Triple Correlations in the ^{56}Fe$(p,\gamma\gamma)^{57}$Co Reaction

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(Received 16 September 1965)

Approximately seventy resonances were observed for the ^{56}Fe$(p,\gamma)^{57}$Co reaction in the range of proton energy from 1300 to 1800 keV. Gamma-ray energy measurements performed with scintillation and lithium-drift silicon spectrometers yield 6.040±0.030 MeV for the Q value of the ^{56}Fe$(p,\gamma)^{57}$Co reaction and show the existence of intermediate states in ^{57}Co at 1.381±0.010, 1.506±0.020, 1.760±0.020, 1.921±0.020, 2.136±0.020, 2.60±0.03, 2.74±0.03, 2.80±0.03, 2.88±0.03, 3.11±0.03, 3.18±0.03, 3.27±0.03, and 3.52±0.03 MeV. Triple-correlation measurements performed with a double sum-coincidence spectrometer permit J^π assignments of $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{5}{2}^-$, and $\frac{5}{2}^+$ to the intermediate states in ^{57}Co at 1.38, 1.76, 1.92, and 2.14 MeV, respectively. These measurements were performed at resonance energies of 1525, 1598, 1622, 1637, 1645, and 1800 keV, where the capturing states at the 1637- and 1800-keV resonances are assigned a J^π value of $\frac{5}{2}^+$, and for the others J^π is $\frac{3}{2}^-$. Ambiguities exist for the $E2/M1$ amplitude ratios for all of the mixed secondary gamma-ray transitions observed in these studies. All measurements were in agreement with the established value of $\frac{7}{2}^-$ for the ground state of ^{57}Co.

INTRODUCTION

At the beginning of this experiment the existing information on low-lying excited states of ^{57}Co resulted from a number of studies[1–4] of the beta decay of ^{57}Ni. These investigations led to ambiguities concerning the spins of several of the states as well as disagreement among the various workers as to the existence of some states weakly populated in this decay. Additionally, the range of energy of states which can be populated in beta decay is limited. Meanwhile, there has been increased theoretical interest for nuclides in this mass region, particularly as to the applicability of the core-excitation model.

It thus appeared desirable to study this nuclide by means of the ^{56}Fe$(p,\gamma\gamma)^{57}$Co reaction. The spins and probable parities of some of the excited states populated by this reaction are accessible to measurement by triple-correlation techniques. A double sum-coincidence spectrometer developed in this laboratory[5,6] was employed and yielded, in addition to the spins and parities, the $E2/M1$ amplitude ratios for the two-part cascades through the levels involved. The sum-coincidence techniques and auxiliary high-resolution studies with a lithium-drift silicon gamma-ray detector also provided identification and measurement of the energies of the states populated in this reaction.

A number of preliminary experiments were performed prior to the correlation measurements to select resonances in the range of proton energy from 1300 to 1800 keV which were suitable for study in the correlation work. Suitability required that the resonance be a singlet state which led to intermediate states of interest in ^{57}Co and that the coincidence counting rate be sufficiently high that acceptable statistics could be obtained in a reasonable length of time. The first part of this paper describes the preliminary work, followed by a discussion of the correlation results involving these states. A preliminary account of this work has been given at a meeting of the American Physical Society.[7]

EXPERIMENTAL APPARATUS AND PROCEDURES

The targets used in this experiment were prepared by electroplating 99.6% enriched ^{56}Fe from an oxalate bath onto 0.025-in.-thick × 0.750-in.-diam pure gold disks. Prior to plating, the gold disks were etched in aqua regia and thoroughly washed in triple-distilled water in order to remove surface contaminants. The targets prepared in this manner were quite clean and of fairly uniform thickness. The etching plus the use of a cold sleeve in front of the target reduced the problem of radiation from contaminants to negligible proportions. Most of the targets used in this work were approximately 2 keV thick to 1.5-MeV protons.

The excitation curve was obtained by placing a 3-in.-diam × 3-in.-long NaI(Tl) detector at 0° with respect to the proton beam, at a distance from the target surface to the front face of the detector of 1.20 cm. The electronics were conventional with a bias level corresponding to a gamma-ray energy of 3.7 MeV, approximately half of the excitation energy. In order that no observable deterioration of the target occur with time the beam current was limited to approximately 5 μA.

High-resolution studies of the primary gamma rays from various capture states were made with a 5.0-cm^2×0.5-cm-thick lithium-drift silicon detector used with a target to detector distance of 1.3 cm. Conventional electronics appropriate to this type of detector were employed, and the detector, mounted in a simple

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[1] G. Friedlander, M. L. Perlman, D. Alburger, and A. W. Sunyar, Phys. Rev. **80**, 30 (1950).
[2] R. Canada and A. C. G. Mitchell, Phys. Rev. **83**, 955 (1951).
[3] J. Konijn, H. L. Hagedoorn, and B. Van Nooijen, Physica **24**, 129 (1958).
[4] G. Chilosi, S. Monaro, and R. A. Ricci, Nuovo Cimento **26**, 440 (1962).
[5] C. R. Gossett and L. S. August, Phys. Rev. **137**, B381 (1965).
[6] C. R. Gossett and L. S. August, U. S. Naval Research Laboratory Report No. 6186, 1965 (unpublished).
[7] L. S. August, C. R. Gossett, and P. A. Treado, Bull. Am. Phys. Soc. **10**, 427 (1965).

vacuum chamber, was used while cooled to lower than $-100°C$. The resolution obtained was about 25 keV or less for gamma rays with energies from 5 to 6 MeV. A better measure of the resolution was not possible because a biased amplifier was not employed and the spectra were observed with a pulse-height analyzer of only 400 channels. A water-cooled target chamber was used in these studies to permit the use of beam currents in the range of from 40 to 50 μA.

The triple-correlation data were obtained with a double sum-coincidence spectrometer consisting of three 3-in.-diam $\times$3-in.-long NaI(Tl) detectors mounted within Pb collimators to reduce the transfer of radiation from one detector to another. The three detectors with their collimators form a simple goniometer with two of the detectors on carriages that move in a horizontal plane and the third held fixed at 90° with respect to the beam and to the horizontal. Each of the horizontal detectors is capable of motion from 0° to 90° with respect to the beam axis.

