Level structure of ^{60}Co†

P. L. Jolivette, J. D. Goss, and C. P. Browne
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556
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Level energies of ^{60}Co were measured using the ^{59}Co$(d, p)^{60}$Co reaction and the 100 cm broad range magnetic spectrograph. In order to excite nearly all states the data were taken at $\theta_{lab} \geq 60°$. Energies for 89 states having $E_x \leq 3.2$ MeV were measured with uncertainties of 1 keV or less.

[NUCLEAR REACTION ^{59}Co(d, p), $E = 5$–8 MeV; measured E_x in ^{60}Co.]

The study of odd-odd nuclei is often inhibited by experimental difficulties. In the example of ^{60}Co the most convenient target, ^{59}Co, has spin $\frac{7}{2}$, and the normally powerful (d, p) stripping and particle-γ correlation techniques for determining spins are not very effective. The early (d, p) studies determined many level energies and numerous transfer l values.[1] While l values yield parities, and for odd l indicate whether the state is primarily of f or p shell configuration, they place little restriction on the possible final J. Additional levels are seen via (n, γ),[2] and this has been the most successful reaction for making spin assignments.[3–5] As capture can be to either 3^- or 4^- states for thermal neutrons, measurements must use two polarizations such as a polarized beam and polarized target, or polarized beam and γ-ray circular polarization, to yield sufficient information. Most of the levels below 1 MeV have been assigned by these means.

The γ rays that decay from the capture state are of special interest for the (n, γ) studies and thus it is important to show that the high energy γ rays are primary decays by confirming the existence of the final states. The level scheme above 1 MeV is not firmly established, however. Previous (d, p) work established many levels, but the resolution, >15 keV, did not separate many doublets, e.g. the second and third excited states at 277 and 288 keV, and the relatively large uncertainties, ≈7 keV, make it difficult to associate many levels seen via (n, γ) with those seen in (d, p). In addition, very weak levels could easily have been missed. On the other hand, there is little (n, γ) coincidence work and, unsurprisingly, the difficult problem of reconstructing the level scheme from only the γ-ray energies has from time to time created spurious levels. In particular, the assumption that all γ rays with energies greater than half the neutron separation energy are primary γ rays is usually made.

In order to clarify the level scheme we have used the ^{59}Co$(d, p)^{60}$Co reaction. We chose this reaction even though it is selective because we could utilize high beam currents and easily made thin pure targets. These factors allowed us to take long runs with good resolution at back angles where stripping may not dominate. Thus we hope to see almost all levels. With a good knowledge of the level scheme a better correlation of previous experiments can be made. The level density will be discussed in relation to the other Co isotopes in a forthcoming paper.

The tandem FN van de Graaff produced deuterons of 5 to 8 MeV, and the reaction products were detected with 50 μm NTA plates after being momentum-analyzed with the 100 cm broad-range magnetic spectrograph. The laboratory reaction angles were 60, 90, or 120°. The analyzing magnet slits limited the beam energy spread to ±0.05% full width at half-maximum (FWHM). The targets of natural Co, 100% ^{59}Co, were evaporated onto a 10–20 μg/cm^2 carbon backing and were thin enough, ≈20 μg/cm^2, to keep the energy loss in the target less than the beam energy spread. The beam was collimated to illuminate a spot on the target 0.5 mm high, and the spectrograph response to this object is a triangular peak 1.5 mm FWHM. The inverse of the dispersion is ≈0.3–0.5 keV/mm MeV and thus the resolution was ≈6 keV with these parameters. Some runs were made with a line target about 0.05 mm high formed by evaporating the Co through a slit. The resolution was somewhat better (Fig. 1), and was limited by the beam spread and target thickness.

While measuring a series of Q values using the 100 cm spectrograph we made a careful analysis of the uncertainties involved and have described them in a previous paper.[6] Most of that analysis is applicable to the present case. However, when measuring excitation energies we do not measure elastic groups from heavy and light targets to

TABLE I. Levels in ^{60}Co.

