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DECAY OF MASS-SEPARATED ^{122}Ag TO LEVELS IN ^{122}Cd

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Decay of mass-separated ^{122}Ag to levels in ^{122}Cd

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A study of gamma-ray de-excitation following the beta decay of ^{122}Ag is reported. Sources were prepared using the TRISTAN on-line isotope separator facility. Gamma-ray singles, gamma-gamma coincidence and gamma-ray multiscale measurements were made using Ge(Li) detectors. A total of 6 gamma rays were assigned to the decay of ^{122}Ag of which 5 were placed in a level scheme for ^{122}Cd consisting of 4 excited states at 569, 1329, 1368 and 1979 keV. Gamma-ray multiscale measurements confirmed that ^{122}Ag has only one isomer. The half-life value obtained was 0.48 ± 0.08 seconds. Spin and parity assignments were deduced on the basis of gamma-ray transition probabilities and beta transition $\log ft$ values. ~~our~~ results are compared with those from previous studies and the systematics of even-even Cd nuclei are discussed.

I. INTRODUCTION

A. Nuclear Decay

Nuclei that are not stable will decay to more stable daughter nuclei by emission of various particles. Nuclei on the neutron-rich side of stability decay so as to increase the ratio of protons to neutrons. For ^{122}Ag , two branches of decay are energetically possible. One process is beta decay in which the atomic number increases by one unit by emission of an electron but the mass number remains constant. For example, ^{122}Ag has a half-life of about 0.5 sec and decays by electron emission to ^{122}Cd . Since ^{122}Cd is not stable it decays to ^{122}In which in turn decays to ^{122}Sn . Another possible mode for ^{122}Ag decay is the delayed-neutron process. Delayed-neutron emission is very important for the control of short-term power fluctuations in a fission reactor. It is of interest to determine if delayed-neutron emission is energetically possible for ^{122}Ag . The delayed-neutron decay mode is illustrated below:

If Q_{β^-} minus S_n is greater than zero, delayed-neutron emission is energetically possible. Q_{β^-} represents the maximum kinetic energy available for the emitted electron and

is the difference in ground-state rest energy between the parent (^{122}Ag) and the daughter (^{122}Cd) nucleus. S_n is the separation energy of the last neutron in ^{122}Cd . S_n for the delayed-neutron process can be defined for ^{122}Ag as:

$$S_n = \text{mass excess } (^{121}\text{Cd}) + \text{mass excess } ({}^1_0\text{n}) - \text{mass excess } (^{122}\text{Cd})$$

According to our calculation Q_{β^-} minus S_n equals 1.19 MeV, therefore delayed-neutron emission is possible for ^{122}Ag . Figure 1 shows the beta decay chain for $A=122$ beginning with ^{122}Ag . The Q_{β^-} shown are from the mass formulas of Garvey et al. (1).

The beta decay usually leaves the daughter nucleus in an excited state which is quite short-lived. It will therefore decay to lower states by emission of a gamma-ray or by the process of internal conversion in which the transition energy is given directly to one of the atomic electrons.

B. Theoretical Motivation

The aim of nuclear studies is to learn more about the nature of the nucleon-nucleon interaction and to use it to describe the properties of the many-body systems called nuclei. In nuclear spectroscopic studies properties of nuclear states are measured which are used to construct appro-

Figure 1. A=122 beta-decay chain studied in this work

priate models for specific nuclei. If the model is successful it can also describe other nuclei in the same mass region with similar nuclear structures. Both Pd ($Z=46$) and Cd ($Z=48$) nuclei are just below singly-magic Sn ($Z=50$) on the nuclear chart. The level structure of many even-even Pd nuclei has been described in terms of a breathing-mode vibrator, asymmetric rotor model with considerable success (2). It is therefore of interest to determine how well this model applies to the even-mass Cd isotopes. A series of studies of levels in neutron-rich even-even Cd nuclei is being carried out by the TRISTAN group. The decay scheme of ^{122}Cd is one of these systematic studies.

C. Previous Work

The first reported observation of neutron-rich ^{122}Ag was made by B. Fogelberg, A. Bäcklin and T. Nagaraajan in 1971 (3). Two gamma rays were observed to be emitted in the beta decay of ^{122}Ag with energies of 570 keV and 760 keV. The gamma-ray singles spectra were taken with a 40 cm³ Ge(Li) detector with 2.0 keV resolution (FWHM) at 1.33 MeV and gamma-gamma coincidence spectra were measured with two such detectors. The half-life was measured by multi-scaling of the stronger peaks in the decay and was determined to be 1.5 ± 0.5 sec. Only one ^{122}Ag isomer was observed, whereas

for ^{116}Ag , ^{118}Ag and ^{120}Ag two isomers are known(3). They also suggested that the 570 keV state in ^{122}Cd had a 2^+ character. Only two gamma ray energies were reported and their intensities were not given.