The electronics associated with these detectors are of a conventional nature except for the sum-coincidence and the gain stabilization circuits. The sum-coincidence circuit provides a sum-amplitude condition and, additionally, a moderately fast time-coincidence condition ($2\tau \approx 80$ nsec) between appropriate pairs of the three detectors. Pulse-height information from the movable detector is stored in one or the other half of the memory of a 400-channel analyzer as determined by a routing pulse initiated by the particular fast time coincidence. It was possible to accumulate data over long periods of time due to the use of a gain stabilization system employing stable, pulsed light sources mounted in light pipes between the crystals and phototubes.

With this double sum-coincidence spectrometer it is possible to obtain correlation data in four different geometries concurrently for each intermediate state observed in a two-part cascade from the capturing level to the ground state at a given resonance. These four geometries are referred to as A, B, C, and D and correspond to the Chalk River Cases I, II, VI, and VII, respectively.[8] The geometries A and B involve the detectors in the horizontal plane with geometry A defined to be that in which the primary gamma ray in a two-part cascade is observed in the movable detector and the secondary in the detector fixed at 90° with respect to the beam axis. Geometry B is the inverse of A. Geometries D and C involve the detector fixed at 90° out of the plane and the movable detector with definitions analogous to A and B.

In obtaining the correlation data the three-angle approach of Reich *et al.*[9] has been used in order to obtain greater statistical precision. The individual correlation runs were normalized in terms of the number of monitor counts obtained from a fixed position detector. In accumulating data on any given day, a 14-run sequence was used, consisting of a systematic arrangement of two, three, and two runs at 0°, 43.6°, and 90°, respectively, to each side of the beam axis. The roles of the two detectors in the horizontal plane were interchanged in order to compensate partially for any instrumental asymmetry that would be introduced by small changes in the current distribution of the beam at the target. The yields obtained at each angle of observation are corrected for unequal absorption of the gamma rays due to the anisotropic distribution of material in the vicinity of the target. The coefficients, A_2 and A_4, and their associated uncertainties are obtained by least-squares analysis of the data to the form of the normalized Legendre polynomial, $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, which characterize the correlations. Comparison between theory and experiment for a given spin sequence is made in terms of the coefficients, where the predicted values of the coefficients have been corrected for finite geometry effects calculated on the basis of the total absorption of the gamma-ray energy in the detector as required by the sum condition. The experimental apparatus, procedures, and the methods of data acquisition and analysis employed in the triple-correlation measurements have been described in a previous paper[5] and in much greater detail in an unpublished report.[6]

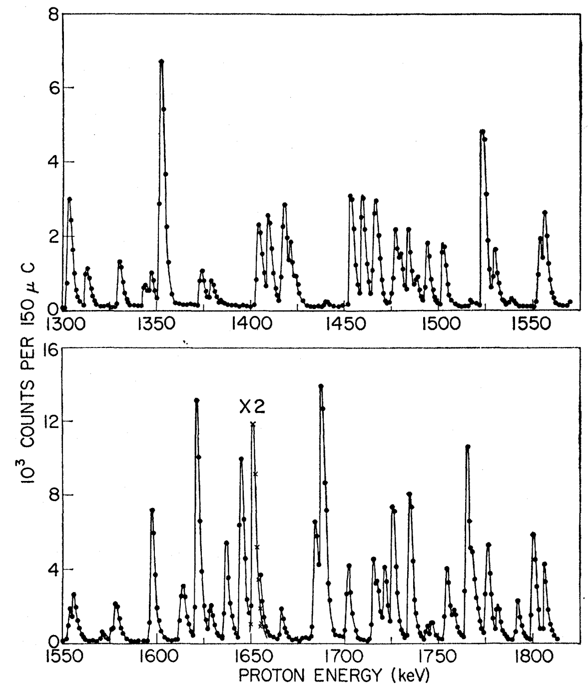

FIG 1. Yield of gamma rays with energies greater than 3.7 MeV plotted as a function of proton energy. The target was approximately 2 keV thick to 1.5-MeV protons. There has been no background subtraction applied to the data.

[8] A. J. Ferguson and A. R. Rutledge, Atomic Energy Commission of Canada, Ltd., CRP-615, AECL-420, 1957, revised and reprinted 1962 (unpublished).

[9] C. W. Reich, J. A. Merrill, and E. D. Klema, Nucl. Instr. Methods 23, 36 (1963).

EXCITATION CURVE

The excitation curve for the $^{56}Fe(p,\gamma)^{57}Co$ reaction is shown in Fig. 1 where the number of counts per 150 μC is plotted as a function of the proton energy. The 1-m-radius electrostatic analyzer used in the present experiments was calibrated by using the accurately measured resonances[10] in the $^{58}Ni(p,\gamma)^{59}Cu$ reaction at 1424.1 $\pm$0.7 and 1843.7$\pm$0.9 keV. There are sixty discernible peaks in the region of proton energy from 1300 to 1800 keV; however, seven of the more intense peaks which appear to be single resonances were subsequently found to be complex. Since not all resonances were investigated for possible structure, it is thought that there are at least 70 resonances in the energy range investigated. The excitation curve was obtained in 1-keV steps with a rather thin target because of the close spacing of the resonances. Several portions of the curve were repeated, indicating that no observable target deterioration had occurred. The maximum yields at various resonances from a much thicker target were compared with the data shown in Fig. 1, and the results were essentially the same for the two targets indicating that the natural widths of the resonances were much less than the instrumental widths observed. Accordingly, yield measurements are given as thick-target yields. Table I summarizes the pertinent results from the excitation-curve data.

The fact that early triple-correlation results from different resonances did not lead to the same spin assignment for the first excited state in ^{57}Co led to the conclusion that some of the capturing states while appearing from the yield curve shapes to be single resonances were in fact complex, i.e., two or more very closely spaced capture states gave rise to the observed yield. That this is the case for the 1353-keV resonance is illustrated by the data shown in Fig. 2. Pairs of singles spectra were taken at the half-maximum intensity points on the low- and high-energy sides of the resonances. Spectra from the 1622-keV resonance are also shown for comparison. The pairs of spectra are arbitrarily normalized to the intensity of the 1.38-MeV gamma-ray peak which appears at about channel 28. It is clear that the spectra do not overlap for the 1353-keV resonance, whereas they do for the 1622-keV resonance, leading to the conclusion that the 1353-keV resonance is complex.

