ON-LINE GAMMA-GAMMA ANGULAR CORRELATION STUDIES
OF CASCADES IN ^{140}Ba , ^{90}Sr , AND ^{140}Cs

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On-line gamma-gamma angular correlation studies
of cascades in ^{140}Ba , ^{90}Sr , and ^{140}Cs ¹

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Angular correlation measurements were made on gamma-ray cascades in ^{140}Ba , ^{90}Sr , and ^{140}Cs . These fission-product activities were isobarically enhanced from Kr and Xe noble-gas parents, which were mass-separated by the TRISTAN isotope separator system. Levels in ^{140}Ba were populated from the 64-sec decay of ^{140}Cs , and in ^{140}Cs from the 14-sec decay of ^{140}Xe . Levels in ^{90}Sr were populated from the 2.7-min decay of ^{90}Rb , which was populated from the decay of ^{90}Kr . The most intense transitions were measured in coincidence with the first excited state to ground state transition in even-even ^{140}Ba and ^{90}Sr . The two-parameter mode of data accumulation was used to study cascades with transitions in coincidence with the 806-keV and 989-keV transitions in odd-odd ^{140}Cs . In the study of cascades in ^{140}Ba definite spin assignments were made for eight levels, and tentative spin

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assignments for five levels. For ^{90}Sr definite spin assignments were made for eight levels, and tentative assignments for six levels. A definite 1^- spin-parity assignment was made for the 103-keV level in ^{140}Cs , and tentative assignments were made for five other levels. Values are given for the angular correlation coefficients, and limits of multipolarity mixing ratios are given where applicable.

I. INTRODUCTION

Nuclear spectroscopic studies often provide valuable information about properties of the nucleus. In particular, the spins and parities of nuclear levels and multipole orders of transitions within the level scheme are of vital importance to an adequate determination of the validity of nuclear model predictions. Usually such assignments are made on the basis of supportive evidence from several experiments, where cross-checking is done for self consistency. A gamma-gamma angular correlation experiment can provide a direct measure of the spins of levels and/or mixing ratios of multipole orders of transitions. A gamma-gamma directional correlation experiment measures the number of coincidences between two gamma rays in a cascade of a nucleus as a function of angle between the emitted gammas.

The first work in directional correlation between transitions was a theoretical treatment by Hamilton (1) done in 1940. Several years of experimental failures left Hamilton's treatment untested. In 1947 Brady and Deutsch (2) performed the first successful directional correlation experiment. The initial experiments were done with two Geiger counters placed at various angles. Data collection was a slow and arduous task. With the introduction of scintillation counters, fast electronics, and reliable multichannel analyzers (3,4,5,6), experimental run time was reduced by a

factor of 10^5 .

Today one can exploit the high energy resolution of semiconductor detectors to extend angular correlation studies. Also, fast logic circuitry has evolved to the point of sophistication where coincidence information can be obtained from several different angles simultaneously. A multidetector system (7,8,9,10,11) has several detectors in fixed positions about the radioactive source. Clearly such a system has the advantage of rapid data accumulation, and eliminates the need for half-life corrections with short-lived activities. However, the complexity of logic circuitry can cause problems in terms of misrouted coincidence events, and give rise to possible differences in rates of coincidence counting of each logic circuit for a detector pair.

For this work a seven-detector angular correlation apparatus was used. Six NaI(Tl) detectors and one Ge(Li) detector were placed around the source chamber. All angles were measured with respect to the Ge(Li) detector. During an experiment, coincidence events between the six Ge(Li)-NaI(Tl) pairs were stored in six regions of a 16384-channel (16K) analyzer.

Two experimental configurations are available for data accumulation. One configuration allows for one energy gate to be set on a given transition for each NaI(Tl) detector. The coincidence data in this mode of operation are stored as

six Ge(Li) spectra, one spectrum per angular separation. The second configuration is the two-parameter mode. In this mode all coincidence events between the Ge(Li) detector and a NaI(Tl) detector are stored as paired channel addresses on a buffer tape, and several energy gates can be set after the experiment is completed.

All previous measurements (12) made with this apparatus have been done on off-line activities. These nuclei were produced by the TRISTAN isotope separator system. For the present work the angular correlation apparatus has been adapted for on-line use with the TRISTAN isotope separator.

This report will present, in order, a discussion of the theoretical background of gamma-gamma angular correlations, a brief description of the apparatus and experimental procedure, and the results of three experiments. Measurements have been made for cascades in two even-even nuclei, ^{140}Ba and ^{90}Sr , and one odd-odd nucleus, ^{140}Cs . The gamma-ray decay schemes for these three nuclei have been determined from previous experimental studies.

II. THEORETICAL FOUNDATION

Whenever two or more gamma rays are emitted in a cascade an angular correlation experiment can, in principle, be performed. Data from such an experiment give a measure of the probability of two coincident gamma rays being emitted in a cascade, and in two directions differing by an angle θ . The probability distribution function can be written

$$W(\theta) = A_0 \left(1 + \sum_{n=2,4,\dots\text{even}} A_n P_n(\cos\theta) \right)$$

where P_n is the Legendre polynomial of order n , and A_0 is an arbitrary normalization constant. Upper-limit restrictions on the value of n will be noted later. It is common in angular correlation work to choose the angle-independent term to be 1, which implies $A_0=1$. This convention is adopted in this work.

From experiment, values for the A_n 's can be determined via a least-squares method. A_n is a function of the spins of the levels and the multipole orders of transitions in the cascade. Hence, information concerning these spectroscopic quantities can be obtained. This chapter contains a discussion of the development of the angular correlation probability distribution function $W(\theta)$. The theoretical treatment presented here has been developed by Williams (13).

A. Radiation and Multipole Fields

A complete discussion of the emission or absorption of electromagnetic radiation requires the framework of the quantum description of radiation. Such a treatment is a topic in field theory involving creation-destruction operator formalism. For most electromagnetic radiation phenomena encountered in the study of the nucleus, however, a classical treatment of electromagnetic fields is sufficient.

The initial assumption made is an affirmation of the validity of Maxwell's equations for nuclear charges and currents. The time-dependent Maxwell's equations are written in Gaussian units as

$$\begin{aligned}\vec{\nabla} \cdot \vec{E}' &= 4\pi\rho_t' \\ \vec{\nabla} \cdot \vec{H}' &= -4\pi\vec{\nabla} \cdot \vec{M}' \\ \vec{\nabla} \times \vec{E}' &= -\frac{1}{c} \frac{d}{dt} (\vec{H}' + 4\pi\vec{M}') \\ \vec{\nabla} \times \vec{H}' &= \frac{4\pi}{c} \vec{J}' + \frac{4\pi}{c} \frac{d\vec{P}'}{dt} + \frac{1}{c} \frac{d\vec{E}'}{dt}\end{aligned}$$

where ρ_t' is the true charge density, $\vec{P}'$ the polarization, $\vec{J}'$ the free current, and $\vec{M}'$ the magnetic moment. The primes indicate that there is an explicit time dependence present. By virtue of a second assumption, namely that electromagnetic transitions between energy levels of a nucleus are single, monochromatic processes, the time dependent variables are written in the form

$$\vec{V}' = \vec{V} e^{-i\omega t} + \vec{V}^* e^{i\omega t}$$

where $\hbar\omega$ is the energy of the photon.

Recognizing the powerful mathematical techniques embodied in the Racah algebra of angular momentum theory, one may classify radiation according to the angular momentum carried off by the field. With this in mind, the usual definition of a 2^J -pole multipole field is the solution to Maxwell's equations in free space, which is also a simultaneous eigenfunction of the square of the total angular momentum operator, one component of the angular momentum, and the parity operator. Also note that: (1) if the parity of the magnetic field is $(-)^J$ then this is said to be an electric multipole of order 2^J , and, (2) if the parity of the magnetic field is $(-)^{J+1}$ then this is said to be a magnetic multipole of order 2^J .

A particular solution of the free space Maxwell's equations which also satisfies the requirements of a 2^J -pole multipole field is the vector spherical harmonic defined as

$$\vec{T}_{JLm}(\theta, \phi) \equiv \sum_{v=-1}^1 (-)^{L-l+m} \sqrt{2J+1} \begin{pmatrix} L & 1 & J \\ m-v & v & -m \end{pmatrix} Y_{L, m-v}(\theta, \phi) \vec{e}_v$$

where $Y_{L, m-v}(\theta, \phi)$ is the spherical harmonic function of order L , the $\vec{e}_v$'s are spherical unit vectors, and the factor with large parentheses is a 3-J symbol. Four angular momentum properties of the vector spherical harmonics of interest here

are

$$\pi \vec{T}_{JLm}(\theta, \varphi) = (-)^L \vec{T}_{JLm}(\theta, \varphi)$$

$$\vec{J}^2 \vec{T}_{JLm}(\theta, \varphi) = J(J+1) \hbar^2 \vec{T}_{JLm}(\theta, \varphi)$$

$$\vec{L}^2 \vec{T}_{JLm}(\theta, \varphi) = L(L+1) \hbar^2 \vec{T}_{JLm}(\theta, \varphi)$$

$$J_z \vec{T}_{JLm}(\theta, \varphi) = m \hbar \vec{T}_{JLm}(\theta, \varphi)$$

The usual method of solution is to expand the $\vec{H}$ field in terms of vector spherical harmonics and solve Maxwell's equation via a variation of parameters, or Green's function method.

The two measured quantities in the solution are the fields $\vec{E}$ and $\vec{H}$. Expressions for these fields are written for each type of multipole field:

i.) For a 2^J -pole electric multipole (will be denoted EJ henceforth)

$$\vec{H} = a_{Jm}(e) h_J(kr) \vec{T}_{JJm}(\theta, \varphi)$$

$$\vec{E} = -a_{Jm}(e) \sum_{\nu=\pm 1} (-)^{J-1} \sqrt{2(J+\nu)+1} \begin{pmatrix} J & 1 & J+\nu \\ 0 & 0 & 0 \end{pmatrix} h_{J-1}(kr) \vec{T}_{J, J-\nu, m}(\theta, \varphi) \quad (1)$$

ii.) For a $2^{J'}$ -pole magnetic multipole (will be denoted MJ' henceforth)

$$\vec{H} = a_{J'm'}(m) \sum_{v=\pm 1} (-)^{J'-1} \sqrt{2(J'+v)+1} \begin{pmatrix} J' & 1 & J'+v \\ 0 & 0 & 0 \end{pmatrix} h_{J'-v}(kr) \vec{T}_{J',J'-v,m'}(\theta,\varphi) \quad (2)$$

$$\vec{E} = a_{J'm'}(m) h_{J'}(kr) \vec{T}_{J',J',m'}(\theta,\varphi)$$

Note that $h_J(kr)$ is the spherical Hankel function of the first kind, k is the wave number, equal to ω/c , and the $a_{Jm}(\frac{e}{m})$'s represent the amplitudes for the 2^J -pole electric/magnetic multipole.

B. Energy Emitted from an Electric/Magnetic

Multipole Mixture per unit Time into Solid Angle $d\Omega(\theta,\phi)$

Consider the time-dependent Poynting vector

$\vec{S}' = \frac{c}{4\pi} (\vec{E}' \times \vec{H}')$. The primes again represent an explicit time dependent character for the corresponding variables. Under the monochromatic, single-process photon assumption it can be shown that the time-averaged Poynting vector is

$$\vec{S} = \frac{c}{2\pi} \text{Re} (\vec{E}^* \times \vec{H}) \quad (3)$$

The Poynting vector represents the energy emitted per unit time per unit area. Let $\underline{u}$ be defined as the energy/time. Then the Poynting vector has a component in the radial direction $\vec{r}$ with value $\vec{e}_r \cdot \vec{S}$, where $\vec{e}_r$ is the radial unit vector.

Then,

$$\vec{e}_r \cdot \vec{S} = \frac{du}{dA} \Big|_{r \text{ direction}} = \frac{1}{r^2} \frac{du}{d\Omega} \Big|_{r \text{ direction}},$$

or the energy emitted per unit time into solid angle $d\Omega(\theta, \phi)$ is

$$\frac{du}{d\Omega(\theta, \phi)} = r^2 \vec{e}_r \cdot \vec{S} \quad (4)$$

In a classical representation of electromagnetic radiation the $\vec{E}$ and $\vec{H}$ fields of a photon are, in general, described by a summation of expressions corresponding to several multipole orders. In particular, for a radiative transition between two levels with spins I_i , I_f angular momentum selection rules limit the multipole orders between $|I_f - I_i|$ and $I_f + I_i$, inclusive. However, transition probabilities decrease rapidly with increasing multipolarity. Indeed, for most cases it is sufficient to express each field of a photon as a sum of two expressions from neighboring multipole orders. Such a description is referred to as a mixed multipole. From equations 1 and 2 it is straightforward to write explicit expressions for the fields of a photon with an MJ'/EJ multipole mixture.

$$\begin{aligned} \vec{H} &= \vec{H}_{EJ} + \vec{H}_{MJ'} \\ \vec{E} &= \vec{E}_{EJ} + \vec{E}_{MJ'} \end{aligned} \quad (5)$$

From equations 1-5 the explicit form for the energy emitted per unit solid angle per unit time is

$$\begin{aligned} \frac{du}{d\Omega(\theta, \varphi)} = & \frac{r^2 c}{2\pi} \vec{e}_r \cdot \text{Re} \left[\left\{ -a_{Jm}(e) \sum_{\nu=\pm 1} (-)^{J-1} \sqrt{2(J+\nu)+1} \begin{pmatrix} J & 1 & J+1 \\ 0 & 0 & 0 \end{pmatrix} \right. \right. \\ & \times h_{J-1}(kr) \vec{T}_{J, J-\nu, m}(\theta, \varphi) + a_{J'm'}(m) h_{J'}(kr) \vec{T}_{J' J' m'}(\theta, \varphi) \left. \right\} \\ & \times \left\{ a_{Jm}(e) h_J(kr) \vec{T}_{Jm}(\theta, \varphi) + a_{J'm'}(m) \sum_{\nu=\pm 1} (-)^{J'-1} \sqrt{2(J'+\nu)+1} \right. \\ & \times \left. \begin{pmatrix} J' & 1 & J'+\nu \\ 0 & 0 & 0 \end{pmatrix} h_{J'-\nu}(kr) \vec{T}_{J', J'-\nu, m'}(\theta, \varphi) \right\} \left. \right] \end{aligned}$$

Clearly four terms result from the cross product. Each term is processed in a straightforward manner with the aid of the identity

$$\begin{aligned} \vec{e}_r \times \vec{T}_{JLm}(\theta, \varphi) = & -i \sqrt{6(2L+1)} \sum_{\lambda} (-)^{L-1+J+\lambda} \sqrt{2\lambda+1} \begin{pmatrix} L & 1 & \lambda \\ 0 & 0 & 0 \end{pmatrix} \left\{ \begin{matrix} J & \lambda & 1 \\ 1 & 1 & L \end{matrix} \right\} \\ & \times \vec{T}_{JLm}(\theta, \varphi) \end{aligned}$$

and the special properties of the 3-J and 6-J symbols as found in Rotenberg, et al. (14). Note that the factor in the curly brackets is defined as the 6-J symbol. The general result is given in equation 6.

$$\begin{aligned}
\frac{du}{d\Omega(\theta, \varphi)} = & \frac{-cr^2}{2\pi} \left\{ |a_{Jm}(e) \vec{T}_{JJm}(\theta, \varphi)|^2 \right. \\
& \times \operatorname{Re} \left[i h_J^*(kr) \left(\frac{J+1}{2J+1} h_{J-1}(kr) - \frac{J}{2J+1} h_{J+1}(kr) \right) \right] \\
& + |a_{J'm'}(m) \vec{T}_{J'J'm'}(\theta, \varphi)|^2 \\
& \times \operatorname{Re} \left[i h_{J'}^*(kr) \left(\frac{J'+1}{2J'+1} h_{J'-1}(kr) - \frac{J'}{2J'+1} h_{J'+1}(kr) \right) \right] \\
& + \operatorname{Re} \left[i a_{J'm}^*(m) a_{Jm}(e) \left[h_{J'}^*(kr) h_J(kr) \left(\sqrt{\frac{J}{2J+1}} \vec{T}_{J,J+1,m}(\theta, \varphi) \right. \right. \right. \\
& \cdot \vec{T}_{J,J'm}^*(\theta, \varphi) + \sqrt{\frac{J+1}{2J+1}} \vec{T}_{J,J-1,m}(\theta, \varphi) \cdot \vec{T}_{J,J'm}^*(\theta, \varphi) \Big) \\
& + \sqrt{\frac{J'+1}{2J'+1}} h_{J'-1}^*(kr) \left(\frac{J+1}{2J+1} h_{J-1}(kr) - \frac{J}{2J+1} h_{J+1}(kr) \right) \vec{T}_{JJm}(\theta, \varphi) \\
& \cdot \vec{T}_{J',J'-1,m}^*(\theta, \varphi) + \sqrt{\frac{J'}{2J'+1}} h_{J'+1}^*(kr) \left(\frac{J}{2J+1} h_{J+1}(kr) \right. \\
& \left. \left. \left. - \frac{J+1}{2J+1} h_{J-1}(kr) \right) \vec{T}_{JJm}(\theta, \varphi) \cdot \vec{T}_{J',J'+1,m}^*(\theta, \varphi) \right] \right] \Big\} \quad (6)
\end{aligned}$$

Note that the explicit angular dependence is found in the dot products between vector spherical harmonics.