	E_x (keV)	Strength (Arbitrary units)	E_x [a] (keV)	Ref.	l_n [b]
0	g.s.	4.3			1
1	58.6± 0.3	2.4	58.566 (1)	7	1
2	277.4± 0.3	0.9	277.137(12)	7	
3	289.1± 0.3	1.7	288.366 (2)	7	1, (3)
4	436.0± 0.4	1.3	435.693(25)	7	3
5	506.4± 0.4	1.5	506.208(18)	7	1
6	542.9± 0.4	1.1	542.702(35)	7	3
7	614.4± 0.4	3.0	614.429(11)	7	1
8	738.4± 0.4	0.4	736(6)	9	
9	785.4± 0.4	2.2	785.557(60)	7	1
10			1003.66(30)	7	
11	1005.2± 0.4	5.2	1005.643(45)	7	1, (3)
12	1131.3± 0.6	0.2	1125	10	
	(1152.3± 1.8)	0.1			
13	1207.8± 0.5	0.3	1207.6(10)	2	
14	1215.7± 0.4	1.4	1214.4(10)	2	(1, 3)
15	1342.7± 0.5	0.4	1342.6(10)	2	
16	1380.2± 0.5	2.6	1380.3(10)	2	(1, 3)
17	1451.5± 0.5	0.4	1451.5(10)	2	
18	1509.6± 0.6	0.3			
19	1515.9± 0.5	0.7	1515.8(10)	2	1
20	1567.4± 1.1	0.1	1566.3(10)	2	
21	1639.2± 0.5	0.7	1639.9(10)	2	
22	1707.2± 0.6	0.2	1710(5)	9	
23	1748.7± 0.6	0.2	1748.8(10)	2	
24	1787.5± 0.6	0.2	1786.6(10)	2	
25	1799.4± 0.5	3.3	1799(6)	1	3
26	1808.2± 0.6	3.0			
27	1830.6± 0.6	0.6	1831.0(10)	2	
28	1851.9± 0.5	1.0	1852.1(10)	2	1
			1876.8(10)	2	
29	1888.7± 0.6	0.6	1888.6(10)	2	(1)
30	1923.6± 0.6	0.3	1923(6)	9	
31	1980.8± 0.6	2.7	1980.2(10)	2	3
32	2032.4± 0.6	0.6	2031(6)	9	1
33	2045.5± 0.6	0.3	2052(5)	9	
34	(2121.8± 1.1)	0.2	2119.2(10)	2	
35	2132.5± 0.6	3.3	2131.2(10)	2	(4)
36	2151.2± 0.6	0.5	2150(6)	9	
37	2200.7± 0.7	0.2			
38	2221.6± 0.7	0.3	2219.2(10)	2	
	(2233.1± 1.0)	0.2			
39	2275.1± 0.6	1.2	2276.7(10)	2	1, (3)
40	2279.6± 0.7	0.5			
41	2309.9± 0.6	0.4	2307.8(10)	2	
42	2318.4± 1.0	0.2	2346.4(10)	2	
43	2342.0± 0.6	0.4			
44	2350.7± 0.6	1.9			3
45	2362.5± 0.9	0.2	2361.8(10)	2	
46	2422.9± 0.7	0.2	2420.6(15)	8	
47	2428.8± 0.9	0.2			
48	2450.9± 0.8	0.1	2445.7(10)	2	
			2458.5(10)	2	
49	2471.2± 0.9	0.2			
50	2487.2± 0.9	0.2	2488.1(10)	2	
51	2527.9± 0.8	0.1	2527.1(10)	2	
			2543.2(10)	2	
52	2560.1± 0.9	0.2			
53	2569.5± 0.9	0.1	2569.0(10)	2	
54	2585.6± 0.7	0.3	2585.1(10)	2	
55	2597.0± 0.7	0.8	2597.2(10)	2	
56	2606.1± 0.8	0.2	2606.8(10)	2	
57	2654.5± 0.9	0.1	2658(5)	9	
58	2684.5± 0.7	0.3			
59	2709.8± 0.8	0.2	2717(5)	9	
60	2735.0± 0.7	0.3	2734(6)	9	
61	2758.0± 0.7	0.8			1
62	2766.1± 0.8	0.5	2765.1(15)	8	
63	2772.3± 0.8	0.3			
64	2786.3± 1.1	0.2	2784.0(15)	8	
65	2802.5± 0.8	0.3			
66	2807.3± 0.8	0.3			
67	2822.8± 0.7	1.7	2823.5(15)	8	
68	2844.8± 0.7	3.2	2841.9(15)	8	0
69	2866.9± 0.9	0.2	2871(5)	9	
70	2884.0± 0.8	1.2	2882.6(15)	8	
71	2897.4± 0.8	0.8	2901(5)	9	
72	2917.6± 0.8	0.4			
73	2939.2± 0.9	0.2	2944(5)	9	
	(2945.2± 1.2)	0.1			
74	2964.9± 0.8	0.4	2964(5)	9	
75	2996.3± 0.8	0.6			
76	3009.1± 0.8	1.4	3017(5)	9	0
77	3020.4± 1.6	0.2			
78	3046.4± 0.8	0.4	3050(5)	9	
79	3063.9± 0.8	1.0	3065(6)	9	
80	3077.6± 1.0	0.1			
81	3084.4± 0.9	0.4			0
82	3096.1± 0.9	0.4	3092(5)	9	
83	3114.7± 0.8	0.4	3118(5)	9	
84	3120.2± 1.1	0.3			
85	3130.4± 0.9	0.3			
86	3153.8± 0.9	0.4	3146(5)	9	
87	3184.6± 1.0	3.1	3187(5)	9	0
88	3199.3± 0.9	0.8			
89	3215.4± 0.9	1.4	3218(5)	9	

[a] The most precise measurement previously reported in the reference given in the next column. Digits in parentheses are uncertainties in units of the last place(s) of the energy.

[b] Reference 9.