ENERGY MEASUREMENTS

In the process of making energy assignments to various transitions in ^{57}Co it became apparent that the previously reported Q values of 5.97$\pm$0.03 MeV [11] and 5.97$\pm$0.04 MeV [12] for the $^{56}Fe(p,\gamma)^{57}Co$ reaction were

[10] J. W. Butler and C. R. Gossett, Phys. Rev. **108**, 1473 (1957).
[11] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C.), NRC 61-2-13, 14.
[12] S. E. Arnell and P. O. Persson, Arkiv. Fysik **26**, 193 (1964).

TABLE I. The proton energy (E_p), excitation energy (E_x), and thick target yield of primary gamma rays with energies greater than 3.7 MeV from the reaction $^{56}Fe(p,\gamma)^{57}Co$ are tabulated. The estimated uncertainties in the measured quantities are given in parentheses below the dimension headings. Entries in the last column (Comments) indicate which resonances were investigated for structure, and whether a resonance is thought to be a singlet (S), or if it was found to be complex (C). See text (Excitation Curve) for a description of the experimental method employed for investigating a resonance for structure.

E_p (keV) ($\pm$3)	E_x (MeV) ($\pm$0.03)	Yield γ rays/μC (factor of 2)	Comments
1303	7.320	240	
1313	7.330	82	
1330	7.347	99	
1344	7.360	47	
1347	7.363	62	
1353	7.369	540	*C*
1374	7.390	76	
1379	7.395	51	
1404	7.419	180	
1409	7.424	190	
1418	7.433	220	
1421	7.436	70	
1424	7.439	43	
1440	7.455	9	
1453	7.468	250	*S*
1460	7.474	230	*S*
1467	7.481	240	*C*
1477	7.491	170	
1480	7.494	62	
1484	7.498	160	
1489	7.503	54	
1494	7.508	140	
1503	7.517	130	
1517	7.530	13	
1525	7.538	390	*S*
1530	7.543	120	
1539	7.552	14	
1554	7.567	150	
1556	7.569	130	
1571	7.584	41	
1576	7.588	54	
1578	7.590	140	
1598	7.610	580	*S*
1614	7.626	250	*C*
1622	7.634	1070	*S*
1629	7.640	160	
1637	7.648	430	*S*
1645	7.656	800	*S*
1651	7.662	1920	*C*
1666	7.677	140	
1678	7.689	20	
1684	7.695	530	*C*
1687	7.697	990	
1702	7.712	340	*S*
1715	7.725	370	
1717	7.727	85	
1721	7.731	320	
1725	7.735	550	
1734	7.744	650	*S*
1744	7.753	67	
1746	7.755	53	
1754	7.763	320	*S*
1758	7.767	87	
1765	7.774	860	
1768	7.777	170	
1776	7.785	430	*C*
1782	7.791	130	
1792	7.801	180	
1800	7.809	470	*S*
1806	7.814	330	*C*

somewhat in disagreement with the energy measurements of the present experiment. Because of this apparent disagreement, a Q-value determination was made by measuring the energy of the ground-state transition for the 1598-keV resonance at which a moderately intense transition is observed. Ungated spectra were obtained with one of the NaI(Tl) detectors under gain stabilized conditions. Energy calibration was performed with sources of ThC″, PoBe, and that from the 1637-keV resonance of the $^{19}F(p,\alpha\gamma)^{16}O$ reaction. The resulting calibration points were fitted by the method of least squares, and the value determined for the excitation energy at the 1598-keV resonance was 7.610 ± 0.030 MeV, yielding a Q value of 6.040 ± 0.030 MeV. Independent measurements with the lithium-drift silicon detector which were made with a somewhat less precise energy calibration are in excellent agreement with this Q value.

A reasonably precise measurement of the 1.38-MeV gamma-ray energy was also made with the NaI(Tl) detector under gain stabilized conditions. The radiation from the 1622-keV resonance was observed for this measurement since the 1.38-MeV state is very strongly populated at this resonance. An accurate background subtraction of the pulse-height distributions from higher energy gamma rays was made in order to more accurately define the peak position. Energy calibration was performed using sources of ^{22}Na, ^{88}Y, ^{137}Cs, and ThC″. The value obtained for the energy of this transition was 1.381 ± 0.010 MeV. In making both of the above measurements the peaks of interest were placed near the top of the 200-channel spectrum in order to give greater sensitivity, and also to insure that the lower energy calibration peaks would be above about channel 50 as the analyzer appears to be somewhat nonlinear below this point.

Spectra were obtained with the lithium-drift silicon detector primarily to utilize the greater resolution of this device in order to determine if any of the intermediate states of interest were multiplets. Spectra were obtained at the same resonances which were studied in the correlation work. The states at 1.38, 1.76, 1.92, and 2.14 MeV for which spin and probable parity assignments are made appear to be singlets to within the 25-keV resolution of the Li-Si detector. The self-consistency of the correlation results strengthens the contention that these states are singlets. Before obtaining the Li-Si spectra spectra it was thought that spin assignments could also be made for a state at 2.74 MeV and a possible state at 3.99 MeV. However, the high-resolution spectra showed more states to exist in these energy regions than was apparent from the sum-coincidence spectra, and as a result such spin and parity assignments are not attempted.