A simplification can be made in equation 6 by noting that for Hankel functions of the first kind

$h_l(x) \xrightarrow{x \text{ large}} \exp(i(x - (l+1)\pi/2))/x$. In the case of equation 6 the argument of the Hankel functions is the product of the

wave number times the radial distance from the source of the photon to the point of observation. Experimentally, typical distances from source to detector lie in a range greater than 10^{-1} meter. For a 1-MeV photon $k=5.1 \times 10^{12} \text{ m}^{-1}$. So $kr > 5.1 \times 10^{11}$ which indeed satisfies the special condition for the above approximation of the Hankel function.

Assume now that the electric/magnetic multipole orders differ by 1, and let $L'=L+1$. Then, two possible cases result for the electric/magnetic multipole mixture: (1) an ML/EL' mixture, or, (2) an EL/ML' mixture. For each case, equation 6 is simplified to the form found in equation 7.

$$\begin{aligned} \frac{du}{d\Omega} \begin{pmatrix} \text{ML, EL} \\ \text{EL, ML} \end{pmatrix} = \frac{c}{2\pi k^2} \left\{ |a_{L,m}^{(e)} \vec{T}_{L,L,m}(\theta,\varphi)|^2 + |a_{L,m}^{(m)} \vec{T}_{LL,m}(\theta,\varphi)|^2 \right. \\ - \text{Re} \left[i a_{L,m}^{(m)*} a_{L,m}^{(e)} \left[\sqrt{\frac{L}{2L+1}} \vec{T}_{L,L+1,m}(\theta,\varphi) \cdot \vec{T}_{LL,m}^*(\theta,\varphi) \right. \right. \\ + \sqrt{\frac{L+1}{2L+1}} \vec{T}_{L,L-1,m}(\theta,\varphi) \cdot \vec{T}_{LL,m}^*(\theta,\varphi) + \sqrt{\frac{L+1}{2L+1}} \vec{T}_{L,L,m}(\theta,\varphi) \\ \left. \left. \cdot \vec{T}_{L,L-1,m}^*(\theta,\varphi) + \sqrt{\frac{L}{2L+1}} \vec{T}_{L,L,m}(\theta,\varphi) \cdot \vec{T}_{L,L+1,m}^*(\theta,\varphi) \right] \right] \left. \right\} \quad (7) \end{aligned}$$

Notice here that the arguments of the field amplitudes indicate the electric/magnetic multipole. In particular, case (1) appears above case (2). Further, note that for the same ratio of $a_{L,m}/a_{L',m}$ in each multipole case, the angular distribution of the radiation mixture is identical. This means

that a measurement of the angular distribution of the radiation does not differentiate between an ML/EL' or EL/ML' mixture. Thus, in the following equations the field amplitudes will not contain any radiation type label.

Finally, by utilizing the identity,

$$\begin{aligned} & \sqrt{\frac{L}{2L+1}} \vec{T}_{L,L+1,m}^*(\theta,\varphi) \cdot \vec{T}_{L',L',m}(\theta,\varphi) + \sqrt{\frac{L+1}{2L+1}} \vec{T}_{L,L-1,m}^*(\theta,\varphi) \cdot \vec{T}_{L',L',m}(\theta,\varphi) \\ &= \sqrt{\frac{L}{2L+1}} \vec{T}_{L',L'+1,m}(\theta,\varphi) \cdot \vec{T}_{LLm}^*(\theta,\varphi) + \sqrt{\frac{L+1}{2L'+1}} \\ & \times \vec{T}_{L',L'-1,m}(\theta,\varphi) \cdot \vec{T}_{LLm}(\theta,\varphi) \end{aligned}$$

equation 7 is recast in the form,

$$\begin{aligned} \frac{du}{d\Omega} = & \frac{c}{2\pi k^2} \left\{ |a_{L'm} \vec{T}_{L',L',m}(\theta,\varphi)|^2 + |a_{Lm} \vec{T}_{LLm}(\theta,\varphi)|^2 \right. \\ & - 2 \operatorname{Re} \left[i a_{Lm}^* a_{L'm} \left[\sqrt{\frac{L}{2L+1}} \vec{T}_{L,L+1,m}^*(\theta,\varphi) \cdot \vec{T}_{L',L',m}(\theta,\varphi) \right. \right. \\ & \left. \left. + \sqrt{\frac{L+1}{2L+1}} \vec{T}_{L,L-1,m}^*(\theta,\varphi) \cdot \vec{T}_{L',L',m}(\theta,\varphi) \right] \right] \left. \right\}. \end{aligned} \quad (8)$$

C. The Angular Correlation Probability

Distribution Function W(θ)

First, choose as a prototype cascade two transitions between three spin states of the nucleus. This cascade is shown in Figure 1(a). The first transition is a multipole mixture of order L_1/L'_1 where $L'_1 \equiv L_1 + 1$. This transition

depopulates the level denoted by total spin I_i and spin projection m_i . The intermediate state with total spin I and spin projection m is, in turn, depopulated by a pure multipole transition of order L_2 . The final spin state is labelled by total spin I_f and has spin projection m_f .

The transition probability of the first photon being emitted into solid angle $d\Omega(\theta, \phi)$ per unit time is given in equation 9,

$$T(I_i \rightarrow I, m, d\Omega(\theta, \phi)) = \frac{1}{\hbar\omega} \frac{du}{d\Omega(\theta, \phi)} \quad (9)$$

where $\hbar\omega$ is the energy of the monochromatic, single-process photon, and m is the spin projection substate in which the nucleus resides after this transition. In order to utilize the explicit expression for $du/(d\Omega(\theta, \phi))$ in equation 8, recall that this equation is a result of a classical treatment of electromagnetic radiation and that translation into quantum mechanical form is necessary. In particular, the field amplitudes in equation 8 are now represented as matrix elements of the form $\langle I_m | a_{L_1 m_1} | I_i m_i \rangle$.

Since interest here lies in the angular distribution between the two gammas emitted, it is appropriate to use the direction of the first gamma ray as defining the z-axis of the coordinate system. By combining equation 8, the Wigner-Eckart Theorem, and some Racah algebra, equation 9 is rewritten in the form

$$\begin{aligned}
T(I_i \rightarrow I, m) &= \frac{c(2I+1)}{8\pi^2 k^2 \hbar \omega(2I_i+1)} | \langle I || a_{L_i} || I_i \rangle |^2 \\
&\times \sum_{m, m'} \left[\delta^2 \begin{pmatrix} I & L_1' & I_i \\ -m & m' & m_i \end{pmatrix}^2 (2L_1'+1)^2 \begin{pmatrix} L_1' & 1 & L_1' \\ 0 & m' & -m' \end{pmatrix} + \right. \\
&+ \begin{pmatrix} I & L_1 & I_i \\ -m & m' & m_i \end{pmatrix} (2L_1+1)^2 \begin{pmatrix} L_1 & 1 & L_1 \\ 0 & m' & -m' \end{pmatrix}^2 \left. \right] \\
&- 2\delta \begin{pmatrix} I & L_1' & I_i \\ -m & m' & m_i \end{pmatrix} \begin{pmatrix} I & L_1 & I_i \\ -m & m' & m_i \end{pmatrix} \left[\frac{\sqrt{L_1+1}}{2L_1+1} (2L_1'+1) \sqrt{2L_1+1} \right. \\
&\left. \begin{pmatrix} L_1' & 1 & L_1' \\ 0 & m' & -m' \end{pmatrix} \begin{pmatrix} L_1-1 & 1 & L_1' \\ 0 & m' & -m' \end{pmatrix} + \sqrt{L_1} (2L_1'+1)^{3/2} \begin{pmatrix} L_1' & 1 & L_1' \\ 0 & m' & -m' \end{pmatrix} \right. \\
&\left. \times \begin{pmatrix} L_1' & 1 & L_1' \\ 0 & m' & -m' \end{pmatrix} \right]
\end{aligned} \tag{10}$$

where $m' \equiv m_1 = m_1'$, $\langle I || a_{L_1} || I_i \rangle$ is the reduced matrix element of the amplitude a_{L_1} , and $\delta \equiv \langle I || a_{L_1'} || I_i \rangle / \langle I || a_{L_1} || I_i \rangle$ is the mixing ratio. The square of the mixing ratio represents the ratio of intensity of the higher order multipole L_1' to that of the lower multipole order L_1 . Thus the expression $100 \times \frac{\delta^2}{1+\delta^2}$ is the percent mixture of multipole order L_1' . Note that the angular dependence is gone since this gamma ray

defines the z-axis, and hence the azimuthal and polar angles are set to zero. Also, by summing over spin projections m_i of the initial spin I_i and dividing by $2I_i+1$, an average over these substates is made. The taking of an average can be justified by noting that at room temperature the substates are equally populated, since the hyperfine splitting of these substates due to the interaction of the magnetic moment of the nucleus with the induced magnetic field of the electrons is much smaller, by several orders of magnitude, than kT for a Boltzman distribution.

Equation 10 gives a measure for the relative population of the intermediate spin substates m . This observation is used together with equation 8 to yield an expression for the transition probability of the second photon being emitted into solid angle $d\Omega(\theta, \phi)$ per unit time and ending up in any final spin projection substate m_f .

$$T(I \rightarrow I_f, d\Omega(\theta, \phi)) = N_1 \sum_{mm_f m_2} T(I_i \rightarrow I, m) \begin{pmatrix} I_f & L_2 & I \\ -m_f & m_2 & m \end{pmatrix}^2$$

$$\times | \langle I_f || a_{L_2} || I \rangle \bar{T}_{L_2 L_2 m_2}(\theta, \phi) |^2$$

Since we are interested in the angular distribution of the radiation, constants are combined into an arbitrary normalization factor N_1 . Note also that this equation is a weighted average in terms of the relative population of the

intermediate spin projection substates $\underline{m}$. Since the z-axis is defined by the direction of first gamma ray, the azimuthal angle θ in this equation represents the angle between these successive transitions. Thus this equation is a measure for the probability distribution of these successive transitions being emitted at an angle θ .

Upon recasting the vector spherical harmonics, the angular dependence is seen explicitly in equation 11.

$$W(\theta) = N_2 \sum_{mm_f m_2} T(I_i \rightarrow I, m) (-)^{m_2} (2\lambda+1) \begin{pmatrix} I_f & L_2 & I \\ -m_f & m_2 & m \end{pmatrix}^2$$

$$\times \begin{pmatrix} L_2 & \lambda & L_2 \\ m_2 & 0 & -m_2 \end{pmatrix} \begin{pmatrix} L_2 & \lambda & L_2 \\ 0 & 0 & 0 \end{pmatrix} \left\{ \begin{matrix} L_2 & L_2 & 1 \\ L_2 & L_2 & \lambda \end{matrix} \right\} P_\lambda(\cos\theta) \quad (11)$$

where $P_\lambda(\cos\theta)$ is the Legendre polynomial of order λ . The triangle rule implied in the 3-J symbol which contains zeroes in the bottom row imposes even values for λ .

By substituting the explicit expression for $T(I_i \rightarrow I, m)$ found in equation 10 into equation 11 and processing the Racah algebra, one obtains a final form for the angular correlation probability distribution function.

$$W(\theta) = 1 + \sum_{n=2,4,\dots,\text{even}} A_n P_n(\cos\theta)$$

$$A_n \equiv a_n(1) a_n(2)$$

$$a_n(1) = \frac{F_n(L_1 L_1 I_1 I_1) + \delta^2 F_n(L_1 L_1 I_1 I_1) + 2\delta F_n(L_1 L_1 I_1 I_1)}{1 + \delta^2}$$

$$a_n(2) = F_n(L_2 L_2 I_1 I_1)$$

(12)

$$F_n(LL' I_1 I_2) \equiv (-)^{I_1+I_2+1} \sqrt{2n+1} \sqrt{2L+1} \sqrt{2L'+1} \sqrt{2I_2+1}$$

$$\begin{pmatrix} L & L' & n \\ 1 & -1 & 0 \end{pmatrix} \left\{ \begin{matrix} I_2 & I_2 & n \\ L & L' & I_1 \end{matrix} \right\}$$

The expressions for $a_n(1)$ and $a_n(2)$ represent functions in parameters of the first and second transitions, respectively. The function $F_n(LL' I_1 I_2)$ is called an F-coefficient. A tabulation of F-coefficients is found in Siegbahn (15).

The spin triangles in the 3-J and 6-J symbols of the F-coefficient $F_n(LL' I_1 I_2)$ impose an upper limit to the value of n . That is, $n_{\max} \leq \min(2I_2, L+L')$.

D. The Angular Correlation Probability Distribution Function for Three Cascades

1. Mixed transitions with one intermediate spin

Recall that the result in equation 12 physically corresponds to the cascade in Figure 1(a). There are two ob-

Figure 1. Three classes of cascades. (a) mixed transitions with one intermediate spin state, (b) pure transitions (c) mixed transitions with two intermediate spins

served transitions and one intermediate spin state here. This cascade is referred to as a direct cascade. One can proceed in precisely the same manner to show that if the second transition has a multipole mixture of order L_2/L_2' , and the first transition has a pure multipole L_1 contribution, that the form of $W(\theta)$ is identical with equation 12, except that $a_n(2)$ is quadratic in the L_2/L_2' mixing ratio and $a_n(1)$ is equal to a single F-coefficient.

