ± 0.07	39 [a]	1	0	5.828	9.5 ± 2.5
55.72 ± 0.07	41 [a]	1			2.7 ± 0.8
57.83 ± 0.08	39 [a]	0	2	27.49	430 ± 40
58.20	41 [b]				
59.86 ± 0.10	39 [a]	1	1	15.93	29 ± 7
			2	26.56	
63.22	41 [c]				
67.04	41 [b]				
68.76 ± 0.10	39 [a]	1	1	13.87	490 ± 60
70.45	41 [c]				
75.44 ± 0.12	41 [a]	1			14 ± 4
78.66 ± 0.12		1			26(0.45 + ag) ± 30%
79.63 ± 0.13	41 [a]	1			24 ± 4
81.01 ± 0.13	(39)	1	(1)	11.77	14 ± 5
83.39 ± 0.13	41 [a]	1			12 ± 4
87.50 ± 0.14	39 [a]	1	1	10.90	165 ± 20
90.33 ± 0.15		1			13(0.55 + ag) ± 20%
91.08 ± 0.15	41 [a]	1			4.5 ± 2.0
92.91 ± 0.16	39 [a]	1			17 ± 4
96.63 ± 0.17	39 [a]	0	1	9.870	210 ± 20
98.40	41 [b]				
99.10 ± 0.17	39 [a]	1			68 ± 15
100.9 ± 0.2	41 [a]	1			15 ± 5
102.0 ± 0.2	(39)	1			21 ± 6
104.2 ± 0.2		1			6.3(0.8 + ag) ± 20%
108.7 ± 0.2	39 [a]	0	1	8.774	700 ± 150
110.3	41 [b]				
115.9 ± 0.3	41 [a]	1			29 ± 9
118.5 ± 0.3	(39)	1			36 ± 6
120.7 ± 0.3	41 [a]	1			14 ± 3
122.5 ± 0.3	(39)	1			16 ± 4
126.9 ± 0.3		1			23(0.71 + ag) ± 20%
132.3 ± 0.3	(39)	1	0	2.403	140 ± 20
			1	7.209	
134.8 ± 0.3	(39)	1	(1)	7.077	77 ± 15
			(2)	11.79	
136.3 ± 0.3	(39)	1			42 ± 12
138.3 ± 0.3		1			17(0.78 + ag) ± 20%
143.9 ± 0.3	(39)	1	2	11.05	100 ± 20
146.0 ± 0.3		1			82 ± 18
147.4 ± 0.3		1			57 ± 14
149.0 ± 0.3		1			39(0.81 + ag) ± 20%
153.9 ± 0.4	39	(1)	(3)	14.46	750 ± 100
162.3 ± 0.4	39	(1)	1	5.876	440 ± 50
			2	9.793	
177.6 ± 0.4	39	(1)	1	5.370	390 ± 50
184.1 ± 0.5		1			24(1.2 + ag) ± 20%
188.3 ± 0.5	39	1			98 ± 20
193.1 ± 0.5	39	0	1	4.940	350 ± 70
198.8 ± 0.5		1			74(1.3 + ag) ± 20%

150 000, and 150 000 bursts, respectively, were used for the above samples. A spectroscopic analysis of the K by Lucius Pitkin, Inc., indicated that the main impurities were about 0.2% Na and 0.03% Ca. None of our reported K resonances are due to the Na, Ca, or other impurities.

III. PRELIMINARY ANALYSIS

The first step in treating the data, after making prompt dead-time corrections, is to study the systematics of all of the data for all of the numerous sample elements and isotopes for which data were obtained and to attempt to make a correct evaluation of the sample- and energy-dependent background subtraction. Once the background subtraction has been made for each sample run and an appropriate B.G. subtracted "open" count vs channel is obtained, one can obtain the set of $(\sigma, T, E)_j$ for each sample vs channel. To the extent that errors are made in the B. G. evaluations, the absolute σ values are in error by a slowly changing amount vs energy. The shapes of the σ or T vs E plots are not influenced by such errors. The evaluations for K were made without the help of the standard filter measurements which proved helpful for the Na data[13] and were arrived at after a long process which we believe is reasonably correct, but is difficult to explain briefly.

The levels in K are mainly relatively narrow, weak, and noninterfering with each other, so our usual area analysis methods provide most of the final results listed for the resonance parameters, other than their energies. Where possible, other methods described in Refs. 7 and 13 were used to help decide on the proper l and J values for favorable resonance cases.

IV. RESULTS AND DISCUSSION

The results for our resonance level parameter evaluations are given in Table II. The energy of the resonance is given in column 1. When the isotope assignment can be made, it is given in column 2. Most of the isotope assignments are from the separated isotope KCl sample studies of Good and Harvey[18] at ORELA. The resonances having isotope assignments not based on the ORELA data were assigned by us on the basis of the favored (ag) value, as described below. Columns 3 and 4 list the assigned best-fit l and J values for the resonances. Column 5, of help in the analysis, lists the implied peak cross section at resonance for a pure scattering resonance before Doppler broadening and without correction for experimental resolution for the (J, l, A) part of the interaction having the resonance. Contributions from the other (J, l, A) parts of the interaction then add to this value. A value $\Gamma_\gamma = 0.5$ eV was assumed in the analysis but our listed results are not very sensitive to the exact choice of Γ_γ near 0.5 eV. A value $\Gamma_\gamma \approx 0.5$ eV is expected[19] for this nuclear mass region both for $l=0$ and $l=1$. The value of $(ag\Gamma_n)$ for the strength of the level is given in the last column. For most of our tabulated levels, $\Gamma_n \gg \Gamma_\gamma$.