In principle the greater resolution of the Li-Si detector permits the location of gamma-ray peaks with considerable precision, and, therefore, more accurate energy determinations should be possible with this detector

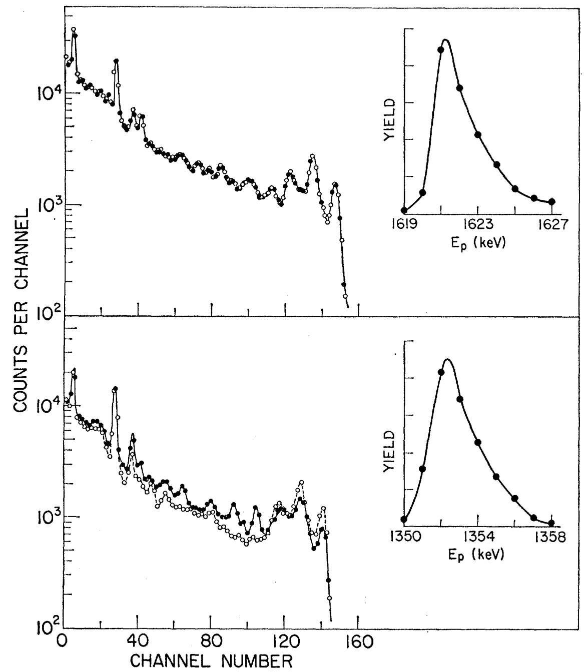

Fig. 2. Singles gamma-ray spectra obtained at the half-maximum intensity points on the low- and high-energy sides of the resonances at 1353 and 1622 keV. The insets show the yields at these resonances. The pairs of spectra have been arbitrarily normalized to the intensity of the 1.38-MeV peak which occurs at about channel 28. Spectra taken on the low-energy side of the resonances are indicated by open circles.

than with the sum-coincidence spectrometer. However, the low efficiency of the detector requires long counting periods, and unless a gain stabilizer is employed, some of this possible precision is lost if an attempt is made to add spectra taken over a period of a number of days. At the time that the data were taken with this detector a gain stabilizer was not available for this type of device; therefore, data were accumulated at a given resonance for only a single working day. Nevertheless, it was possible to obtain more accurate energies for the states at 1.51, 1.76, 1.92, and 2.14 MeV with the Li-Si detector than could be obtained with the sum-coincidence spectrometer. This improvement was achieved by measuring energy differences between the peaks produced by transitions to the 1.381-MeV state and such of the other low-lying states as are populated sufficiently to give reasonable statistics at the resonances studied. The Compton background in this region of the spectrum is also relatively small. The energies of the states above 2.14 MeV are less well established since the peak positions could not be as well determined in the Li-Si spectra because of the statistics obtained and the relatively large background of Compton interactions upon which the peaks of these states are superimposed. The uncertainty in the energy determinations made with the Li-Si detector for the higher energy states is thought to be approximately 30 keV. The value for the energies as determined from the two types of spectra were in good

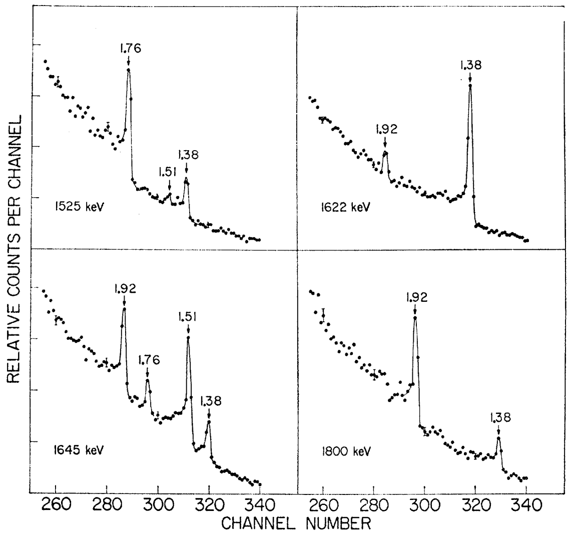

FIG. 3. Partial gamma-ray spectra obtained with a cooled 5.0-cm^2×0.5-cm-thick lithium-drifted silicon detector at the resonances specified. The peaks observed are the double escape peaks from the pair production interaction of the primary gamma rays. The numbers above the peaks are the energies in MeV of the intermediate states in ^{57}Co populated by these primaries. For the peaks shown the energies of the primary gamma rays ranged from about 5 to 6 MeV.

agreement. Where small differences occurred, the values from the Li-Si data were chosen in order to have a consistent set of energies.

Figure 3 shows partial spectra taken with the Li-Si detector at the 1525-, 1622-, 1645-, and 1800-keV resonances. The spectra from the 1525- and 1645-keV resonances show the existence of transitions to a state at 1.51 MeV which is not observed in the sum-coincidence spectra. Beta-decay results[3,4] have shown that the 1.51-MeV state decays to the ground state exculsively via a 0.13-MeV stopover transition through the 1.38-MeV state with no observable crossover transition from the 1.51-MeV state direct to the ground state. Because of this triple cascading, a 1.51-MeV gamma ray is not observed in the sum-coincidence spectra. However, it should be noted that the 1525- and 1645-keV resonances are not suitable for performing triple-correlation measurements on the 1.38-MeV state with the present arrangements because of the cascading through the 1.51-MeV state. This difficulty arises because the sum window is sufficiently wide that some primary transitions to the 1.51-MeV state are counted as if the transitions had occurred directly to the 1.38-MeV state, the 0.13-MeV gamma ray not being detected. Thus, such events in triple cascade mimic a double cascade, and the data acquired cannot be properly analyzed. In order to perform valid triple-correlation measurements on the 1.38-MeV state it is necessary to select resonances which do not significantly populate the 1.51-MeV state. Two such resonances are those at 1622 and 1800 keV. Spectra for these resonances are shown on the right side of Fig. 3.

The method of making the identification of the primary and secondary members of the two-part cascades and the corresponding intermediate states is illustrated in Fig. 4 where sum-coincidence spectra obtained at the 1525-, 1622-, and 1800-keV resonances are shown. Additional sum-coincidence spectra as well as spectra taken with the lithium-drift silicon detector confirm and add to the information on states indicated in Fig. 4. From a consideration of all of the above information and measurements the following intermediate states are proposed for ^{57}Co: 1.381±0.010, 1.506±0.020, 1.760 ±0.020, 1.921±0.020, 2.136±0.020, 2.60±0.03, 2.74 ±0.03, 2.80±0.03, 2.88±0.03, 3.11±0.03, 3.18±0.03, 3.27±0.03, 3.52±0.03, (3.60 or 4.04)±0.03, (3.65 or 3.99)±0.03, and (3.71 or 3.92)±0.03 MeV. The energies of the three highest intermediate states are shown in parentheses since transitions through these states were not observed at a sufficient number of resonances to establish which transitions were primaries and which were secondaries. It is clear that three states exist, but the energies of these could be either of the two values listed in the parentheses.