2. Pure transitions with one intermediate spin

In Figure 1(b) each of the two transitions has only one multipole component. This is a limiting case in equation 12 where the L_1' admixture in the first transition is zero. That is, the mixing ratio is equal to zero, and the angular correlation coefficient A_n is just a product of the two F-coefficients, $F_n(L_1 L_1 I_i I) F_n(L_2 L_2 I_f I)$. From this it is clear that the highest order term in the summation is

$$n_{\max} \leq \min(2I, 2L_1, 2L_2).$$

3. Mixed transitions with two identical spins

Figure 1(c) shows the case where there are three gamma rays emitted in the cascade with two intermediate spins. The angular correlation measured for this cascade is between the first and third gamma rays. The intermediate gamma ray is not detected. This cascade is referred to as a gamma-skip-gamma cascade. One can proceed in similar fashion to that outlined above to obtain an analytical expression for the

angular distribution function. The results of such a treatment are found in Siegbahn (15). In summary, the angular correlation coefficient A_n is a product of three factors $a_n(1) u_n(L_u L_u' II') a_n(2)$. The a 's refer to the two observed gamma rays and their forms are identical with those in equation 12. The third factor has the form

$$u_n(L_u L_u' II') \equiv \sqrt{2I+1} \sqrt{2I'+1} (-)^{I+I'}$$

$$\times \frac{\left[(-)^{L_u} \left\{ \begin{matrix} 1 & 1 & n \\ 1 & 1 & L_u \end{matrix} \right\} + \delta_u^2 (-)^{L_u'} \left\{ \begin{matrix} 1 & 1 & n \\ 1 & 1 & L_u' \end{matrix} \right\} \right]}{1 + \delta_u^2}$$

where δ_u is the mixing ratio for the mixed multipole orders L_u/L_u' in the intermediate transition. The limit on the summation for this case is given by $n_{\max} \leq \min(2I, 2I', 2L_1, 2L_2)$.

III. EXPERIMENTAL ARRANGEMENT

A. The TRISTAN Isotope Separator System

The source activities of the angular correlation studies in this work were obtained from the TRISTAN on-line isotope separator system at the Ames Laboratory Research Reactor. A detailed description of the system is found elsewhere (16,17,18,19,20,21) so only a brief outline will follow.

A schematic view of the TRISTAN facility is shown in Figure 2. A ^{235}U -enriched sample is placed in a neutron flux of about 3×10^9 thermal neutrons per $\text{cm}^2\text{-sec}$ at a reactor face. Noble gas fission products emanate from the stearate sample and are carried to the ion source through a 1.6-meter transport tube. The mass distribution of thermal-induced fission of ^{235}U is shown in Figure 3. The noble gases krypton and xenon have yield peaks at masses 90 and 139. To date, experimental decay data have been collected for mass ranges 85-94 and 136-144 with TRISTAN.

The fission products are ionized, accelerated through 50kV, focused through two electrostatic lenses, and then introduced into a 90° sector magnet. Upon leaving the analyzer magnet the ion beam is dispersed and arrives at the collector box for mass selection and beam position stabilization. From the collector box the beam is directed, via the switching magnet, to the appropriate experimental station.

Figure 2. Schematic layout of the TRISTAN isotope separator facility

Figure 3. ^{235}U fission yield as a function of mass number and proton number

For the angular correlation studies in this report the ion beam was deposited on an aluminized Mylar tape at the moving tape collector (MTC) (see Reference 22). The MTC contains two reels of Mylar tape which can be driven in forward or reverse directions. The MTC was used here to enhance isobarically certain decay products of krypton or xenon, and in particular ^{140}Ba , ^{140}Cs , and ^{90}Sr . This was accomplished by delaying transport of the deposit point, after the source was collected, to the center of the angular correlation chamber. Further amplification of this point will appear in the next chapter.

B. The Angular Correlation Apparatus

A top view of the angular correlation apparatus, connected to the MTC, is shown in Figure 4. The apparatus consists of six NaI(Tl) detectors carefully positioned at specific angles with respect to one Ge(Li) detector. The Ge(Li) detector, positioned in a liquid nitrogen dewar in Figure 4, is labelled detector 6 for future reference. The six NaI(Tl) detectors are labelled 1-5, and 7. NaI(Tl) detector 1 appears, in the figure, above the angular correlation chamber and just to the right of a vertical line through the center of the circular table top. Detectors 1-6 are spaced clockwise at 45° intervals, and NaI(Tl) detector 7 bisects the 135° angle between the Ge(Li) detector (number 6) and NaI(Tl) detector 1.

Figure 4. Angular correlation apparatus connected to the moving tape collector

Simultaneous gamma-gamma coincidence measurements are made between the six Ge(Li)-NaI(Tl) pairs. Thus this apparatus provides a measure for the angular correlation distribution function at six angles. Let θ_i be the angle between the i^{th} NaI(Tl) detector and the Ge(Li) detector. Then,

$$\begin{aligned}\theta_1 &= \theta_3 = 135^\circ & \theta_5 &= 45^\circ \\ \theta_2 &= 180^\circ & \theta_7 &= 67.5^\circ \\ \theta_4 &= 90^\circ\end{aligned}$$

The placement of the NaI(Tl) detectors is indicated on a plot of Legendre polynomials P_2 and P_4 versus θ in Figure 5. Note that P_4 passes through a maximum or minimum at 45° intervals. Thus, such a detector placement should make this apparatus sensitive to the magnitude of the correlation coefficient A_4 . The angle $\theta_7=67.5^\circ$ is chosen so that not all the coincidence data are gathered at 45° intervals with respect to the Ge(Li) detector.

The NaI(Tl) detectors each have cylindrical dimensions of 5 cm (height) x 5 cm (diameter), and are optically coupled to R.C.A. 6342A (ten-stage) photomultiplier tubes. The preamplifier has been modified by Basinger (12) so that an energy signal is taken from the ninth dynode, and a timing signal from the anode of the phototube. The Ge(Li) detector is an ORTEC Model 8101-0924, having 57.7 cm³ active volume, a depletion depth of 1.25 cm, and a resolution of 2.4 keV full-width-at-half-maximum for a 1.33-MeV gamma ray. The

Figure 5. Legendre polynomials $P_2(\cos \theta)$ and $P_4(\cos \theta)$ with detector placement

efficiency of the detector is rated at 9.9% with respect to a 7.6-cm x 7.6-cm cylindrical NaI(Tl) detector at 1.33 Mev.

There are two outputs on the preamplifier, one output used as the timing signal and the other as the energy signal.

C. Experimental Configurations

The angular correlation apparatus was used in two different experimental configurations for the studies in this work. For the cascades in ^{140}Ba and ^{90}Sr , six single channel analyzers (SCA's) selected an energy gate from the six NaI(Tl) detectors. The two-parameter mode of data accumulation was used for measurements of cascades in ^{140}Cs . A complete description of the individual electronics units can be found in the work by Basinger (12).

1. SCA-gated configuration

The connection between electronics units for this configuration is indicated in Figure 6. As pointed out in the last section each of the seven detectors provides a timing and an energy signal.

In the case of the Ge(Li) detector, the energy pulse is shaped and amplified by a Nuclear Data ND-524 amplifier. The signal then passes through a 3-microsecond delay and is digitized by a Geoscience 8050 analog-to-digital converter (ADC "A" in Figure 6). The Ge(Li) timing pulse is first amplified and shaped by an ORTEC Model 454 Timing Filter Amplifier and then goes to an ORTEC 453 Constant Fraction

Figure 6. Equipment configuration in which the single channel analyzers (SCA's) are set on one transition

Timing Unit. The timing signal arrives at a Chronetics Model 114 Discriminator for pulse shaping, and finally for input to the fast coincidence logic circuitry (FCLC) where coincidence determinations are made.

The energy pulse from each NaI(Tl) detector is amplified, shaped (using an ND-524 amplifier) and split into two identical signals. One signal goes directly to the input of an SCA, while the other passes through a 3 microsecond delay and is then input to a linear gate. The timing pulse initially goes to a fast amplifier with a risetime of a few nanoseconds. From the fast amplifier the timing signal is pulse-shaped by a Chronetics Model 114 Discriminator (as is the Ge(Li) timing signal) and is then input to the FCLC.

In preparing for an angular correlation experiment, it is critical to establish that the timing signals from each Ge(Li)-NaI(Tl) pair arrive at the FCLC well within the resolving time (about 40 nanoseconds) of the coincidence circuitry. Prior to the start of each angular correlation experiment, delays were checked (see description of delay curves in Reference 12) and reset. It proved convenient to adjust the delays for the NaI(Tl) detectors. The timing signals for each Ge(Li)-NaI(Tl) pair typically arrived at the FCLC within 1-2 ns of one another. Whenever two timing signals arrive at the FCLC within the resolving time of the circuitry, two corresponding logic pulses appear at the out-

put of the FCLC, establishing the existence of a fast coincidence event.

When operating the angular correlation apparatus in this mode, SCA windows are set on one transition, T_G , in the level scheme. All transitions that are in coincidence, electronically, with T_G will be collected for each Ge(Li)-NaI(Tl) pair and stored as Ge(Li) spectra in a 16384-channel analyzer. The 16K analyzer stores six Ge(Li) spectra, one spectrum for each Ge(Li)-NaI(Tl) detector pair. An energy peak in the i^{th} spectrum then corresponds to the number of coincidence events between the transition represented by the peak and that of the gating transition T_G at angle θ_i . In this mode the 16K analyzer can be divided into eight 2K regions, two of which would not be accessed.

The logic pulses from the output of the SCA's trigger the linear gates. Note that the slow logic unit (SLU) is set so that the SCA output is directly connected to the linear gate trigger (the dashed lines in Figure 6 indicate this). The linear gate opens when triggered by the SCA and passes an energy signal from a NaI(Tl) detector to be digitized by ADC "B" and recorded in the analyzer memory during setup to provide an accurate visual measure for the window setting of the SCA about the gating transition T_G .

During coincidence counting the SLU is set to a coincidence mode so that only output number 6 produces logic

pulses. The SLU provides an output logic pulse when: (1) logic pulses are seen from the FCLC for a Ge(Li)-NaI(Tl) pair, and, (2) the NaI(Tl) energy signal lies within the window setting in the SCA. The output from the SLU is used to trigger ADC "A" to accept and digitize the Ge(Li) energy signal. The connection to the input of ADC "B" provides a dummy pulse to flag the analyzer, and the Ge(Li) energy signal from ADC "A" is stored.

As bits are transferred from ADC "A" the routing unit directs this information into the appropriate 2K section of the memory corresponding to the detector pair. This is done by passing three bits from the routing unit through the bit-patching interface to positions 2^{13} , 2^{12} , 2^{11} in the analyzer. For example, if SCA 3 gates the routing unit, the bit configuration at the analyzer would be: 2^{13} -false, 2^{12} -true, 2^{11} -false which indicates the third 2K of memory. The remaining 11 bits are provided by the Ge(Li) energy pulse as digitized by ADC "A".

2. Two-parameter configuration

The connection between the electronics units is indicated in Figure 7. There are no substantial changes in the amplification and pulse shaping of signals from the detectors.

In this mode of operation the SCA's directly trigger the linear gates. A logic pulse from the SLU now triggers both ADC's whenever any coincidence between a Ge(Li)-NaI(Tl) pair

is registered by the PCLC. When triggered, each ADC transfers a 12-bit address to the 16K analyzer. These addresses represent the energies of the two transitions in coincidence. The coincidence events are, in turn, placed on a magnetic buffer tape as a set of four six-bit words. Thus all coincidence events are recorded for the experiment. This method of data accumulation has the advantage of allowing the experimenter to set as many gates as desired on the spectra from one of the detectors after the experiment is performed.

Since 2^{11} is the maximum bit transferred to the buffer tape, the Ge(Li) and NaI(Tl) channel numbers are limited to the value 4096. Thus the Ge(Li) spectrum can be, at most, 4K in length. The 4096 channels allotted to the six NaI(Tl) detectors must be divided into eight 512-channel regions, two of which are not accessed. The routing unit provides a 3-bit configuration ($2^{11}, 2^{10}, 2^9$) to route a NaI(Tl) energy signal into the correct 512-channel spectrum.

For both experimental configurations, continuous monitoring of scaler singles during data accumulation is made possible by gating the scalers with SCA logic pulses. The scalers have been modified to provide digital readout onto a teletype and punched paper tape at regular intervals.

IV. PROCEDURE AND ANALYSIS

A. Experimental Procedure

The results of three angular correlation experiments appear in this report. These experiments yield spectroscopic information on levels and transitions in ^{140}Ba , ^{90}Sr , and ^{140}Cs .

The angular correlation measurements for cascades in ^{140}Ba and ^{90}Sr were obtained by gating the six NaI(Tl) SCA's on the transition from the first excited state to the ground state in each nucleus. Both ^{140}Ba and ^{90}Sr are even-even nuclei and thus the ground state (0^+) and first excited state (2^+) spins are well established. This implies that the first-excited-state-to-ground-state transition is a pure E2 multipole. The unknown factors for direct cascades through the first excited state are the spin of the initial state and the multipole order and mixing ratio of the transition populating the first excited state. Since there are many observed transitions from higher energy states to the first excited state in both ^{140}Ba and ^{90}Sr , the study of several levels and transitions is possible. In addition, the first-excited-state-to-ground-state transition is the most intense transition in the level scheme for each of these nuclei, which suggests that coincidence measurements with acceptable statistics are possible for many of these cascades.

In the case of the angular correlation experiment on ^{140}Cs the two-parameter mode of data accumulation was used. ^{140}Cs is an odd-odd nucleus and thus spin assignment systematics can not be exploited. Indeed, prior to this work the spin for only one level had been definitely established. This is the 1^+ spin assignment for the 1427.57-keV level as is discussed elsewhere (23,24). Thus the angular correlation measurements in ^{140}Cs should have the 1427.57-keV level as the initial level of the cascade. There are no gamma transitions which populate this level. However, six of the most intense transitions depopulate the 1427.57-keV level. This suggests that any complete study of measurable cascades in this nucleus would include a number of cascades depopulating this level through some of these intense transitions. Hence, there is a need to set more than one energy gate here, and the two-parameter mode appears applicable and desirable for this situation.

The three nuclei in this report are obtained from the decays of neutron-rich fission products of the noble gases Kr and Xe which are mass-separated by the TRISTAN system. ^{140}Ba levels are populated in the 64-sec decay of ^{140}Cs , while ^{140}Cs levels are populated in the 14-sec decay of ^{140}Xe . The levels of ^{90}Sr are populated in the 2.7-min decay of ^{90}Rb , which is the daughter of ^{90}Kr . The separated Xe or Kr activities are deposited on an aluminum-Mylar tape in the MTC.