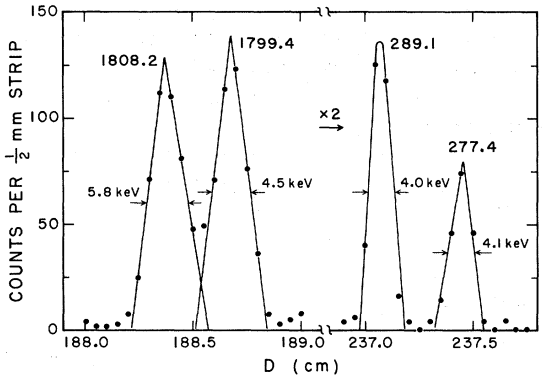

FIG. 1. An example of the best resolution obtained in this experiment. The run was at $E_d = 6$ MeV, $\theta_{lab} = 90°$. A line target 0.05 mm high was used.

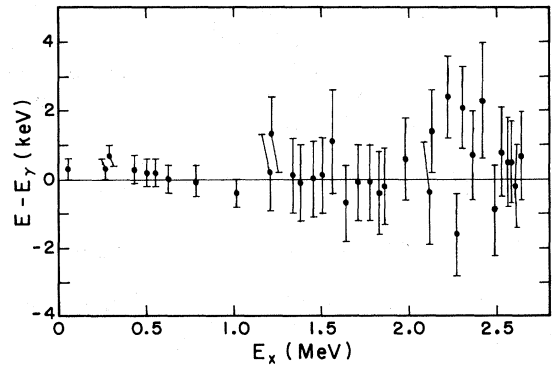

FIG. 2. A comparison of our excitation energies with those determined from γ-ray measurements. Below 1.2 MeV we compare with Ref. 7 and the error bars represent only our uncertainties. The errors in Ref. 7 are <0.1 keV. Above 1.2 MeV we compare to Ref. 2 and the error bars are a quadratic combination of our uncertainties and the larger one of Ref. 2.

determine the energy and angle. Instead the nominal angle at which the spectrograph is set is used, and the input energy is then determined from the ground state group. Experience with the Q-value measurements indicates that we should assign random and systematic uncertainties of 0.05° each to the reaction angle. The uncertainty in measuring the position of the ground state then determines the uncertainties in excitation energy due to the input energy. The contribution to the uncertainties in the excitation energies due to the input energy uncertainty was about 0.6 keV, as most of the systematic effects will cancel.

As the outgoing particles are all of the same type (protons) for the excitation energy measurement, the peak shape analysis, which determines the effects of target stopping and finite angular acceptance, (described in Ref. 6), is relatively unimportant and so no corrections were made. (If we had been detecting α's, however, there would have been an important differential energy loss for the outgoing particles which would have had to be considered.) The small uncertainties that arise from the peak shape analysis were retained to cover any residual error.

The other uncertainties which arise in determining peak position and beam spot position, calibration, and magnetic field measurements are the same as Ref. 6. However, as only differences between the ground state and excited state energies are involved, many uncertainties are reduced by cancellation.

The excitation energies are given in Table I along with a comparison with the best previous results. For each level the strength, averaged over all runs in which it was seen, is also tabulated. This is not simply related to the spectroscopic factor as all angles were off the stripping peak. Where an l value was previously assigned to a peak which we find to be a doublet, we assume it describes the stronger member.

We considered a peak to be definitely a level in ^{60}Co if it was seen in at least four spectra including all three angles. Peaks seen at only two angles or in only three runs are tentatively assigned to ^{60}Co and are enclosed in brackets.

The agreement between our excitation energies and γ-ray values is good (Fig. 2). Below 1 MeV the agreement with the very precise bent crystal spectrometer values of Ref. 7 is excellent. Above that we also agree with the ±1 keV numbers of Ref. 2. The systematic shift of our values relative to Refs. 2 and 7 is 0.25 ± 0.30 keV and is insignificant. There is an apparent systematic shift from Ref. 8.

We terminated our measurements at $E_x \approx 3.2$ MeV, where the average level spacing is ≈10 keV and a very high percentage of the peaks are unresolved multiplets. We feel that the list is nearly complete to about 2.8 MeV. We found 20 previously unreported levels below 3 MeV, ≈25% of the total, the first being at 1510 keV. Most of these are weak or are members of closely spaced, <10 keV, doublets. In addition we confirm the existence of a number of levels inferred by assuming that they were fed by primary capture γ-rays.

A few levels need individual comment:

1003-1005 keV doublet. Our measurement

agrees with the value for the upper member. The individual runs are in excellent agreement (rms deviation <0.3 keV). We believe that any contribution from the 1003 keV level must be less than 20% of the very strong 1005 keV group. The existence of the 1003 keV level is inferred from summations of the very precise singles γ-ray energies of Ref. 7.

1799-1808 keV. This doublet was assigned $l_n = 3$ in Ref. 1. As the strength of the two members is nearly identical in all our measurements, they are probably both $l_n = 3$.

The levels at 314, 1319, 1684, 2052, 2084, and 2391 keV which are listed in the $A = 60$ Nuclear Data Sheets[9] compilation were not seen in this work or any other done since the compilation and probably do not exist.

1877 keV. We see no indication of this level which was inferred from a high energy γ ray following n capture. It is probably not a primary γ ray.

The level scheme presented in this paper should aid in future studies of ^{60}Co.

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