CORRELATION RESULTS

Triple-correlation measurements were obtained for resonances at proton energies of 1525, 1598, 1622, 1637, 1645, and 1800 keV. The preliminary work indicated that these resonances are each singlets, and provide

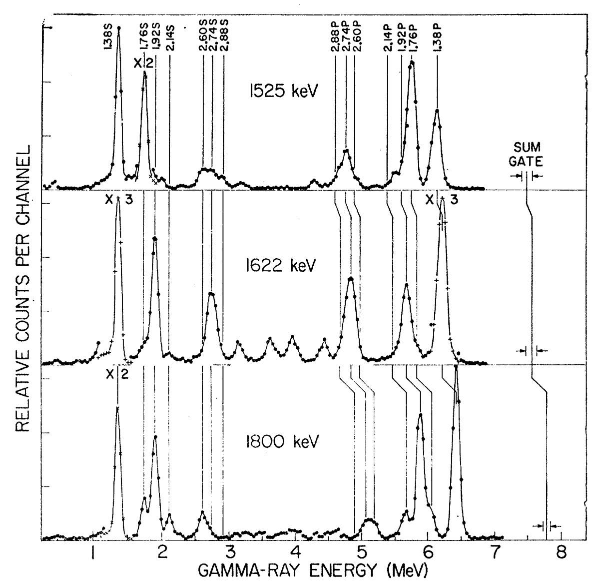

FIG. 4. Sum-coincidence spectra obtained at the resonances indicated. These spectra illustrate the shift in energy of the primary gamma rays corresponding to the difference in the excitation energy of the capturing levels, and hence serve to identify the secondary gamma rays and the corresponding intermediate excited states. The numbers above the peaks are the energies of the secondary transitions. Primary and secondary transitions are identified by the letters P and S, respectively. The data points represented by the ×'s and +'s indicate that the scale should be multiplied by the listed factors for those peaks.

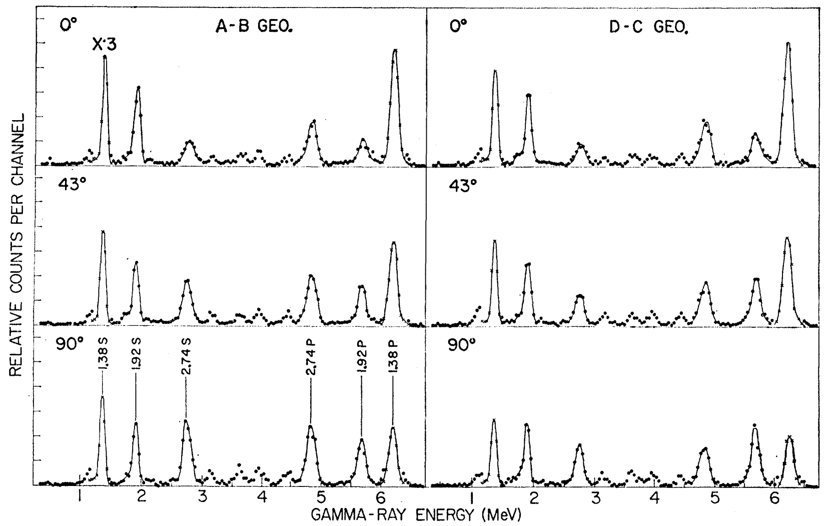

FIG. 5. Sums of runs according to angle and geometry pair for all of the triple-correlation data taken at the 1622-keV resonance. Absorption corrections, which are greatest at 90° and least at 0°, have not been applied to the data. The peaks are identified according to the energies of the intermediate states. Primary and secondary transitions are identified by the letters P and S, respectively. The data points represented by X's indicate that the scale should be multiplied by a factor of 3 for those peaks.

useful information on the states at 1.38, 1.76, 1.92, and 2.14 MeV in ^{57}Co. In general, each resonance studied strongly populated the 1.38-MeV state and only one of the other states of interest. Because of this fact it was necessary to obtain data at more different resonances than might ordinarily be studied in work of this type. On the other hand, this circumstance was rather fortuitous in the case of ^{57}Co because the 1.76-, 1.92-, and 2.14-MeV states are sufficiently close in energy to provide difficulty in resolving the primary transitions if these states were populated with nearly equal intensities at all of the resonances.

An example of the spectra produced with the double sum-coincidence spectrometer is provided in Fig. 5 which shows the sums of runs according to angle and geometry pair for all of the triple-correlation data taken at the 1622-keV resonance. The peaks labeled 2.74 MeV are due to four cascades, although the strongest one apparently involves the 2.74-MeV state. Because of the uncertain contributions to the peak intensities introduced by these other transitions to states at 2.60, 2.80, and 2.88 MeV, it has not been possible to extract valid correlation data for the 2.74-MeV state. However, from these data useful correlation results were obtained on the 1.38- and 1.92-MeV states.

In the consideration of the triple-correlation results, the intermediate states will be discussed in the order of increasing energy. Not all of the comparisons of the data with the predicted correlation functions will be shown, but typical results will illustrate the four types of two-part cascades which can be observed, i.e., pure-pure, pure-mixed, mixed-pure, and mixed-mixed cascades. These comparisons are made principally in terms of the A_2 coefficients, the A_4 coefficients not being very useful since they are generally quite small and have associated uncertainties as large as those associated with the A_2 coefficients. However, in some cases it is possible to exclude certain large quadrupole admixture ratio possibilities when these require large A_4 coefficients and the experimentally observed values are small.

1.38-MeV State

Figure 6 shows the predicted A_2 coefficients plotted as a function of the quadrupole admixture ratio δ_2 of the primary gamma-ray transition for each geometry for the spin sequence $\frac{3}{2}^- \rightarrow \frac{3}{2}^- \rightarrow \frac{7}{2}^-$, a mixed-pure case. The experimental A_2 values observed at the 1622-keV resonance are indicated by pairs of horizontal lines where the separation between these lines is a measure of the associated errors. The possible ranges of δ_2 values compatible with the experimental ranges of A_2 values are determined by the intersections of the pairs of horizontal lines with the predicted curves. For the assigned spin sequence to be consistent with the experimental A_2 values, there must be an allowed range of δ_2 values common to all geometries since the quadrupole admixture ratio of the primary transition cannot depend upon the geometry of observation. There is only one such range of δ_2 values, and it is indicated by the vertical hatched band.