Since the nuclei studied here are either daughter or granddaughters of the noble gas activities, the enhancement of the desired isobar is obtained by setting an appropriate time delay between source deposition and subsequent transport to the center of the angular correlation chamber. The daughter analysis system (DAS) can be set to control, in sequence, the deposition time and length of delay before moving the tape and subsequent data accumulation. In the angular correlation experiments performed, coincidence data were accumulated in the 16K analyzer as the DAS cycled through the deposit/delay/accumulate sequence. For the ^{140}Ba experiment, activity was deposited for 90 seconds, then delayed 30 seconds. Data were accumulated during the entire 120-sec cycle. For the ^{90}Sr experiment, the deposit time used was 160 seconds, the delay time was 110 seconds and the accumulate time was 270 seconds. For the ^{140}Cs experiment, the deposit and accumulate times were both 20 seconds, and there was a one-second delay to move the tape.

The scaler singles count rates of the six NaI(Tl) detectors were continuously monitored during the three experiments. Each SCA was carefully set on the most intense transition in the energy level scheme in order to include the same energy range about the gated photopeak. Logic pulses from the SCA's were recorded in six scalers which, in turn, were read out at regular time intervals onto a teletype

printer and punched paper tape. The coincidence counts at each angle were divided by the sum of the scaler singles in order to provide a first-order correction for source eccentricity and differences in efficiencies of the NaI(Tl) detectors.

In order to obtain an accurate value for the photopeak area one must, at times, correct for the fact that some of the coincidence counts in the photopeak gate are due to accidental coincidences. When gammas from different nuclei are detected within the resolving time of the coincidence circuitry they register as coincidence events. These are known as accidental coincidences. If the accidental contribution to the photopeak area is small with respect to the statistical uncertainty then it can be neglected. However, for intense sources the accidentals may significantly compete with statistical error and a numerical determination of the effect must be made. A derivation of the expression for the accidental rate of two gamma rays is found in reference (12). The accidental rate between a pair of detectors is equal to the product of the individual detection rates of the two gamma rays times the resolving time, t , of the coincidence circuitry for the detector pair. For example, let R_j be the rate which NaI(Tl) detector j sees the gating gamma T_G . Likewise R_6 is the rate which the Ge(Li) detector (labelled detector 6) sees the other gamma ray in the cascade. Then

$R_{accj6} = R_j R_{6t}$ and the ratio of the accidental rate to the rate of true coincidences is $R_{accj6}/R_{truej6} = R_{jt}$. The resolving times for the six pairs of coincidence circuits have been measured and found to be consistent with the range 35-44 nanoseconds reported earlier (12) for this apparatus.

For the ^{140}Cs experiment background gates were set above the gating photopeak so that the accidentals correction could be determined empirically. However, in the ^{140}Ba and ^{90}Sr experiments, where SCA gates were set on the photopeak, there was no provision for accidentals correction. The source strength in the ^{140}Ba - ^{90}Sr experiments was thus held down so that the ratio of R_{accj6}/R_{truej6} was small enough (less than 2%) to make an accidentals correction unnecessary. The source strength was monitored on an activity meter throughout the experiments.

B. Data Analysis

For the nuclei studied in this report the summation in the expression for the angular correlation distribution function $W(\theta)$ does not extend beyond $n=4$, and A_4 is the highest order angular correlation coefficient measured. In interpreting the results of experimental data all gamma-ray transitions are assumed to be of multipole order 1 or 2, as higher order multipolarities typically occur with much lower probability, and would not be expected to have sufficient intensity to be readily observed in coincidence measurements.

In particular, M1, E1, E2 and mixed M1-E2 transitions are the most probable choices. M1-E2 mixing is chosen over E1-M2 as the nature of significantly mixed (greater than ten percent mixing) gamma-ray transitions, since M2 radiation does not compete significantly with E1 radiation, whereas E2 radiation can often compete with M1 radiation.

1. Computer programs

Three computer programs were used in each of the three studies which appear in this report. They are SKEWGAUS, AFIT, and ELPS. Two additional programs, BUFFTape and BUFFREAD, were useful in transferring and recording coincidence data from the ^{140}Cs experiment which was performed in the two-parameter mode. The following sections provide a brief description of each computer program.

a. SKEWGAUS SKEWGAUS provides a non-linear, least-squares fit to individual photopeaks or multiplets as they are recorded in spectra from a multichannel analyser. A detailed description of the program can be found in references (12,18,25). Each peak fit is divided into three regions, and each region is fit to a distinct analytical function. The parameters which appear in the fitting functions are varied to obtain the best fit. A linear or quadratic background is also varied along with other parameters so that an area representing the area of the peak above background can be computed.

The salient feature of the program, which is crucial to an angular correlation analysis is an accurate determination of the area of the photopeak. The area of one peak represents the number of coincidence events detected for a particular cascade at a specific angle. The peaks in six coincidence spectra, which correspond to cascades at six distinct angles, are fit in precisely the same manner with SKEWGAUS. That is, the input information which regulates initial estimates of the fit parameters and their status is exactly the same for a given peak at each angle (i.e. within each spectrum). The channel range of the fit region is first specified along with the number of peaks to be fit within the region. Initial estimates are provided for the channel location of the centroid, height above background, full-width-at-half-maximum, and tau (a parameter describing the amount of skewing of the lower side of the peak). However, for this study the centroid and height were the only parameters allowed to vary. FWHM and tau were held at their initial estimates. Also a linear background was fit for each peak.

b. AFIT This computer program, as described in Reference (12), fits the peak areas (usually obtained from SKEWGAUS) corresponding to six detector pairs to

$$W'(\theta) = A_0' + A_2' P_2(\cos \theta) + A_4' P_4(\cos \theta)$$

where $W'(\theta)$ represents individual peak areas corrected by counts in background gates and scaler singles. A_0' , A_2' and A_4' are then corrected for the finite solid angle subtended by the detectors, as indicated in References (12,26). The fitting subroutine adopted in this program is similar to the subroutine LEGFIT found in Bevington (2/).

In addition to providing fitted values for $A_2 = A_2'/A_0'$ and $A_4 = A_4'/A_0'$ AFIT also produces a plot of the fit-function $W'(\theta)$ versus θ . Both the corrected areas with error bars and the fitted function appear on this plot.

c. ELPS In nearly every cascade in this report there is one transition for which the multipole mixing is not known. A convenient graphical technique is used to facilitate measurement of the mixing ratio. A plot of A_4 versus A_2 can be made for various spin sequence possibilities of a cascade. Each expression for A_2 and A_4 is parameterized by the mixing ratio as is seen in equation 12. It may be shown (12) that the locus of points corresponding to the ordered pair (A_2, A_4) , which is obtained by varying the mixing ratio such that the per cent L=2 admixture ranges from zero to one hundred, is an ellipse. Each individual spin sequence can correspond to an A_2 - A_4 ellipse parameterized by the mixing ratio of the unknown transition. Thus, by plotting

the data point corresponding to the angular correlation coefficients A_2 , A_4 on an A_4 versus A_2 graph one has a quick visual measure for the correct spin sequence and the extent of L=2 multipole admixture in the transition.

The program ELPS plots specific A_2 - A_4 spin sequence ellipses and data points. Given the measured values of A_2 and A_4 , ELPS also provides an option to solve the quadratic form in equation 12 for the mixing ratio. The values of the mixing ratio and % L=2 admixture which appear in the tables of this report are calculated from the program ELPS. In addition, ELPS will plot a percent of L=2 versus A_2 graph when circumstances indicate $A_4=0$.

Input information is kept simple by virtue of the 3-J and 6-J subroutines in ELPS. These subroutines have been developed from analytical expressions in Rotenberg, et al. (14) for the 3-J and 6-J symbols. In particular, ELPS requires the spin sequences of the skip or direct cascades, the multipole order of the transitions, and an indication of which transition is mixed. Ellipse plots will be used extensively in the discussion and interpretation of measured values for A_2 and A_4 .

d. BUFFTAPE and BUFFPREAD These two computer programs provide a convenient method of handling data collected in the two-parameter mode. The program BUFFTAP is used to run gates on magnetic buffer tapes from the 16K :

analyser. BUFFTape is written in assembler language. In brief, the program sorts through channel pairs which are stored on the buffer tape as coincidence events, and records the coincidence spectra on a 7-track output magnetic tape. The channel pairs on the buffer tape are ordered pairs so that BUFFTape can inspect the channel value of the first or second member (as specified in the input information) and test whether or not the value lies within the channel gate established by the program user. If the channel value is within the gate then its channel complement is accepted into the coincidence spectrum for the gate.

The sister program BUFFREAD can then be used to read spectra from the output tape of BUFFTape. Spectra are read by tag word or spectrum sequence, and can subsequently be added, subtracted, shifted for gain changes, printed out and/or recorded on disk for future reference.

2. Error analysis

The concept of counting statistics is used extensively throughout experimental nuclear spectroscopy. This principle is specifically related to this study in terms of statistical error in scaler singles counts, and in counts per channel in energy coincidence spectra. If a detector registers N gamma rays in a certain time period and the gamma rays fall within a certain energy range, then the standard deviation in measurement is $\sqrt{N}$. For example, to obtain one percent statisti-

cal uncertainty in the measurement of a coincidence peak, the area of the peak would need to consist of 10^4 counts.

Consider now a least-squares fit to an analytic function

$$f(x) = \sum_{i=1}^{N_a} a_i X_i(x)$$

where N_a is the number of variable coefficients $\underline{a}$. The variable $\underline{x}$ appears as the argument of the polynomial X_i . Let N_m represent the number of measurements made on $\underline{f}$ and $\underline{x}$. Then let F_k be the k th measurement of the function $\underline{f}$, with error σ_k , and x_k the k th measurement of the variable $\underline{x}$. One then proceeds, via a least-squares technique outlined in Bevington (27), to obtain the best fit for the $\underline{a}$ coefficients. In particular,

$$\begin{pmatrix} a_1 \\ a_2 \\ \cdot \\ \cdot \\ \cdot \\ a_{N_a} \end{pmatrix} = \tau b \quad (13)$$

where

$$\tau \equiv \eta^{-1}$$

$$\eta_{ij} = \eta_{ji} = \sum_{k=1}^{N_m} \rho_k x_j(x_k) x_i(x_k)$$

$$b_j = \sum_{k=1}^{N_m} x_j(x_k) \rho_k F_k$$

$$\rho_k = \frac{1}{\sigma_k^2}$$

One can easily show that the i^{th} diagonal element of the symmetric error matrix τ is equal to $\sigma_{a_i}^2$. Also it can be shown that the off-diagonal elements of the error matrix correspond to the covariance of respective a coefficients.

For this study the function to be fit is

$$W'(\theta) = A_0 + A_2 P_2(\cos \theta) + A_4 P_4(\cos \theta)$$

where $W'(\theta)$ is fit to photopeak areas that are corrected by scaler singles. According to the prescription in equation 13,

$$x_1 = P_0 = 1$$

$$x_2 = P_2$$

$$x_3 = P_4$$

$$\rho_k = \frac{1}{\sigma_{W'_k}^2}$$

$$\theta_1 = \theta_3 = 135^\circ$$

$$\theta_2 = 180^\circ$$

$$\theta_4 = 90^\circ$$

$$\theta_5 = 45^\circ$$

$$\theta_7 = 67.5^\circ$$

For example,

$$\eta_{12} = \sum_{k=1}^7 \rho_k p_2(\cos \theta_k)$$

#6

$$b_2 = \sum_{k=1}^7 \rho_k p_2(\cos \theta_k) w_k$$

#6

The final results from the fitting process are $A_2 = A_2^i / A_0^i$ and $A_4 = A_4^i / A_0^i$. The corresponding value for the variance of A_2 and A_4 are

$$\sigma_{A_2} = \frac{A_2^i}{A_0^i} \sqrt{\frac{\tau_{11}}{A_0^i{}^2} + \frac{\tau_{22}}{A_2^i{}^2} - \frac{2\tau_{12}}{A_0^i A_2^i}} \quad (14)$$

$$\sigma_{A_4} = \frac{A_4^i}{A_0^i} \sqrt{\frac{\tau_{11}}{A_0^i{}^2} + \frac{\tau_{33}}{A_4^i{}^2} - \frac{2\tau_{13}}{A_0^i A_4^i}}$$

The values of the variances for A_2 and A_4 quoted in this report are given by equations 14 whenever the sample variance is less than one. In order to take the goodness of fit into consideration the variances in equations 14 are multiplied by the sample variance σ_s , whenever σ_s exceeds the value one. In this case,

$$\sigma_s^2 = \frac{1}{3} \sum_{\substack{i=1 \\ \neq 6}}^7 \frac{(w_k' - w'(\theta_k))^2}{\sigma_k^2}$$

where w_k' is the experimental value of the angular correlation probability function measured at angle θ_k , σ_k is the error in w_k' , and $w'(\theta_k)$ is the value of the fitted function at θ_k .

V. RESULTS

A. Levels in ^{140}Ba

A skeletal level scheme of ^{140}Ba from Reference 28 is shown in Figure 8. The transitions shown were included in the study; other transitions exist but are not shown. The direct cascades are represented as solid arrows, and the gamma-skip-gamma cascades by dashed arrows. The gating gamma ray appears as the double-lined arrow in Figure 8 and is the 602-keV transition between the first excited state (2^+) and the ground state (0^+) in this even-even nucleus. This choice as an energy gate has the advantage of establishing a pure multipolarity in one of the gamma rays of the cascade and definite spins for two of the energy levels.

Spin assignment possibilities are made in accordance with the angular momentum triangle rule on the adjacent energy level (spin I) in the cascade. Since the maximum multiplicity order under consideration is 2, the spin possibilities are from $I-2$ to $I+2$ with unit increments. If there is a competing transition from the energy level under consideration to another level of known spin then spin choices must be consistent with the assumption that the highest multipole order for the crossover transition is 2. For instance, if there is an observed crossover transition to a 0^+ ground state in an even-even nucleus then the spin possibilities for the excited state are 1 and 2, as these are the only two spin

Figure 8. Skeletal decay scheme of ^{140}Ba , indicating the transitions included in the study

choices that are consistent with multipole order of 1 or 2.

A Ge(Li) singles gamma-ray spectrum of ^{140}Ba is shown in Figure 9. The energy range is from approximately 500 keV to 2350 keV. This choice of energies includes most of the strong gamma rays that are in coincidence with the 602-keV gating transition. This range is thus limited also to give sufficiently good energy resolution for accurate fitting of peaks for an analysis of the experiment.

1. Results and discussions for 'unique' direct cascades

'Unique' direct cascades are defined in this report as those cascades which involve one gamma ray in coincidence with the gating transition, and also provide the only angular correlation data for that particular energy level. Contrast these cascades with the other direct cascades which have complementary skip cascades that may give corroborative evidence for a spin choice of the energy level considered. For example, in Figure 8 the 1131-keV energy level which involves the 528-602 keV cascade is a 'unique' direct cascade, whereas the 2138-keV energy level has both a direct cascade and a gamma-skip-gamma cascade.