Half-life determinations of mass-separated delayed-neutron precursors produced in fission were carried out by E. Lund and G. Rudstam in 1976 (4). They reported that a weak activity was found at mass number 122 with a half-life of about 1 sec. They further stated that the half-life was in agreement with the value of 1.5 ± 0.5 sec attributed to ^{122}Ag and obtained from gamma-ray studies at their laboratory.

D. Object of Study

The purpose of this study is to determine a decay scheme for ^{122}Ag . Results from measurements of gamma-singles spectra, half-lives and gamma-gamma coincidences will be used. The decay schemes of $^{114}-^{120}\text{Ag}$ from reference (3) have been adopted in this work for comparison with the decay scheme of ^{122}Ag . The ratio of the 4^+ to 2^+ excitation energies was reported to rise slightly from ^{114}Cd to ^{116}Cd and then stay constant at about 2.38 for ^{116}Cd , ^{118}Cd and ^{120}Cd . They indicated 3^+ or 3^- to be the J^π for the Ag ground state based on $\log ft$ values for β^- decay of the ^{116}Ag ,

^{118}Ag and ^{120}Ag ground states to the low-lying 2^+ and 4^+ states in the corresponding Cd nuclei. One motivation of this study is to use our results on the level scheme of ^{122}Cd to determine if the rotation-vibration model of Hsu, Williams and Wohn (5) is valid for very neutron-rich even-even Cd nuclei.

II. EXPERIMENTAL PROCEDURE

A. The TRISTAN Separator System

Figure 2 gives a schematic layout of the TRISTAN isotope separator facility which has been described earlier (6). The experimental procedure for obtaining mass-separated fission products is described below. Neutrons from the core of the Ames Laboratory Research Reactor pass through a beam tube and strike an external target which consists of a graphite cloth sleeve containing $^{235}\text{UO}_2$ inside an ion source. The ion source is located in the neutron beam which has a flux of 3×10^9 thermal neutrons/cm²/sec. After fission the resulting products are ionized and drawn out of the ion source by an extractor. The ion beam from the source is electrostatically transported and focused by a system of electrostatic lenses in front of the entrance to a 90° sector magnet with a mean radius of 160 cm. In the sector magnet, the ions with different masses are separated and emerge into a collector box. The focal plane of the ion beam is in the collector box. A slit allows the desired mass to pass through while stopping the neighboring masses. The ion beam is then deflected 45° by a switch magnet located down stream from the collector box. The deflected ion beam is then collected on the movable tape of the moving tape collector (MTC) which is controlled by the daughter

Figure 2. Schematic layout of the TRISTAN isotope-separator facility

analysis system.

A new in-beam ion source of the type used at the OSIRIS facility (7) in Sweden was installed in the TRISTAN facility which allows the ion source to be placed in the neutron beam and enables us to study many non-gaseous fission products. Figure 3 shows the ion source arrangement. A graphite cloth sleeve containing the $^{235}\text{UO}_2$ as a target is wrapped inside the hollow cylindrical graphite anode. The discharge chamber consists of a tungsten filament, graphite anode, boron nitride insulators and niobium heat shield. The fission products are produced when thermal neutrons cause ^{235}U nuclei to fission in the $^{235}\text{UO}_2$ target. The resulting fission fragments are thermalized by the graphite and diffuse into the plasma along the axis of the anode. The fission products in the ion source are insufficient to sustain a plasma discharge, so 5 to 10 uTorr of helium support gas containing Kr and Xe mass markers is used to maintain the stable discharge between the filament and anode. The ion source operates in a direct-discharge mode providing an adequate yield of short-lived fission activities.