Figure 7 gives a comparison for the four geometries at the 1800-keV resonance between the experimental A_2 values shown by the dots with error bars, and the predicted values shown by the crosses for the pure-pure case, $\frac{5}{2}^+ \rightarrow \frac{3}{2}^- \rightarrow \frac{7}{2}^-$. The agreement between prediction and experiment is reasonably good for the assigned spin sequence, and strengthens the $\frac{3}{2}^-$ assignment for the 1.38-MeV state.

1.76-MeV State

In Fig. 8 is shown a comparison between the predicted and experimental A_2 values observed at the 1637-keV resonance for the spin sequence $\frac{5}{2}^+ \rightarrow \frac{5}{2}^- \rightarrow \frac{7}{2}^-$, a pure-mixed cascade. For this case the predicted A_2 coefficients

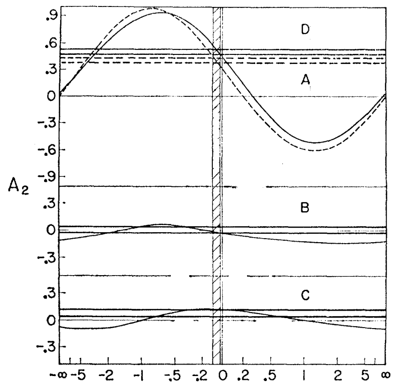

FIG. 6. The predicted variation for the four geometries, A, B, C, and D, of the A_2 coefficient plotted as a function of the arctangent of the primary quadrupole admixture ratio δ_2 for the spin sequence $\frac{3}{2}^- \to \frac{3}{2}^- \to \frac{7}{2}^-$, a mixed-pure cascade. The experimental A_2 values, indicated by pairs of horizontal lines, are for the 1.38-MeV state as observed at the 1622-keV resonance. The hatched vertical band indicates the range of δ_2 common to all geometries. The sign convention for the quadrupole admixture ratio is that due to Goldfarb. See Ref. 13.

are plotted as a function of the secondary quadrupole admixture ratio δ_3. It is to be noted that there are two regions of allowable δ_3 values. As a consequence of these two possible ranges of δ_3, the quadrupole admixture ratio of the secondary transition is ambiguous. The 1.76-MeV state was also studied at the 1525- and 1598-keV resonances. Essentially the same two ranges of δ_3 values are allowed at these resonances, and the A_4 coefficients are compatible with either range. It has not been possible, therefore, to eliminate the ambiguity concerning the secondary quadrupole admixture ratio for the 1.76-MeV transition.

TABLE II. Values of the A_2 and A_4 coefficients of the normalized Legendre polynomial obtained from least-squares analyses of all of the experimental triple-correlation data. The results are identified according to the resonance energy, the energy of the intermediate state, and the geometry of observation. When a coefficient is predicted to be zero, the fact is noted by enclosure of the experimentally determined value in parentheses.

Resonance (keV)	State (MeV)	Geometry	A_2	A_4
1525	1.76	A	−0.294±0.039	0.024±0.037
		B	0.070±0.048	(−0.029±0.034)
		C	0.078±0.040	(0.024±0.037)
		D	−0.298±0.038	(0.013±0.036)
1598	1.76	A	−0.258±0.052	0.020±0.048
		B	0.067±0.052	(0.092±0.087)
		C	0.104±0.054	(0.008±0.050)
		D	−0.258±0.050	(0.019±0.047)
1622	1.38	A	0.396±0.026	(0.043±0.025)
		B	0.010±0.028	(0.068±0.027)
		C	0.067±0.031	(0.009±0.030)
		D	0.491±0.025	(0.001±0.024)
	1.92	A	−0.380±0.053	−0.046±0.050
		B	0.055±0.055	(0.110±0.052)
		C	0.022±0.052	(0.071±0.057)
		D	−0.374±0.047	(−0.034±0.045)
1637	1.76	A	0.416±0.073	(0.065±0.069)
		B	0.037±0.075	(0.027±0.071)
		C	0.047±0.084	(0.051±0.078)
		D	0.516±0.070	(−0.020±0.067)
	2.14	A	0.101±0.059	−0.113±0.056
		B	(−0.081±0.063)	(0.094±0.059)
		C	−0.061±0.064	(−0.065±0.060)
		D	0.074±0.060	−0.120±0.055
1645	1.92	A	−0.087±0.046	−0.064±0.047
		B	0.082±0.050	(−0.011±0.059)
		C	0.084±0.052	(0.083±0.058)
		D	−0.184±0.036	(0.015±0.034)
1800	1.38	A	−0.359±0.048	(0.055±0.037)
		B	0.116±0.035	(−0.013±0.035)
		C	0.126±0.044	(0.028±0.041)
		D	−0.306±0.044	(0.013±0.036)
	1.92	A	0.361±0.051	(−0.059±0.049)
		B	0.114±0.056	(0.051±0.053)
		C	0.078±0.069	(0.027±0.060)
		D	0.525±0.056	(0.020±0.053)

1.92-MeV State

Figure 9 is a comparison in the form of a contour plot for the 1622-keV resonance between experiment and the predictions for the spin sequence $\frac{3}{2}^- \to \frac{5}{2}^- \to \frac{7}{2}^-$, a mixed-mixed case. Agreement between the predictions and experiment is manifest by an overlap of all four bands. The overlap is quite good, although there are six regions where it occurs. Thus, ambiguities exist for both the primary and secondary quadrupole admixture ratios. The A_4 contour plot for all four geometries is compatible with all six regions of overlap. The 1.92-MeV state was also studied at the 1645- and 1800-keV resonances. The same general ranges of δ_3 are allowed for these resonances, and, therefore, the ambiguities persist.