Five representative fit-function curves for different cascades are shown in Figures 10 through 12. The first two curves (Figure 10) show the angular correlation fit-function for two 'unique' direct cascades, the 528-602 keV cascade and the 1221-602 keV cascade. Figures 11 and 12 show the three

Figure 9. ^{140}Ba singles spectrum taken with the Ge(Li) detector

Figure 10. Fit-function curves from the ^{140}Ba experiment for cascades 528-602 and 1222-602

Figure 11. Fit-function curves from the ^{140}Ba experiment for cascades 1130-(1200)-602 and 1422-(908)-602

Figure 12. Fit-function curve from the ^{140}Ba experiment for the 2331-602 cascade

fit-functions of cascades which yield information about the spin of the 2933-keV energy level. Figure 11 has the fit-functions of two gamma-skip-gamma cascades and Figure 12 has the fit-function of the 2331-602 keV direct cascade. The 2933-keV energy level will be discussed in another section. Table 1 summarizes the results for all cascades considered. The values of the mixing ratios which appear in Table 1 were calculated by solving the quadratic in equation 12. Three experimental values of A_2 were used: $A_2 - \sigma_{A_2}$, A_2 , and $A_2 + \sigma_{A_2}$. The corresponding values of $\% L=2$ appear in the final columns of the table. At times, because of the data point position or poor statistics, the data point plus error bars is consistent with more than one part of a particular spin sequence ellipse. In such cases two ranges in the mixing ratio are given for the spin sequence.

a. 1131-keV level (528-602 cascade) The experimental data points are shown with the fit-function for this cascade in Figure 10. The data point in Figure 13 for this cascade is consistent with the 4-2-0 theoretical point. However, within the error bars, spin choices 1, 2, or 3 cannot be ruled out. Even so, one expects to see a low-lying 4+ level in an even-even nucleus, and if the nucleus has a vibrational nature, the 4+ state is expected at about twice the energy of the first excited (2+) state. This spin choice is reinforced as the other low-lying states are considered.

Table 1. Results from the ^{140}Ba experiment

Level (keV)	Cascade	A_2	A_4	Spin sequence	Mixing ratio range			% L=2 range		
1131	528-602	0.083 ± 0.021	-0.027 ± 0.023	4-2-0						
1511	908-602	0.436 ± 0.023	0.147 ± 0.028	2-2-0	1.2	1.1	0.96	60.	55.	48.
1824	1222-602	0.352 ± 0.055	1.275 ± 0.059	0-2-0						
1994	1391-602	0.126 ± 0.041	0.014 ± 0.045	2-2-0	-0.22	-0.16	-0.11	4.4	2.6	1.2
2237	1635-602	-0.267 ± 0.051	0.040 ± 0.053	1-2-0 2-2-0	-0.06 -0.74	-0.02 -4.5	0.03	0.4 36.	0.0 95.	0.1
2310	1707-602	0.154 ± 0.061	0.048 ± 0.065	2-2-0	-0.20	-0.13	-0.05	4.0	1.6	0.2
2430	1827-602	0.324 ± 0.175	-0.300 ± 0.185	1-2-0	0.35	0.55	0.90	11.	23.	45.
2704	2102-602	-0.061 ± 0.031	0.031 ± 0.034	1-2-0	0.14	0.16	0.19	1.8	2.6	3.5
2870	2268-602	0.379 ± 0.064	0.059 ± 0.068	2-2-0	0.09	0.20	0.35	0.9	3.9	11.

Table 1. (continued)

Level (keV)	Cascade	A_2	A_4	Spin sequence	Mixing ratio range			% L=2 range		
1803	672- (528) -602	-0.143 ± 0.038	-0.008 ± 0.042	3-4-2-0	-0.05	0.0	0.04	0.2	0.0	0.2
	1200-602	-0.065 ± 0.015	0.015 ± 0.018	3-2-0	0.01	-3.01	0.03	0.0	0.0	0.1
2138	1008- (528) -602	0.080 ± 0.071	0.001 ± 0.086	3-4-2-0	0.18	0.27	0.37	3.0	6.6	12.
	1536-602	0.006 ± 0.102	-0.168 ± 0.118	3-2-0 3-2-0	-7.3 0.03	-3.6 -0.10	-2.3 -0.26	98. 0.1	93. 1.0	84. 6.2
2933	1130- (1200) -602	-0.294 ± 0.018	-0.174 ± 0.020	2-3-2-0	-a					
	1422- (908) -602	-0.057 ± 0.054	0.008 ± 0.062	2-2-2-0 2-2-2-0	-1.3 -1.8	-0.60 -8.3	-0.34 11.	64. 76.	26. 99.	10. 99.
	2331-602	0.215 ± 0.068	0.055 ± 0.081	2-2-0	-0.13	-0.03	0.07	1.6	0.1	0.5
1951	820- (528) -602	0.389 ± 0.101	-0.158 ± 0.113	3-4-2-0	0.51	2.4		20.	85.	

^aData point closest to 2-3-2-0 ellipse, but doesn't intercept it.

Figure 13. Direct cascades from ^{140}Ba experiment:
528-602, 1391-602, 1635-602, 1200-602,
and 1536-602

Spin choice $4+$ is definitely ruled out for these other low-lying states.

b. 1511-keV level (908-602 cascade) The data point for this cascade is shown in Figure 14. This data point lies clearly on the 2-2-0 ellipse. There is significant mixing, about 50% E2, for the 908-keV transition. This amount of mixing is indicative of an M1-E2 type of radiation and suggests that there is no parity change from the 602-keV ($2+$) level to the 1511-keV level. Thus the choice of $2+$ is made for the 1511-keV level.

c. 1824-keV level (1222-602 cascade) The fit-function curve to the experimental data points is shown in Figure 10. The shape of this curve indicates a huge anisotropy in angular correlation work, and combined with the experimental values for A_2 and A_4 , unmistakably assigns a 0-2-0 cascade to these two transitions in coincidence. The additional positive parity assignment is made on the assumption that the 1222-keV transition is E2 rather than M2. Also, it is worth noting that a 0-2-0 cascade is strong evidence for a $0+$ ground state and a $2+$ intermediate state.

d. 1994-keV level (1391-602 cascade) The data point in Figure 13 lies directly on the 2-2-0 ellipse but the error bars overlap the 3-2-0 ellipse and the 4-2-0 theoretical point. There is, however, an observed crossover transition to the ground state from this level which would eliminate

Figure 14. Direct cascades from ^{140}Ba experiment:
908-602, and 2268-602

spin choices 3 and 4. The ground-state transition favors a positive parity choice for the 1994-keV level as M2 transitions do not compete with E2 transitions. The mixing ratio indicates a small amount of L=2 mixing ($1.2 \leq \%L=2 \leq 4.4$).

e. 2237-keV level (1635-602 cascade) The data point in Figure 13 lies within one standard deviation of both the 1-2-0 and 3-2-0 ellipses. Also the 2-2-0 ellipse is just outside the error bars. There is an observed ground-state crossover transition which eliminates spin choice 3. The data point position suggests that spin choice 1 is favored over 2. For spin choice 1 the 1634-keV transition is nearly pure dipole, which would not indicate a parity preference. For spin choice 2, the data point lies on the 2-2-0 ellipse in a region which would indicate an L=2 admixture of greater than 36%. This spin choice would yield a positive parity prediction.

f. 2310-keV level (1707-602 cascade) The data point for this cascade appears in Figure 15. The data point itself is nearest to the 2-2-0 ellipse, but the error bars also overlap the 3-2-0 ellipse and the 4-2-0 point. A ground-state crossover transition is observed which suggests a spin 2 choice. Because the ground-state transition is most likely an E2 transition, positive parity is also favored. The percent E2 mixing ranges from 0.2% to 4%.

Figure 15. Direct cascades from ^{140}Ba experiment:
1707-602, 1827-602, 2102-602, and
2331-602

g. 2430-keV level (1827-602 cascade) Figure 15

contains the data point for this cascade. Due to statistical uncertainty the data point has large error bars. Fortunately the data point lies far enough out on the 1-2-0 ellipse to make this choice distinct. The error bars give a large range, between 11% and 45%, in the $L=2$ admixture. However, this large amount of mixing does suggest an $M1-E2$ admixture and thus a positive parity assignment.

h. 2704-keV level (2102-602 cascade) The error bars with this data point, in Figure 15, overlap the 2-2-0, 1-2-0, and 3-2-0 ellipses. There is an observed ground-state crossover transition which eliminates spin choice 3. The choice between spins 1 and 2, however, is not clear. The data point intercepts the 1-2-0 ellipse at about 2-4% $L=2$ admixture, from which the multipole mixing could be either $E1-M2$ or $M1-E2$. The intersection with the 2-2-0 ellipse is at about 15% $L=2$ admixture, or a likely $M1-E2$ multipole mixture. The spin choice 2 would thus dictate a positive parity assignment.

i. 2870-keV level (2268-602 cascade) This data point lies clearly on the 2-2-0 ellipse as shown in Figure 14. The range in multipole ($L=2$) mixing is from 1% to 11%, so that it is not clear whether it is $M1-E2$ or $E1-M2$, and thus no parity assignment can be made. Also, there is no observed crossover transition to help in this determination.

2. Results and discussions for direct and gamma-skip-gamma cascades from the same energy level

This section contains a discussion of energy levels from which there are corroborative gamma-skip-gamma and direct cascades. Although there is reason to hope for a good double check of results, often the statistics associated with a data point make it difficult to say anything useful as far as spin assignments go.

a. 1803-keV level

1) 672-(528)-602 cascade The angular correlation coefficients for this cascade are plotted in Figure 16. The data point nearly lies on both the 3-4-2-0 and 5-4-2-0 ellipses. One should note that the intermediate gamma (528 keV) is assumed to be pure E2. Choices 2-4-2-0, 6-4-2-0, and 4-4-2-0 are ruled out on the basis of the data point placement. There is an observed 1200-keV gamma transition to the 602-keV (2+) level which would make spin choice 5 highly improbable for the 1803-keV level. For spin 3, the data point suggests a pure dipole transition in the 672-keV gamma. This could be either M1 or E1, and no parity prediction can be made on this basis.

Figure 16. Gamma-skip-gamma cascades from ^{140}Ba
 experiment: 672-(528)-602,
 820-(528)-602, and 1008-(528)-602

2) 1200-602 cascade Figure 13 contains the angular correlation coefficients for this cascade. Although the error bars are relatively small, the data point lies in a region where the ellipses are close together. The data point is nearest to the 3-2-0 ellipse and the 1-2-0 ellipse is on the border of the error bar limits with ellipse 2-2-0 less than two standard deviations from the data point. Spin 1 is ruled out, however, since the 672-keV transition connects the 1803-keV level with the 1131-keV level (4^+). Also, note that there is no crossover transition to the ground state which is consistent with spin choice 3.

When the results for the two cascades from the 1803-keV level are compared, it is clear that a unique spin assignment of 3 may be made for this level, but that the parity is not determined.

b. 2138-keV level

1) 1008-(528)-602 cascade The data point plus error bars for this cascade overlap a number of spin possibilities as shown in Figure 16. This data point seems to eliminate only the 2-4-2-0 spin sequence. There is an observed gamma transition (1536-keV) to the 602-keV (2^+) energy level which rules out the spin choices 5 and 6. For spin sequence 3-4-2-0 the 1008-keV transition has an $L=2$ admixture of 3% to 12% whereas the range is 2% to 21% for spin sequence 4-4-2-0.

2) 1536-602 cascade There are relatively large error bars associated with the data point for this cascade. The data point itself, as shown in Figure 13, is far from any ellipse. The error bars barely intercept ellipses 1-2-0 and 3-2-0. Spin 1 is ruled out because the 1008-keV transition connects the 2138-keV level with the 1131-keV level (4+). The point 4-2-0 appears outside the range of the data point as does the 2-2-0 ellipse. Combining this information with that of the 1008-(528)-602 cascade implies a tentative spin 3 assignment for the 2138-keV level.

c. 2933-keV level The experimental angular correlation fit-functions and data points for the three cascades associated with the 2933-keV level are given in Figures 11 and 12.

1) 1130-(1200)-602 cascade The angular correlation coefficients for this cascade are plotted in Figure 17. This data point clearly misses all ellipses. Upon some reflection of the fitted energy peaks, there may be reason to believe that the 1130-keV energy peak is actually an unresolved doublet and that would tend to upset the results obtained for the angular correlation coefficients. A component of the 1130-keV energy peak may be a photo-escape peak or possibly a contaminant. If it is assumed that this undesirable component is small relative to the 1130-keV transition in the gamma-skip-gamma cascade, then the values for

Figure 17. 1130-(1200)-602 gamma-skip-gamma cascade
from ^{140}Ba experiment

the angular correlation coefficients may not change by much. The strong correlation observed in the fit-function curve in figure 4 seems to indicate that this may be the case. If indeed this is so, then the data point for this cascade is either consistent with spin sequences 2-3-2-0, or 4-3-2-0 with significant mixing to predict a positive parity state. The 1200-keV skip gamma is assumed to be pure dipole as suggested earlier.

2) 1422-(908)-602_cascade The 908-keV skip gamma has significant mixing and this is accounted for in plotting the ellipses in Figure 18. The data point for this cascade appears with error bars which overlap all of the ellipses. The 4-2-2-0 point is just outside the error bars. The 0-2-2-0 point lies off the plot and is eliminated as a possibility.

3) 2331-602_cascade Figure 15 has the angular correlation coefficients for this cascade. The data point is nearest to the 2-2-0 ellipse, but the error bars barely intercept the 3-2-0 ellipse. The point 4-2-0 is just outside the error bars. This position seems to favor spin choice 2 over spins 3 or 4. For spin 2, the multipole order $L=2$ mixing is less than 2% for the 2331-keV transition.

A tentative 2^+ spin assignment for the 2933-keV level is consistent with each of the three cascades considered.

Figure 18. 1422-(908)-602 gamma-skip-gamma cascade
from ^{140}Ba experiment

d. 1951-keV level (820-(528)-602 cascade) There is one gamma-skip-gamma cascade that has no corroborative direct cascade. This is the 820-(528)-602 cascade from the 1951-keV energy level. The angular correlation coefficients are plotted with error bars in Figure 16. Although the error bars are relatively large the data point occurs far enough away from the other ellipses to make the spin sequence choice 3-4-2-0 tentative but reasonable. The L=2 multipole mixing range is from 20% to 85% suggesting an M1-E2 admixture and a positive parity for the 1951-keV energy level.

B. Levels in ^{90}Sr

The gating gamma ray was the 832-keV transition from the first excited state (2^+) to the ground state (0^+) in this even-even nucleus. This report contains results from the study of nine direct cascades and twelve gamma-skip-gamma cascades. A skeletal decay scheme of ^{90}Sr from Reference 29 is shown in Figure 19. The transitions shown were included in the study; other transitions exist but are not shown. Gamma rays from six direct cascades provide the intermediate, or skip, transitions for all of the gamma-skip-gamma cascades studied. Thus an accurate measure for the mixing ratio of these transitions is imperative for the correct analysis of the gamma-skip-gamma cascades.

A Ge(Li) detector singles spectrum for the ^{90}Sr nucleus is shown in Figure 20. The energy range is from about 800

Figure 19. Skeletal decay scheme of ^{90}Sr , indicating the transitions included in this study

Figure 20. ^{90}Sr singles spectrum taken with the Ge(Li) detector

keV to 2780 keV. This range includes most of the intense gammas in coincidence with the 832-keV gamma, and yet provides acceptable energy resolution.