Where the data for a given sample thickness have a transmission dip at the resonance with the dip "area" established without too large fractional uncertainty, an implied relation between $ag\Gamma_n$ and Γ is obtained with some statistical uncertainty.

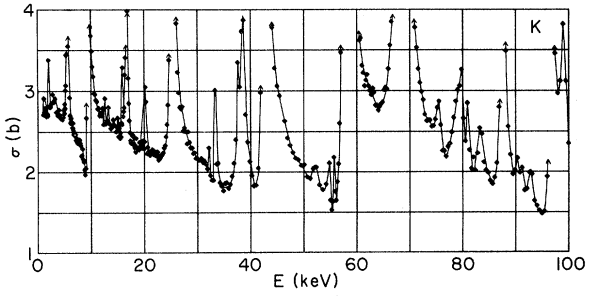

FIG. 1. The measured thick sample ($1/n = 2.45$ b/atom) σ_t vs E for natural potassium from 1 to 100 keV using many-channel averages. The plot emphasizes the cross-section behavior between levels, with no attempt to indicate peak cross sections at resonance.

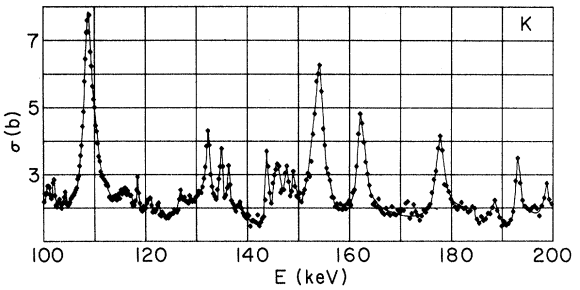

FIG. 2. The measured single channel σ_t vs E for the thickest K sample, from 100 to 200 keV.

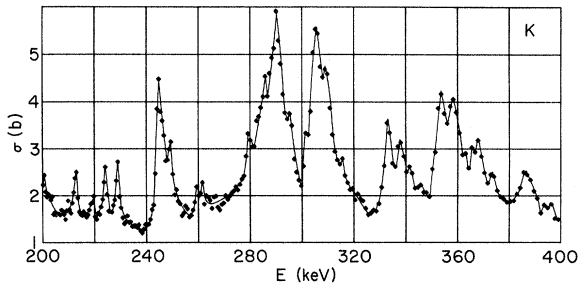

FIG. 3. The measured single channel σ_t vs E for the thickest K sample from 200 to 400 keV.

When two or more different sample thickness dips yield intersecting $ag\Gamma_n$ vs Γ curves, a favored ($ag\Gamma_n$, Γ) may be established. This $ag\Gamma_n$ value should equal $ag(\Gamma - 0.5$ eV) within the statistical uncertainty. Since, as seen in Table I, the possible (ag) values differ appreciably from one another, this provides one method for choosing a favored (ag) value and thus J, if A is known, or both A and J if A is not known from the separated isotope data.[18] Where Γ is established without too large an uncertainty, we make a further test as follows. A computer program calculates the expected resonant peak cross section for three values of Γ covering the region of uncertainty in Γ and for various possible (ag) values. The program includes the effect of Doppler broadening on σ and of experimental resolution broadening on T. Comparison with the measured peak resonant σ then yields a favored ag value. In those cases where a functional relation between $ag\Gamma_n$ and Γ is established, but $ag\Gamma_n$ and (ag) are not separately established, the favored choice for $ag\Gamma_n$ may be sensitive to the choice of (ag). We have indicated this dependence in such cases in Table II.

Figure 1 shows the thick sample measured σ vs E from 1 to 100 keV using many channel averages to reduce statistical fluctuations, emphasizing the behavior between resonances with no attempt to indicate peak measured cross sections at resonance. Figures 2 and 3 show the single-channel σ vs E behavior for the thick sample, including the resonance peaks. The data from 200 to 400 keV of Fig. 3 have not been analyzed for resonance parameters. The curves are intended as an aid to the eye only. As mentioned above, our absolute σ vs E values between resonances may have a small energy-dependent shift error in σ due to uncertainties in establishing the sample $T=0$ and $T=1$ energy-dependent count rates over the spectrum.

Below 110 keV, we have six levels in ^{39}K classified as $l=0$, giving $10^4S_0 = (0.66^{+0.63}_{-0.30})$. For the less abundant isotope ^{41}K, we have four levels below 40 keV classified as $l=0$, giving $10^4S_0 = (0.78^{+1.08}_{-0.41})$. Below 103 keV, we have 18 levels in ^{39}K assigned as p levels. There are three extra weak levels which are probably p levels. For the purpose of assigning strength functions, we arbitrarily assign two of these to ^{39}K and one to ^{41}K. (The final answer is insensitive to the means of treating these three levels.) This gives 20 levels in ^{39}K to 102 keV assigned as $l=1$, giving $10^4S_1 = (1.8^{+0.7}_{-0.5})$. For ^{41}K to 102 keV, this gives 14 levels assigned as $l=1$, giving $10^4S_1 = (2.4^{+1.3}_{-0.8})$. The level at 68.76 keV contributes about 57% of the total $\sum g\Gamma_n$[1] for ^{39}K. This level appears to be quite symmetric, so it is difficult to "force" it to be $l=0$. Since ^{39}K has the $N=20$ closed neutron shell, this may represent an intermediate structure peaking of the net contribution to S_1 in this resonance. The uncertainties quoted above for 10^4S_0 and 10^4S_1 are based on the method given in Ref. 20.

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