2.14-MeV State

Triple-correlation measurements were made on the 2.14-MeV state at only the 1637-keV resonance. The data are compatible with a spin sequence assignment of $\frac{5}{2}^+ \to \frac{5}{2}^+ \to \frac{7}{2}^-$, a mixed-pure case. While it is generally desirable to study a given intermediate state at more than one resonance, this state was not sufficiently populated at other acceptable resonances to make measurement practicable. However, at the 1637-keV resonance measurements were also made for the 1.76-MeV

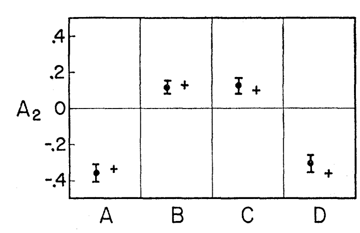

FIG. 7. A comparison for the geometries A, B, C, and D between prediction and experiment for the pure-pure cascade, $\frac{5}{2}^+ \to \frac{3}{2}^- \to \frac{7}{2}^-$ for the 1.38-MeV state as observed at the 1800-keV resonance. The experimental values are shown by dots with error bars, and the predicted values by crosses.

TABLE III. Summary of values determined for the spins and parities of the capturing state (J_b^π), those of the intermediate state (J_c^π), and the primary and secondary quadrupole admixture ratios, δ_2 and δ_3. For those δ_3 values determined at more than one resonance, the last value given (in brackets) in the column is the average. The tabulated quantities are identified according to the energy of the intermediate state and the resonance of observation. The sign convention for the δ's is that due to Goldfarb. See Ref. 13.

State (MeV)	Resonance (keV)	J_b^π	J_c^π	δ_2	δ_3
1.38	1622	$\frac{3}{2}^-$	$\frac{3}{2}^-$	-0.04 ± 0.04	
	1800	$\frac{5}{2}^+$	$\frac{3}{2}^-$		
1.76	1525	$\frac{3}{2}^-$	$\frac{5}{2}^-$	-0.19 ± 0.06	0.18 ± 0.05 or 3.62 ± 0.72
	1598	$\frac{3}{2}^-$	$\frac{5}{2}^-$	-0.16 ± 0.07	0.18 ± 0.07 or 3.46 ± 0.56
	1637	$\frac{5}{2}^+$	$\frac{5}{2}^-$		0.20 ± 0.15 or 3.64 ± 1.50 $[0.19\pm0.06]_{av}$ or $[3.57\pm0.58]_{av}$
1.92	1622	$\frac{3}{2}^-$	$\frac{5}{2}^-$	-0.27 ± 0.08 or <-9.5 or >28.6	0.12 ± 0.07 or 4.11 ± 1.03
	1645	$\frac{3}{2}^-$	$\frac{5}{2}^-$	-0.07 ± 0.05	0.24 ± 0.12 or 3.00 ± 1.07
	1800	$\frac{5}{2}^+$	$\frac{5}{2}^-$		0.23 ± 0.13 or 2.90 ± 1.06 $[0.20\pm0.06]_{av}$ or $[3.34\pm0.61]_{av}$
2.14	1637	$\frac{5}{2}^+$	$\frac{5}{2}^+$	0.33 ± 0.11	

state. The results for the 1.76-MeV state as observed at this resonance are in good agreement with the results obtained at the 1525- and 1598-keV resonances. This consistency strengthens the $\frac{5}{2}^+$ assignment for the capturing state at the 1637-keV resonance.

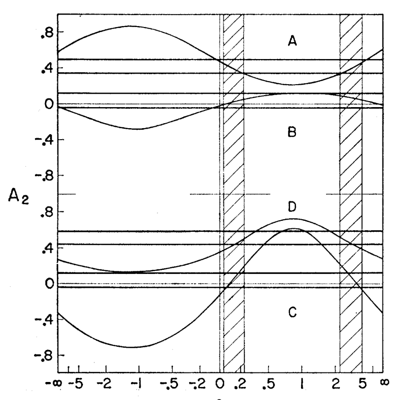

FIG. 8. The predicted variation for the geometries A, B, C, and D of the A_2 coefficient plotted as a function of the arctangent of the secondary quadrupole ratio δ_3 for the spin sequence $\frac{5}{2}^+ \to \frac{5}{2}^- \to \frac{7}{2}^-$, a pure-mixed cascade. The experimental A_2 values, indicated by pairs of horizontal lines, are for the 1.76-MeV state as observed at the 1637-keV resonance. An ambiguity exists for the secondary quadrupole admixture ratio since two ranges of values are allowed.

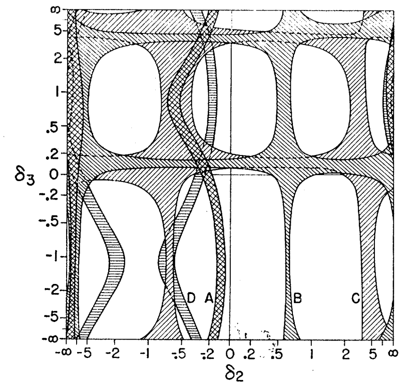

FIG. 9. Contour plot for the spin sequence $\frac{3}{2}^- \to \frac{5}{2}^- \to \frac{7}{2}^-$, a mixed-mixed cascade, for the 1.92-MeV state as observed at the 1622-keV resonance. The experimental results are shown as a function of the secondary and primary quadrupole admixture ratios, δ_3 and δ_2, respectively. Here the range of values of the admixture ratios allowed by the ranges of the experimental A_2 values is indicated by different hatching for each geometry. The admixture ratio axes are in the arctangent representation. Agreement between experiment and the predicted correlation functions is indicated by an overlap of all four bands. There are six regions where an overlap occurs, and, as a consequence, ambiguities exist for both δ_2 and δ_3.

Summary

Table II presents the results for the weighted least-squares fits for the coefficients of the normalized Legendre expansion for all of the triple-correlation measurements. For details of the data analysis consult Refs. 5 and 6. In Table III is listed a summary of the spins and probable parities of the capturing and intermediate states discussed above along with the quadrupole admixture ratios. The error estimates for the admixture ratios are somewhat subjective in that they were arrived at by considering the effects of small statistical or systematic errors on the ranges of the allowed δ_2 and/or δ_3 values and also the quality of the overlap for the four geometries. The sign convention adopted for the δ's is that due to Goldfarb.[13]

In the assignment of spin and probable parity to the various states, consistency conditions have been met. Thus, for any given intermediate state, the spin and parity deduced from the correlation data are the same for all resonances at which the state is studied, and the quadrupole admixture ratios of the transitions from the intermediate to the ground state are also the same, within errors. At a given resonance the spin and parity deduced for the capturing state are the same for all two-part cascades investigated at that resonance. However, the quadrupole admixture ratios for the primary transitions to a given state need not be the same at different resonances even if the spins and parities of the different states are the same. Finally, it should be noted that all assignments are consistent with the established J^π value[14] of $\frac{7}{2}^-$ for the ground state of ^{57}Co.