Representative angular correlation fit-function curves are shown for three direct cascades in Figures 21 and 22, and for two gamma-skip-gamma cascades in Figure 23. As will be noted individually later, the two fit-function curves in Figure 21 both indicate a 2-2-0 cascade, but with different $L=2$ mixing. The curve at the top of Figure 21 has approximately 18% $L=2$ admixture, and the curve at the bottom indicates an effective 0% $L=2$ admixture. This comparison is indicative of the great effect mixing has upon the shape of the angular correlation fit-function curve. Figure 22 contains the distinctive 0-2-0 cascade angular correlation curve. The two curves in Figure 23 correspond to two gamma-skip-gamma cascades which give supportive spin evidence for an every level that will be discussed later.

A summary of results for all cascades in ^{90}Sr is given in Table 2.

1. Results and discussions for direct cascades

a. 1656-keV level (824-832 cascade) The angular correlation coefficients for this cascade are plotted in Figure 24. The data point with error bars is consistent with the 4-2-0 point and with the 2-2-0 and 3-2-0 ellipses. From the data point position there is no reason to favor spin

Figure 21. Fit-function curves from the ^{90}Sr experiment for cascades 1375-832 and 1665-832

Figure 22. Fit-function curve from the ^{90}Sr experiment for the cascade 2139-832

Figure 23. Fit-function curves from the ^{90}Sr experiment for cascades 1838-(1665)-832 and 2128-(1375)-832

Table 2. Results for the ^{90}Sr experiment

Level (keV)	Cascade	A_2	A_4	Spin sequence	Mixing ratio range			% L=2 range		
1656	824-832	0.120 ± 0.052	0.043 ± 0.058	4-2-0						
1892	1060-832	-0.105 ± 0.016	0.083 ± 0.018	2-2-0	-0.52	-0.44	-0.47	22.	20.	18.
2207	1375-832	-0.089 ± 0.013	0.051 ± 0.015	2-2-0	-0.49	-0.47	-0.45	19.	18.	17.
2497	1665-832	0.228 ± 0.032	0.017 ± 0.034	2-2-0	-0.07	-0.03	0.01	0.5	0.1	0.0
2571	1738-832	-0.167 ± 0.070	0.106 ± 0.078	1-2-0	0.01	0.07	0.13	0.0	0.5	1.7
				2-2-0	-0.81	-0.62	-0.48	39.	28.	19.
				3-2-0	0.21	0.12	0.03	4.3	1.4	0.1
2971	2139-832	0.231 ± 0.119	1.28 ± 0.14	0-2-0						
3039	2207-832	-0.470 ± 0.100	-0.014 ± 0.116	1-2-0	-0.38	-0.23	-0.12	13.	4.9	1.3
3556	2724-832	0.183 ± 0.214	0.337 ± 0.225	2-2-0	-a					
3583	2752-832	0.239 ± 0.029	-0.056 ± 0.030	3-2-0	-0.48	-1.4		19.	67.	

^aThe 2-2-0 ellipse is intercepted, but error bars are too large for any reasonable numerical estimate for the mixing ratio.

Table 2. (continued)

Gamma-skip-gamma cascades

Level (keV)	Cascade	A_2	A_4	Spin sequence	Mixing ratio range			% L=2 range		
2528	871-(824) -832	0.026 ± 0.106	-0.145 ± 0.110	3-4-2-0 3-4-2-0	0.07 -8.5	0.20 140.	0.34 7.2	0.5 99.	3.8 100	10. 98.
2927	1271-(824) -832	0.184 ± 0.046	0.007 ± 0.050	3-4-2-0 4-4-2-0	0.35 -0.25	0.45 -0.03	0.52 0.23	11. 6.1	17. 0.1	21. 4.9
3033	1140-(1060) -832	0.313 ± 0.135	-0.113 ± 0.157	2-2-2-0	-b					
3450	1793-(824) -832	-0.016 ± 0.151	0.017 ± 0.167	-c						
	1242-(1375) -832	0.008 ± 0.043	-0.022 ± 0.045	3-2-2-0	0.01	-0.12	-0.27	0.0	1.3	6.6
	952-(1665) -832	-0.101 ± 0.091	0.162 ± 0.108	3-2-2-0 3-2-2-0	3.9 0.44	<-100 0.17	-4.2 -0.07	94. 16.	100 2.7	65. 0.5

^b The data point lies nearest the 2-2-2-0 ellipse.

^c Due to large error bars, spins 2, 3, 4 remain as possibilities with spin 2 less likely.

Table 2. (continued)

Level (keV)	Cascade	A_2	A_4	Spin sequence	Mixing ratio range			% L=2 range		
4037	1829-(1375) -832	-0.238 ± 0.223	-0.153 ± 0.259	-d						
	997-(2707) -832	0.107 ± 0.109	0.020 ± 0.131	2-1-2-0 2-1-2-0	-2.6 -0.07	-1.7 -0.24	-1.0 -0.52	87. 75. 52. 0.5 5.3 21.		
4149	2256-(1060) -832	0.079 ± 0.207	0.212 ± 0.240	-e						
4335	2128-(1375) -832	-0.074 ± 0.033	0.050 ± 0.038	1-2-2-0 3-2-2-0 3-2-2-0	0.01 24. 0.21	0.07 -20. 0.12	0.14 -7.0 0.03	0.0 0.6 1.8 100 100 98. 4.4 1.4 0.1		
	1838-(1665) -832	0.293 ± 0.145	0.180 ± 0.161	1-2-2-0	0.52	1.5		21. 69.		
4366	2473-(1060) -832	-0.119 ± 0.068	0.065 ± 0.079	1-2-2-0	-0.17	-0.02	0.12	2.7 0.0 1.4		

^d The data point intercepts ellipses 2-2-2-0 and 3-2-2-0, while point 4-2-2-0 lies outside error bars.

^e Spin 0 is ruled out but spins 1, 2, 3, 4 remain possibilities.

Figure 24. Direct cascades from ^{90}Sr experiment:
824-832, 1060-832, 1375-832, and 1665-832

choice 4 over 2 or 3. However, one does expect to find a low-lying 4^+ state in an even-even nucleus. If the nucleus exhibits vibrational characteristics, the 4^+ state is expected to be present at approximately twice the energy of the first excited (2^+) state. This is indeed the case for the 1656-keV level. Perhaps stronger evidence for the 4^+ assignment of this level is that upon further analysis none of the other low-lying levels is found to be consistent with the 4^+ choice.

b. 1892-keV level (1060-832 cascade) The data point for this cascade also appears in Figure 24. This point unambiguously intercepts only the 2-2-0 ellipse. Note that there is an observed crossover transition to the ground state which is consistent with a spin 2 choice. The 1060-keV transition has approximately 20% $L=2$ admixture and thus this transition is most probably an $M1$ - $E2$ mixture. This implies positive parity for the 1892-keV level.

c. 2207-keV level (1375-832 cascade) The angular correlation fit-function curve for this cascade appears in Figure 21. The angular correlation coefficients as plotted in Figure 24 are quite close to those for the 1060-832 cascade. Again a 2^+ spin assignment is quite clear. The mixing for the 1375-keV transition is about 18% $E2$.

d. 2497-keV level (1665-832 cascade) The curve near the bottom of Figure 21 corresponds to this cascade. The data point in Figure 24 is itself closest to the 2-2-0 ellipse but is consistent with the 3-2-0 ellipse. There is an observed ground-state crossover transition which favors the spin 2 choice. The L=2 mixing for the spin 2 choice is less than 0.5% which indicates that the 1665-keV transition may be pure dipole.

e. 2571-keV level (1738-832 cascade) Figure 25 has the angular correlation coefficients plotted for this cascade. The point itself is nearly on the 2-2-0 ellipse. However, ellipses 1-2-0 and 3-2-0 are less than one and one-half standard deviations from the data point. These data certainly favor the spin 2 choice, but spins 1 and 3 cannot be ruled out on this basis. For spin 2 there is significant L=2 admixture, 19 to 39%, which means that the 1738-keV transition is M1-E2 and a positive parity assignment can be made for the energy level. The 1738-keV transition would be nearly pure dipole for either spin choice 1 or 3.

f. 2971-keV level (2139-832 cascade) Figure 22 shows the angular correlation fit-function curve for this cascade. The unique characteristics of this curve in angular correlation work reveal a 0-2-0 cascade because of the large anisotropy evident. The relatively large values of A_2 and A_4 as seen in Table 2 numerically confirm this cascade as a

Figure 25. Direct cascades from ^{90}Sr experiment:
1738-832, 2207-832, 2724-832, and
2752-832

0-2-0 sequence.

g. 3039-keV level (2207-832 cascade) The angular correlation coefficients plotted in Figure 25 for this cascade are consistent with the 1-2-0 and 3-2-0 ellipses. The observed ground-state crossover transition effectively eliminates the spin 3 choice. The 2207-keV transition has an $L=2$ admixture in the range 1% to 13%.

h. 3556-keV level (2724-832 cascade) Due to poor statistics the data point for this cascade appears in Figure 25 with quite large error bars. However, the data point itself lies in an isolated region of the 2-2-0 ellipse and any other spin choice seems unlikely. The location of the data point further suggests that there is significant mixing present and a tentative positive parity assignment is made.

i. 3583-keV level (2752-832 cascade) Although the error bars for this data point are relatively small, the point itself is located in a region of the graph in Figure 25 in which the three ellipses are not well separated. The data point plus error bars is, however, only consistent with the 3-2-0 ellipse. The $L=2$ mixing is between 19 and 67% which implies an $M1-E2$ character for the 2752-keV gamma transition. The parity assignment would thus be positive.

2. Results and discussions for gamma-skip-gamma cascades

For many of the cascades in this section the angular correlation coefficients have large error bars. This often makes an unambiguous spin prediction impossible. In such cases the elimination of certain spin possibilities may be the most significant result obtained from the data. Coupling this with observed transitions to previously identified spin states often gives further evidence for the spin prediction.

a. 2528-keV level (871-(824)-832 cascade) Figure 26 has the angular correlation coefficients for this cascade. The large error bars overlap the 3-4-2-0 and the 5-4-2-0 ellipses. All other choices are ruled out. There is an observed 1696-keV transition from this level to the 832-keV (2⁺) level which makes spin 5 unlikely. For spin choice 3 the L=2 component is probably large, indicating a positive parity assignment. Although less likely, the data point could be consistent with another part of the 3-4-2-0 ellipse with an L=2 mixing of less than 10%.

b. 2927-keV level (1271-(824)-832 cascade) The data point as shown in Figure 26 lies nearly on the 4-4-2-0 ellipse, but the error bars make spin sequences 3-4-2-0 and 5-4-2-0 acceptable possibilities for this cascade. There is an observed 720-keV transition from this level to the 2207-keV (2⁺) energy level which would make the 5-4-2-0 se-

Figure 26. Gamma-skip-gamma cascades from ^{90}Sr
 experiment: 871-(824)-832,
 1271-(824)-832, and 1793-(824)-832

quence unlikely. For spin choice 3 the $L=2$ admixture for the 1271-keV transition would be in the range from 11% to 21%, whereas spin 4 places the $L=2$ admixture at less than 6%.

c. 3033-keV level (1140-(1060)-832 cascade) The angular correlation coefficients for this cascade in Figure 27 lie nearest to the 2-2-2-0 ellipse. This location plus the error bars make this spin sequence the most probable. Also there is an observed crossover transition to the ground state which would limit the choice of spins to 1 or 2. As noted earlier the unobserved 1060-keV skip gamma in this cascade has significant E2 mixing. This result is taken into account in formulating the ellipses in Figure 20.

d. 3450-keV level
 1) 1793-(824)-832 cascade The huge error bars associated with this data point in Figure 26 make it difficult to say anything conclusive about the nature of this cascade. It does appear that the spin sequence 2-4-2-0 is less probable than the others plotted in the figure. There is an observed 2617-keV transition from the level to the 832-keV (2^+) level. Also the 1793-keV gamma goes from the 3450-keV level to the 1656-keV (4^+) level. Together these observations limit the spin choices for the 3450-keV level to 2, 3, and 4 with spin 2 being least likely.

Figure 27. Gamma-skip-gamma cascades from ^{90}Sr
 experiment: 1140-(1060)-832,
 2256-(1060)-832, and 2473-(1060)-832

2) 1242-(1375)-832_cascade The data point for this cascade is shown in Figure 28. This point clearly illustrates the inopportune nature of some locations on an A_4 versus A_2 graph. Even with reasonably small error bars, the data point is consistent with spin choices 2, 3, and 4.

3) 952-(1665)-832_cascade The angular correlation coefficients plotted in Figure 29 lie closest to the 3-2-2-0 ellipse. In fact, the error bars barely overlap this ellipse. The 2-2-2-0 ellipse and the 4-2-2-0 point each lie at least one and one half standard deviations away from the data point. This suggests that spin 3 is favored over spin 4 or spin 2. Noting the discussion of the 1793-(824)-832 cascade, spin 2 seems the least likely choice.

e. 4037-keV_level

1) 1829-(1375)-832_cascade Figure 28 shows the relatively large error bars associated with the data point for this cascade. The three ellipses 1-2-2-0, 2-2-2-0, 3-2-2-0 appear equally likely according to the nature of this data. The 4-2-2-0 point is outside the error bars and would seem a less likely choice. There is a 2381-keV gamma transition to the 1656-keV (4^+) level and also a 997-keV transition to the 3039-keV (spin 1) level. This information suggests a spin choice of 2 or 3, and supports the elimination of 4 as a spin possibility.

Figure 28. Gamma-skip-gamma cascades from ^{90}Sr
 experiment: 1242-(1375)-832,
 1829-(1375)-832, and 2128-(1375)-832

Figure 29. Gamma-skip-gamma cascades from ^{90}Sr experiment: 952-(1665)-832, and 1838-(1665)-832

2) 997-(2207)-832 cascade One of the intermediate spins in this cascade is spin 1 which implies that A_4 is equal to 0. Thus Figure 30 is a parameterized plot of percent L=2 admixture versus corresponding A_2 values. Note that the data point overlaps the 1-1-2-0 and 2-1-2-0 ellipses and furthermore is quite close to the 3-1-2-0 point. This unfortunate location of the data point does not yield any new information concerning the spin assignment.

f. 4149-keV level (2256-(1060)-832 cascade) The error bars for this data point make an unambiguous spin assignment prohibitive. However, the data point itself, as shown in Figure 27, is nearest the 1-2-2-0 ellipse and this choice may be favored. From Figure 27 one can rule out the spin sequence 0-2-2-0 as a possibility. The other spin sequences that are reasonable are 3-2-2-0, 2-2-2-0, and 4-2-2-0.

g. 4335-keV level

1) 2128-(1375)-832 cascade The angular correlation fit-function curve for this cascade is shown at the top of Figure 23. This fitted curve gives rise to the angular correlation coefficients plotted in Figure 28. The data point lies nearly on the 3-2-2-0 ellipse, while the 1-2-2-0 ellipse is barely outside the error bar limits. This favors the spin 3 assignment but spin 1 cannot be ruled out. Note that for spin 3 choice the L=2 admixture is, most like-

Figure 30. 997-(2207)-832 gamma-skip-gamma cascade from ^{90}Sr experiment

ly, greater than 98%, which suggests a pure E2 multipolarity for the 2128-keV transition and a tentative positive parity assignment to the 4335-keV level. On the other hand, for the spin 1 choice the L=2 admixture is less than 2%.

2) 1838-(1665)-832 cascade At the bottom of Figure 23 is the angular correlation fit-function curve for this sister cascade. Poor statistics contribute to the relatively large errors in the angular correlation coefficients as plotted in Figure 29. However, the location of the data point clearly favors the spin sequence 1-2-2-0 over 3-2-2-0. For spin choice 1 the L=2 admixture ranges from 21 to 69% for the 1838-keV transition, indicating a positive parity assignment.

h. 4366-keV level (2473-(1060)-832 cascade) The data point for this cascade appears in Figure 27. Within the error bars, the data point is consistent with spin sequences 3-2-2-0 and 1-2-2-0. The point itself is nearest to the 3-2-2-0 ellipse. There is an observed crossover to the ground state which virtually eliminates the spin 3 choice. For spin 1, the L=2 mixing in the 2473-keV transition is less than 3%.

C. Levels in ^{140}Cs

Tentative spin assignments are made for several energy levels of ^{140}Cs populated by the 14-second decay of ^{140}Xe . The two-parameter mode of coincidence data collection was used in this study to allow more than one coincidence gate to be set easily. The two-parameter mode stores coincidence events as channel pairs on magnetic buffer tapes, each tape with a storage capacity of about 3.3 million event pairs. In this study coincidence data was obtained from seven such buffer tapes.

A profile of coincidence events for the Ge(Li) detector is shown in Figure 31. The energy range for this profile is from approximately 50 keV to 1500 keV. A skeletal decay scheme from Reference 23 is shown in Figure 32. Note that only direct cascades appear in this study. The two double-lined arrows in the figure represent the transitions which were selected as energy gates. In order to utilize the superior energy resolution of the Ge(Li) detector in fitting coincidence peaks, gates were set on the same energy peak for each of the six NaI(Tl) detectors. A background energy gate was also set for each gating transition. The background gate contained channels just above the channel range of the energy gate. The area of a peak appearing in the background gated spectrum was subtracted from the area of the corresponding

Figure 31. ^{140}Cs coincidence profile taken with the Ge(Li) detector

Figure 32. Skeletal decay scheme of ^{140}Cs , indicating the transitions included in this study

peak in coincidence with the gating transition. This determined the number of true coincidences measured for the cascade.

The energies (and intensities) of the two gating transitions are: 805.52 keV (100) and 989.02 keV (15.2). Gates were set on the 653.40-keV, 1309.08-keV, and 1315.05-keV transitions, but the results were not useful. Note that each gating transition is among the most intense in the decay scheme, and also depopulates the 1427.57-keV energy level. These criteria were chosen because: (1) better statistics are obtained through more intense cascades, and (2) the 1427.57-keV level has the only definite spin assignment in the level scheme prior to this work.

^{140}Xe , which is an even-even nucleus, beta decays from its 0^+ ground state to levels in the odd-odd daughter, ^{140}Cs . Spin 1^+ is assigned to the 1427.52-keV level on the basis of the $\log ft$ value of 4.5 which is obtained from the work done by J.P. Adams, *et al.* (23). An allowed transition is clearly indicated, and a spin choice of 0 or 1 is made for this level. Further, from the rule suggested by Raman and Gove (30), which states that beta transitions with $\log ft$ values between 3.6 and 5.9 are not 0^+ to 0^+ , the spin choice for the 1427.57-keV level is 1^+ . This is also consistent with the simple shell model interpretation. The low $\log ft$ value can be understood if one of a pair of $h(9/2)$ neutrons in ^{140}Xe

changes into a $h(11/2)$ proton in ^{140}Cs . The odd $h(11/2)$ proton and $h(9/2)$ neutron in ^{140}Cs can couple to give spin 1, but not 0.

It may be appropriate at this time to point out that spin-assignment arguments will be presented in this study which utilize $\log ft$, internal conversion coefficient (ICC), and gamma-intensity measurements. These measurements and interpretations are found in the work done by J. P. Adams, *et al.* (23). The gamma-gamma directional correlation measurements of cascades in this nucleus will supplement these arguments in the sense of corroborating and/or limiting spin assignments already made.

There are eleven gamma rays which depopulate the 1427.57-keV level (1^+). Among these, the 805.52-keV and 653.40-keV gammas have ICC's which indicate pure E1 multipolarities. This definitely establishes odd parity for the 774.12-keV and 622.02-keV levels. Further ICC measurements for transitions between levels with energies less than 774.12-keV indicate that these low-lying levels all have odd parity.

In constructing a spin assignment framework, a plausible rule to follow (Reference 23) is that any transition depopulating the 1427.57-keV level with an intensity greater than or equal to one percent of the 805.52-keV gamma is not pure M2. According to the Weisskopf single-particle

estimates, the probability ratio of a 1-MeV transition being pure E1 to pure M2 is 10%. It is thus unlikely that all E1 transitions from the 1427.57-keV level are hindered to such a degree as to permit pure M2 transitions to compete successfully. This implies that energy levels populated by transitions from the 1427.57-keV level with intensities greater than one percent of the 805.52-keV gamma have spin possibilities 0, 1, or 2.

1. Results for direct cascades in ^{140}Cs

The first transition in each cascade depopulates the 1427.57-keV level (1^+). It will further be assumed that the first transition in each cascade is essentially pure E1. Under this assumption the angular correlation coefficient A_4 is zero. Thus, graphs representing percent E2 (for the second transition) versus A_2 will be presented for various spin sequences. Each independent variable, %E2 and A_2 , is parameterized by the mixing ratio and ellipses result from the variation of the mixing ratio. Even if a small amount of M2 mixing is present in the first transition, this will not substantially shift the ellipses or modify the shapes of the ellipses. To be sure, spin choices are eliminated in the following discussion only when the data point is far from such a spin sequence ellipse.

Four representative angular correlation fit-function curves are shown in Figures 33 and 34. These curves are fit

Figure 33. Fit-function curves from the ^{140}Cs experiment for cascades 806-622 and 989-439

Figure 34. Fit-function curves from the ^{140}Cs experiment for cascades 806-557 and 989-374

via a least-squares method to the angular correlation distribution function $W(\theta) = 1 + A_2 P_2(\cos(\theta))$. In each of the two figures, the top fit-function curve represents a cascade from the 805.52-keV transition gate, and the curve at the bottom a cascade from the 989.02-keV gate. Further references to these figures will be made at appropriate points below.

Table 3 summarizes the results of all cascades considered.

Analysis of these cascades is complicated by the fact that the spin of the intermediate state is not known. According to the above discussion, the possible spin choices are 0, 1, or 2. Since many of the correlations, involving both the 806 and 989 keV gates, have significant anisotropies, it follows that $I=0$ is not possible for the intermediate state. However, $I=1$ and $I=2$ both remain as possibilities for the 439 and 622 keV levels. Therefore, in the following discussion two sets of ellipses are plotted for each cascade, one set with intermediate spin 1 and another set with intermediate spin 2.

a. 103.1-keV level (806-519 cascade) The angular correlation coefficient A_2 is shown plotted in Figure 35 for a spin choice of 1 for the intermediate state and Figure 36 for an intermediate spin of 2.

Table 3. Results from the ^{140}Cs experiment

Level (keV)	Cascade	A_2	Intermediate spin	Spin sequence	Mixing ratio range			% L=2 range		
0	806-622	0.272 ± 0.047	1	1-1-1	0.14	0.20	0.28	1.8	4.0	7.3
				1-1-1	7.4	4.9	3.6	98.	96.	93.
			2	1-2-1	-2.2	-1.8	-1.6	83.	77.	71.
				1-2-1	-0.07	-0.13	-0.21	0.4	1.7	4.2
				1-2-2	0.34	0.45	0.61	10.	17.	27.
				1-2-2	6.3	3.8	2.5	98.	93.	86.
	989-439	0.135 ± 0.030	1	1-1-1	-0.03	0.01	0.05	0.1	0.0	0.3
			2	1-2-1	0.09	0.05	0.01	0.8	0.3	0.0
				1-2-2	-0.58	-0.68	-0.80	25.	31.	39.
13	806-608	-0.211 ± 0.046	1	1-1-0		-a				
				1-1-2	3.3	7.9		91.	98.	
				1-1-2	0.67	0.44		31.	16.	
			2	1-2-0						
				1-2-2	1.5	1.9	2.4	69.	78.	85.
				1-2-2	0.18	0.07	-0.02	3.1	0.5	0.0

^apoint corresponding to this spin sequence lies within error bars.

Table 3. (continued)

Level (keV)	Cascade	A_2	Intermediate spin	Spin sequence	Mixing ratio range			% L=2 range		
65	806-557	0.089 ± 0.025	1	1-1-1	-0.08	-0.05	-0.02	0.7	0.2	0.0
				1-1-2	-0.32	-1.45		9.5	68.	
				1-1-3		-b				
			2	1-2-1	0.14	0.11	0.08	1.9	1.1	0.6
				1-2-2	-0.54	-0.85		23.	42.	
				1-2-3	0.03	0.07	0.12	0.1	0.5	1.3
	989-374	0.306 ± 0.087	1	1-1-1	0.13	0.26	0.42	1.6	6.2	15.
				1-1-1	7.9	3.9	2.4	98.	94.	85.
				1-1-3						
			2	1-2-1	-2.2	-1.6	-1.2	83.	73.	57.
				1-2-1	-0.06	-0.19	-0.37	0.3	3.3	12.
				1-2-3	0.32	6.9		9.4	98.	
103	806-519	0.174 ± 0.082	1	1-1-1	-0.04	0.07	0.18	0.2	0.4	3.2
				1-1-1	-22.	15.	5.5	100	100	97.
			2	1-2-1	-3.7	-2.6	-1.9	93.	87.	79.
				1-2-1	0.10	0.0	-0.11	1.1	0.0	1.2

^b Point corresponding to spin sequence 1-1-3 lies just outside error bars.

Table 3. continued

Level (keV)	Cascade	A_2	Intermediate spin	Spin sequence	Mixing ratio range			% L=2 range		
113	806-510	-0.058 ± 0.083	1	1-1-1	-0.42	-0.26	-0.14	15.	6.4	1.8
				1-1-1	-2.4	-3.8	-7.4	85.	94.	98.
				1-1-2	21.	-5.1	-2.1	100	96.	81.
				1-1-2	0.35	0.10	-0.16	11.	0.9	2.5
			2	1-2-1	49.	-12.	-5.4	100	99.	97.
				1-2-1	0.41	0.29	0.19	14.	7.8	3.3
				1-2-2	2.7	4.8	18.	88.	96.	100
				1-2-2	-0.07	-0.22	-0.38	0.4	4.5	13.
232	806-390	0.123 ± 0.046	1	1-1-1	-0.06	0.0		0.4	0.0	
				1-1-1	-16.	>100.		100	100	
				1-1-2	-1.3	-0.41		61.	14.	
				1-1-3		-b				
			2	1-2-1	-4.0	-3.2	-2.7	94.	91.	88.
				1-2-1	0.12	0.06	0.01	1.4	0.4	0.0
				1-2-2	-21.	-6.7	3.6	100	98.	93.
				1-2-2	-0.51	-0.64	-0.83	20.	29.	41.
				1-2-3	0.05	0.13	0.22	0.3	1.8	4.6
				1-2-3	-8.5	-28.	21.	99.	100	100

Figure 35. ^{140}Cs cascades 806-519 and 806-557 for intermediate spin 1

Figure 36. ^{140}Cs cascades 806-519 and 806-557 for intermediate spin 2

1) Intermediate spin 1 In Figure 35, the data point plus error bars are consistent with the spin sequence ellipse 1-1-1. The error bar intercepts the 1-1-2 ellipse in the range of 20% to 50% E2 mixing. The point corresponding to spin sequence 1-1-3 lies about one half standard deviation outside the error bars, which makes this sequence possible but not probable. Spin sequence 1-1-0 is definitely ruled out since the theoretical point lies far from the error bars of the data point.

2) Intermediate spin 2 Spin sequences 1-2-1, 1-2-2, and 1-2-3 are all consistent with the data point shown in Figure 36. However, points representing spin sequences 1-2-0 and 1-2-4 are definitely eliminated.

The beta feeding to this level has a measured $\log ft$ value of 6.73 which indicates a probable first-forbidden nonunique beta transition, and thus limits the spin possibilities to 0 and 1. In each case above spin 0 is ruled out. Thus, spin choice 1 is assigned for the 103.1-keV level.

b. Ground state (806-622, 989-439 cascades) For each of the two energy gates there is a direct cascade to the ground state. The fit-function curves for the two cascades 806-622 and 989-439 are shown in Figure 33. The second transition in the 806-622 cascade has a measured internal conversion coefficient corresponding to approximately 60% E2 mixing. For the 989-439 cascade the second transition could

have an E2 mixture as high as 20% to 30%. This is also based on an ICC measurement. Thus the angular correlation coefficient should intercept, within limits of statistical uncertainty, the ellipse corresponding to the correct spin sequence in the appropriate ranges of percent E2 mixing.

1) 806-622 cascade Figures 37 and 38 indicate sets of ellipses with intermediate spin 1 and 2 respectively.

In Figure 37 the only possible spin sequence choice that is consistent with the data is 1-1-1. The error bars intercept this ellipse in the ranges 1.8% to 7.3% and 93% to 98% L=2 admixture. Unfortunately the error bars on the ICC measurement are large and although the data point itself corresponds to 60% L=2 admixture the error bars extend the measurement nearly to the M1 and E2 lines. Thus the angular correlation measurement for this cascade does not rule out either range of mixing.

For intermediate spin 2, the data point intercepts the 1-2-1 ellipse in the 71% to 83% L=2 range. This is consistent with the ICC measurement for the 622-keV transition. The 1-2-2 ellipse lies just outside the error bars. The closest point on this ellipse corresponds to an L=2 admixture of 70%. The point corresponding to spin sequence 1-2-0 lies far from the data point and this sequence is ruled out. Another possibility in this figure would be spin sequence 1-2-3. This ellipse is intercepted in the range 86% to 98% L=2 admixture.

Figure 37. ^{140}Cs cascades 806-622 and 806-608 for intermediate spin 1

Figure 38. ^{140}Cs cascades 806-622 and 806-608 for intermediate spin 2

However, spin 3 can be ruled out for the ground state on the basis of beta feeding to the ground state (0^+) of even-even ^{140}Ba . The $\log ft$ value is reported by Schick and Talbert (28) to be 7.34, and that is certainly not third forbidden which would be the necessary classification for a 3^- to 0^+ beta transition.

In summary, spins 1 and 2 are plausible spin choices for the ground state, and spin 0 is ruled out.

2) 989-439 cascade Figures 39 and 40 show ellipses with intermediate spins 1 and 2. In this case the percent E2 mixing should be consistent with a small value, perhaps $<20\%$, since ICC measurements indicate a pure M1 multipolarity for the 439-keV transition.

From Figure 39 it is clear that spin sequence 1-1-1 is consistent with a zero L=2 admixture. The percent L=2 mixing ranges from 0 to 0.3 for this spin sequence.