[13] L. J. B. Goldfarb, in *Nuclear Reactions*, edited by P. M. Endt and M. Demeur (North-Holland Publishing Company, Amsterdam, 1959), Vol. 1, p. 159.

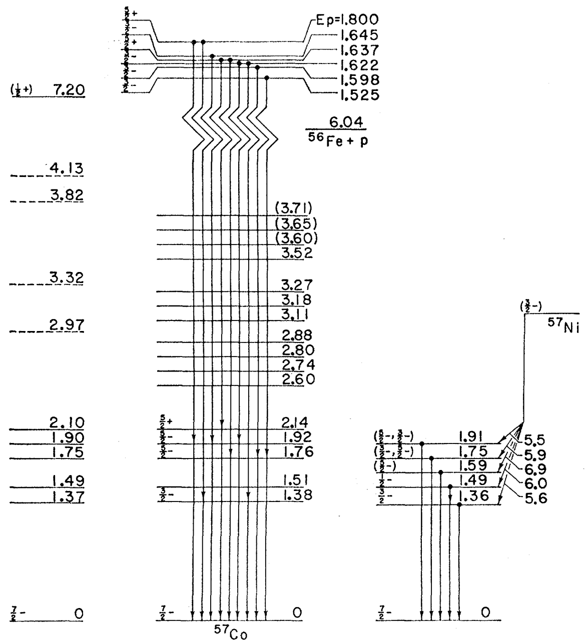

FIG. 10. Level diagram for ^{57}Co which summarizes the results of the present experiment in the middle of the figure; the (p,γ) results of Arnell and Persson (Ref. 12) and the beta-decay data of Chilosi *et al.* (Ref. 4) are shown for purposes of comparison. For the present work only those double cascades are shown by arrows for which valid triple-correlation measurements were performed.

Certain assumptions are implicit in the unique spin and parity assignments that have been made. It is assumed that any strong transition involved in the double cascades studied will be either dipole or quadrupole or an admixture of these and that higher multipole possiblities do not occur. Also, in a number of cases it has been possible to obtain agreement between prediction and experiment for both p-wave and f-wave capture. Because of the difference in barrier transmission f-wave capture is considerably less probable than p-wave capture. Since in this work observations were limited to the strongest resonances, it is therefore assumed that the resonances studied could not be due to f-wave capture, but that only s-, p-, and d-wave capture are possible. The reasonableness of this assumption is supported by the fact that where comparisons are possible the beta-decay results agree with the p-wave capture assignments, but disagree with the f-wave possibilities. An additional assumption that $M2$ radiation will not be observed to compete with $E1$ radiation permits parity assignments in cases where significant admixture is observed in the correlation results. In this paper the use of the word ***probable*** before parity implies only that polarization measurements have not been performed.

[14] J. M. Baker, B. Bleaney, K. D. Bowers, P. F. D. Shaw, and R. S. Trenam, Proc. Phys. Soc. (London) **66A**, 305 (1953).

DISCUSSION

The results of the present experiment are summarized in Fig. 10 with regard to the energies, spins, and parities of the levels of ^{57}Co. The level diagram deduced from the (p,γ) studies of Arnell and Persson[12] and the beta-decay results of Chilosi *et al.*[4] are shown for purposes of comparison. The various experimental results are in good agreement, considering uncertainties, regarding the existence of levels at 1.38, 1.51, 1.76, 1.92, and 2.14 MeV. However, the level reported by Chilosi *et al.* at 1.59 MeV has not been observed in the present work or in any other investigation of the levels of ^{57}Co. Also, for levels with energies greater than 2.14 MeV a comparison between the various results is not made since there was no observable feeding by electron capture, and Arnell and Persson have made somewhat tentative assignments for only a few higher energy states.

The spin and parity assignments for the intermediate states made as a result of the present investigation are consistent with the beta-decay results. The $\frac{5}{2}^-$ assignments to the levels at 1.76 and 1.92 MeV remove the ambiguities associated with these levels. The $\frac{3}{2}^-$ assignment to the 1.38-MeV state is in agreement with the previous $\frac{3}{2}^-$ assignment made by Konijn *et al.*[3] as a result of γ-γ correlation measurements. The $\frac{5}{2}^+$ assignment for the 2.14-MeV state is also consistent with the beta-decay results of Chilosi *et al.* to the extent that there was no beta transition reported to this state, although there was some slight evidence for a very weak transition. Such a beta transition would be first forbidden and would not be expected to compete favorably with the allowed transitions.

Chilosi *et al.* have commented at length on the applicability of the core-excitation model to the observed level structure of ^{57}Co. On the basis of one of the simplest versions of this model[15] one expects a quintet of levels with spins and parities of $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$, $\frac{9}{2}^-$, and $\frac{11}{2}^-$ with the center of gravity of the quintet being at the energy of the first 2^+ excited state of ^{58}Ni at 1452 keV. The $\frac{1}{2}^-$ state reported by Konijn *et al.* and the extra $\frac{5}{2}^-$ state as well as the $\frac{5}{2}^+$ state of the present experiment clearly are not predicted by this simple model. In order to explain these additional states other coupling schemes are necessary. Because of the paucity of experimental data on higher excited states, any comparison between the existing results and more complicated coupling schemes would not appear to be meaningful at this time.

ACKNOWLEDGMENTS

The authors wish to thank Miss Doris Ellis for preparing several computer programs employed in this work. The general laboratory assistance provided by Carl Starling is gratefully acknowledged. They also appreciate the continuing support given this work by Dr. L. A. Beach.

[15] R. D. Lawson and J. L. Uretsky, Phys. Rev. **108**, 1300 (1957).