There are two plausible spin sequence choices in Figure 40. Both ellipses 1-2-1 and 1-2-3 are intercepted near the pure L=1 point. The 1-2-1 ellipse indicates an L=2 admixture between 0% and 0.8%, while the 1-2-3 ellipse is intercepted in the range 1.0% to 4.2%. However, as noted earlier, spin 3 is definitely eliminated as a viable spin possibility for the ground state on the basis of beta feeding to ^{140}Ba . Also from Figure 40 the error bars almost extend down to 25% L=2 admixture on the 1-2-2 ellipse. However, from ICC

Figure 39. ^{140}Cs cascades 989-439 and 989-374 for intermediate spin 1

Figure 40. ^{140}Cs cascades 989-439 and 989-374 for intermediate spin 2

measurements the maximum acceptable $L=2$ mixing is 20% for the 439-keV transition. So spin 2 seems unlikely for the ground state, but can not quite be ruled out.

Thus the measured angular correlation coefficient for the 989-439 cascade strongly favors spin choice 1 for the ground state.

Strong arguments have been made in the preceding discussion to help interpret angular correlation measurements in terms of making definite spin assignments. The discussion of remaining levels which appear in this report contain weak supportive arguments to the angular correlation data. Many of these arguments are based on the spin assignment of the 64.75-keV level.

c. 64.75-keV level (806-557, 989-374 cascades) As reported here, two direct cascades populate the 64.75-keV energy level. The angular correlation fit-function curves for these cascades are shown in Figure 34. The second transition in the 806-557 cascade is known, on the basis of ICC measurement, to have an E2 mixture of less than about 50%.

1) 806-557 cascade Sets of ellipses with intermediate spins 1 and 2 are shown in Figures 35 and 36 respectively.

The data point as plotted in Figure 35 is consistent with ellipse 1-1-1. The range of $L=2$ mixing for this spin

sequence is 0% to 0.7%. Although the point corresponding to spin sequence 1-1-3 is just outside the error bar, this sequence is excluded because of the predominantly M1 nature of the 557-keV transition. The data point plus error bars intercept the 1-1-2 ellipse in the range 9.5% to 68% L=2 admixture. Thus spin sequences 1-1-1 and 1-1-2 are possibilities for intermediate spin 1.

In Figure 36, the spin sequences 1-2-1, 1-2-2, and 1-2-3 are possibilities. The theoretical point for spin sequence 1-2-4 is very far from the data point and is eliminated as a possibility. Further, it is not consistent with the M1 multipolarity for the 557-keV transition. The range of percent L=2 admixture for spin sequence 1-2-1 is 0.6% to 1.9% and is 0.1% to 1.3% for the sequence 1-2-3. For spin sequence 1-2-2 the admixture is 23% to 42%.

This cascade yields five spin sequences that remain definite candidates: 1-1-1, 1-1-2, 1-2-1, 1-2-2, and 1-2-3.

2) 989-374_cascade Figure 39 contains ellipses with intermediate spin 1. The data point plus error bars intercept only the 1-1-1 ellipse. The 1-1-2 ellipse lies more than two standard deviations outside the error bars and can be ruled out.

The data point in Figure 40 intercepts ellipses 1-2-1, 1-2-2, 1-2-3. Sequence 1-2-2 is perhaps less likely than the other two. The theoretical point 1-2-4 is far from the data

point and is excluded as a possibility.

Combining the results for these two cascades indicates that both spins 1 and 3 are possible assignments for the 64.75-keV level. At this point, weak arguments can be made which favor spin 3. In the energy level scheme a transition is noticeably absent from the 1427.57-keV level to the 64.75-keV level. One possible explanation is that the spin of the 64.75-keV level is such that a transition from the 1^+ level is hindered, because the spin of the 64.75-keV level is at least as large as spin 3. Also, note that there is an observed transition from the 1427.57-keV level (1^+) to the ground state, which has a spin 1 assignment, so that one might expect to see a transition to the 64.75-keV level if it also had spin 1. A third point favoring spin choice 3 is that no transition from the 64.75-keV level to the ground state (spin 1^-) has been observed, although a search was made for one (23). The low-energy transitions in this nucleus tend to be predominantly M1, with little E2 contribution. If the 64.75-keV level is 1^- , then there could be an M1 transition to the first excited state. If the 64.75-keV level is 3^- , however, the transition to the ground state would be E2, and its absence would be consistent with the general weakness of low energy E2 transitions in this nucleus.

d. 622.02-keV level This level is the intermediate spin state for all direct cascades involving the 805.52-keV E1 transition. The 557.26-keV transition occurs between the 622.02-keV and 64.75-keV levels. This transition is measured (ICC) to be M1 which, if one assumes that spin 3 is the proper choice for the 64.75-keV level, implies that the spin of the 622.02-keV level is at least as large as 2. This argument leads to a definite spin 2 assignment for this level. However, since the spin of the 64.75-keV level is not definitely 3-, spin 1 is not entirely excluded as the 622.02-keV level assignment.

e. 13.13-keV level (806-608 cascade) The data point for this cascade is plotted in Figures 37 and 38.

1) Intermediate spin 1 Ellipses 1-1-1 and 1-1-2 are intercepted by error bars in Figure 37. For ellipse 1-1-1 the L=2 mixing is 18% to 82%, while ellipse 1-2-1 is intercepted in the range 16% to 98%. Also, the point corresponding to the spin sequence 1-1-0 is within the error bars. Spin sequence 1-1-3 however can be eliminated as a possibility since this point is far outside the data point error bars. Thus spins 0, 1, and 2 are possibilities for the 13.13-keV level.

2) Intermediate spin 2 In Figure 38 note that spin sequences 1-2-0, 1-2-1, 1-2-2, 1-2-3 are all consistent with the data point. Spin 3 can be ruled out since there is a 1413.66-keV transition from the 1^+ level. However, spin sequence 1-2-2 may be favored over 1-2-1 and 1-2-3 as the mixing ratio for the 1-2-2 ellipse indicates that the 608.05-keV transition to be nearly pure M1, whereas ellipses 1-2-1 and 1-2-3 are consistent with a fair amount ($>16\%$ and $>25\%$, respectively) of E2 mixing. Clearly spin sequence 1-2-4 is ruled out from the figure. Spins 0, 1, 2, 3 are thus possibilities for the 13.13-keV level with spins 0 and 2 perhaps slightly favored over spins 1 and 3.

From the angular correlation coefficient measurement for this cascade only spin 4 can be definitely ruled out as a spin assignment for the 13.13-keV level. Since the 622.02-keV level is the intermediate state in this cascade, and if one accepts its tentative spin 2 assignment, spins 0, 2 may be slightly favored. Note that in the energy level scheme the 64.75-keV level (a tentative spin 3 state) decays to the 13.13-keV level by an M1 (50.8-keV) transition. This statement implies that the spin of the 13.13-keV level must be greater than or equal to 2. A spin choice of 2 would be consistent with the angular correlation data. However, this is a weak argument, and spins 0 and 1 are not excluded.

f. 112.52-keV level (806-510 cascade) The experimental angular correlation coefficient for this cascade is shown in Figures 41 and 42. There is an observed 1315.05-keV transition from the 1427.57-keV level (1^+) to indicate that spin possibilities for the 112.52-keV level are limited to 0, 1, and 2.

1) Intermediate spin 1 In Figure 41 the data point is consistent with ellipses 1-1-1, 1-1-2. The theoretical point corresponding to spin sequence 1-1-0 is approximately one standard deviation outside the error bars and appears an unlikely candidate.

2) Intermediate spin 2 Ellipses 1-2-1 and 1-2-2 are consistent with the data point as is shown in Figure 42. The theoretical point 1-2-0 lies approximately one standard deviation outside the error bars.

For each intermediate spin choice, spin 0 remains an unlikely assignment for the 112.52-keV level. This is consistent with the observed presence of the 47.75-keV transition from the 112.52-keV level to the 64.75-keV level (3^-). Thus spins 1 and 2 remain as viable possibilities for this level.

Figure 41. 806-510 ^{140}Cs cascade for intermediate spin 1

Figure 42. 806-510 $140cs$ cascade for intermediate spin 2

g. 232.09-keV level (806-390 cascade)

1) Intermediate spin 1 The data point in Figure 43 is consistent with ellipses 1-1-1 and 1-1-2. Also, the theoretical point corresponding to 1-1-3 is less than one standard deviation outside the error bars. One can, however, unambiguously rule out spin sequence 1-1-0 as this point lies far outside the error bars.

2) Intermediate spin 2 Ellipses 1-2-1, 1-2-2, and 1-2-3 are consistent with the data point as is shown in Figure 44. Both theoretical points 1-2-0 and 1-2-4 are far outside the error bars and can be excluded from spin possibilities.

The angular correlation measurement for this cascade indicates that spins 1, 2, 3 are definite possibilities for the 232.09-keV level, and that spins 0 and 4 are not.

Contrary to most of the low-lying energy levels in this scheme there is no observed transition to the 232.09-keV level from the 1427.57-keV level (1^+). As in the case of the 64.75-keV level a weak argument can be made from this statement. That is, the spin of the 232.09-keV level is such that a transition from the 1^+ state would have multipolarity M2 or higher. If the 232.09-keV level has a spin greater than or equal to 3, then the transition would have to be, at least, a pure M2 which would indeed be hindered. Spin 3 is thus favored over spins 1 and 2.

Figure 43. $806-390$ ^{140}Cs cascade for intermediate spin 1

Figure 44. 806-390 ^{140}Cs cascade for intermediate spin 2

VI. DISCUSSION AND CONCLUSIONS

The results of angular correlation measurements of cascades in ^{140}Ba give rise to definite spin assignments for eight levels, tentative assignments for five levels, and a choice between two spins for two levels. In searching for a plausible explanation for level assignments in ^{140}Ba note that Basinger, Schick, and Talbert (31) have discussed levels in another even-even $N=84$ nucleus, ^{142}Ce , in terms of a hydrodynamic model of the nucleus. An $N=84$ nucleus, such as ^{140}Ba , has two neutrons outside a closed shell and may have oscillations about a spherical equilibrium shape.

The first excited state in ^{140}Ba would be identified as a 1-phonon state in this model, and the levels at 1131 keV (4^+) and 1511 keV (2^+) are possible members of a 2-phonon triplet. There is no observed ground-state transition from either level, in agreement with the model. Also there is significant ($>45\%$) E2 mixing in the 908-keV transition between the two 2^+ levels as this transition, according to this model identification of states, connects a 2-phonon state with a 1-phonon state.

The 0^+ state at 1824 keV could be the third member of the 2-phonon triplet. However, it occurs at a fairly high energy and is more likely to be a member of the 3-phonon multiplet. The nearby 3^+ state at 1951 keV is another candidate for a 3-phonon state. There is no observed transition

from this level to the 1-phonon state (2^+) and such a transition is forbidden by the model. Also, the 821-keV transition from the 1951-keV state to the 2-phonon (4^+) level at 1131 keV has an $L=2$ admixture of about 20%.

The spin assignments to levels in ^{140}Ba provide further information to the systematics in $N=84$ nuclei. The first three excited states (spins 2^+ , 4^+ , 2^+) in ^{140}Ba are consistent with the trend of energies in corresponding levels in the $N=84$ isotones. The first three excited states monotonically decrease in energy as the number of protons decreases from $Z=64$ in ^{148}Gd toward the magic number 50. In contrast to the monotonic decrease in energy of the first three excited states, the 3^- state (1803 keV in ^{140}Ba) increases in energy with decreasing proton number.

It would be useful to have energy-level information for ^{136}Te and ^{134}Sn to see if the lowest energy levels increase drastically in energy as predicted by the shell model.

The results of angular correlation measurements of cascades in ^{90}Sr yield definite spin assignments for eight levels. Six levels have tentative assignments, three levels have a choice of two spins, and one level has a choice of three spins.

Recent (t,p) reaction studies (32) confirm the spin assignments made in this work for the first three excited states and the spin 0 state at 2971 keV. However, there is a

conflict in the assignment of the 2207-keV level. The reaction studies indicate a 3^- spin, while the angular correlation coefficients for the 1375-832 direct cascade dictate a spin 2 with substantial $L=2$ mixing ($>15\%$).

Like ^{140}Ba , ^{90}Sr ($N=52$) has two neutrons outside a closed shell. It may prove useful, for comparison, to look at the spin assignments for ^{90}Sr also in terms of oscillations about a spherical equilibrium shape. The first excited state would be a 1-phonon state as before. The next two levels (spins 2^+ , 4^+) could be identified as members of the 2-phonon triplet. A weak ground-state transition is indicated from the 2^+ level at 1892 keV (forbidden by the model), but this placement was made without coincidence information for the 1892-keV transition. Further, the 1060-keV transition, which connects the 2-phonon 1892-keV level (2^+) to the 1-phonon (2^+) level, has a significant ($>15\%$) $L=2$ admixture.

The spin 0 state at 2971 keV is probably too high in energy to be identified as a member of the 2-phonon triplet. It is more likely a member of the 3-phonon multiplet. Although it is difficult to identify other possible members of the 3-phonon multiplet the 2927-keV level (spin 4 or 3^+) may be such a member. There are no observed transitions from this level to either the ground state or the 1-phonon first excited state. This observation is consistent with the model.

The results of angular correlation measurements in ^{140}Cs , plus other available experimental data, yield a definite spin assignment for one level, tentative assignments for five levels, and a choice between two spins for two levels.

^{140}Cs is an odd-odd nucleus with five protons ($Z=55$) outside the closed shell at 50, and three neutrons ($N=85$) outside the closed shell at 82. According to the shell model the $1g_{7/2}$ state would be the first single-particle state to be filled after the magic number 50, although there is not a large separation from the next level configuration of $2d_{5/2}$. One might expect that the odd proton has a spin of either $7/2$ or $5/2$. Further, for nearby Cs isotopes with $A=133$, 135 , and 137 the ground state and first excited state have spins $7/2^+$ and $5/2^+$. The first single-particle shell model neutron state above magic number 82 is $2f_{7/2}$. For the $N=85$ nucleus ^{143}Ce the ground state has spin $7/2^-$. For ^{145}Nd the two lowest lying energy levels have spins $7/2^-$ and $3/2^-$. This suggests that the three neutrons outside the closed shell in ^{140}Cs couple, in the $(2f_{7/2})^3$ configuration, to spin $3/2$ or $7/2$.

Assuming the ground-state configuration of five $1g_{7/2}$ protons coupled to $7/2$ and three $2f_{7/2}$ neutrons coupled to $3/2$, there are four possible states from the neutron-proton

spin coupling. These states would have spins 2, 3, 4, 5. On the other hand, if the neutrons couple to $7/2$, the protons could combine to form eight states with spins 0, 1, 2, 3, 4, 5, 6, 7. Recoupling the protons to spin $5/2$ and combining them with the three neutrons coupled to, first $7/2$, and then $5/2$, gives states of spins 1, 2, 3, 4 and 1, 2, 3, 4, 5, 6. By excluding spin states greater than 3, the following states are possible, according to this coupling scheme, for the low-lying levels in ^{140}Cs : one state with spin 0, three spin 1 states, four spin 2 states, and four spin 3 states. Some of these twelve possibilities may be seen for six of the lowest lying levels indicated in Figure 32.

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