P. Gamma-ray Singles Measurements

1. Gamma-ray detection

When a photon passes through a medium, it loses its energy rapidly through interaction with the atoms and elec-

Figure 3. New in-beam ion source

trons in the medium. Three major processes are responsible for most of this energy lost. They are the photoelectric effect, the Compton effect and pair production. If the energy of the incoming photon is much less than the rest energy of an electron, the photo-electric effect is the dominant one. In this study, a LEPS detector is used to measure low-energy gamma rays. It has a thin Be window that allows gamma rays with energy less than 100 keV to enter the detector with high efficiency. The Compton effect is the scattering process between a photon and an atomic electron. The third mode of energy loss is pair production which occurs when the gamma transition energy is greater than twice the electron rest mass (1.02 MeV). In pair-production a positron-electron pair is created with a total energy equal to the energy of the photon. The produced electron may stop in the detector while the positron annihilates with an electron to produce two 511-keV gamma rays. Events in which one of the 511-keV gamma rays escapes from the detector produce a single-escape peak with an energy of $E_\gamma - 511$ keV. Events in which both gamma rays escape from the detector produce a double-escape peak with an energy of $E_\gamma - 1022$ keV. The above losses can be minimized by using the largest volume detector available. The detector used in this study was a Ge(Li) detector which is a solid state diode fabricated from a single crystal of high purity p-type

germanium. An evaporated lithium coating has been drifted into the Ge creating a large intrinsic region. The incoming photons create electron-hole pairs along their paths. The number of the electron-hole pairs and the charge separated by the electric field is linearly dependent on the energy transferred. The advantage of using a Ge(Li) detector is the high energy resolution and peak-to-Compton ratio.

2. Experimental apparatus

In order to identify the gamma rays from the decay of ^{122}Ag , four major runs are necessary, namely parent, daughter, granddaughter and background runs. In the parent run gamma rays from the decay of ^{122}Ag , the rest of the 122 decay chain, and background contamination were observed. The daughter run eliminated only the ^{122}Ag gamma rays but not those from ^{122}Cd and ^{122}In . This provided a comparison for identifying the ^{122}Ag parent gamma rays. In the granddaughter run only background radiation from fast neutrons and the environment was observed. This was used advantageously for double checking the accuracy of the parent decay identification. The parent spectrum included longer-lived decay products such as ^{122}In which were seen in the daughter but not the granddaughter run. The background and granddaughter spectra turned out to be essentially the same. This was due to the fact that the longest-lived mem-

ber of the decay chain had a half-life of only 10 sec. The reason for the granddaughter run was thus to identify the longest-lived nuclei associated with the decay chain. Table I summarizes the details of the above four runs.

Table I. Timing for gamma-ray singles runs

Accumulate			
Run type	and	Delay time	Purpose
collect time			

Parent run	3 sec	1.5 sec	Provide information on ^{122}Ag gamma rays.
Daughter run	10 sec	6 sec	Identify the gamma rays from ^{122}Cd and ^{122}In decay.
Grand- daughter run	120 sec	30 sec	Identify any long-lived ($T_{1/2} > 20$ sec) decay products.
Background run	-----	-----	Provide information on background radiation.

The block diagram of the equipment used in the collection of gamma-ray singles data is shown in Figure 4. The Ge(Li)

Figure 4. Block diagram of gamma singles electronics

detector is mounted at the parent or daughter port of the MTC so that we can arrange various delay, accumulate and collect times in order to obtain the parent, daughter and granddaughter activities. The signal from the detector is fed to the preamplifier whose output goes to a linear amplifier. The amplifier signal is processed by a 8192-channel analog-to-digital converter (ADC). The ADC has a maximum capacity of $10^5 - 1$ counts per channel. The information was stored in the memory of a 16K multichannel analyzer and dumped onto magnetic tape at the end of the run for later analysis.

C. Multi-scale Measurement

1. Purpose of measurement

The radioactive decay law applies equally well to the decay of radionuclides which emit alpha particles, beta particles, or gamma quanta. If at time $t=0$, the number of nuclei present is N_0 then at time $t=t$ the number of nuclei remaining is N . The relation between N and N_0 can be written as

$$N = N_0 e^{-\lambda t}$$

where λ is the decay constant. The half-life is given by $T_{1/2} = \ln 2 / \lambda = 0.693 / \lambda$. From this equation, it is simple to determine the half-life, if we can measure total gamma-ray

or beta-ray counts as a function of time.

The technique used in the measurement of the ^{122}Ag half-life consisted first of the selection of the photopeak from the most intense gamma-ray from ^{122}Ag decay. From the time-dependent decrease of intensity of the gamma transition, we can measure the half-life. The advantage of this technique is that it minimizes interference from other isotopes.

2. Measurement apparatus and procedure

The beam of mass 122 was selected at the focal plane and passed through a switching magnet onto the tape of the MTC. The activity deposited on the tape was used to observe the decay activities. In earlier work (3), the ^{122}Ag half-life was found to be 1.5 sec. In order to collect enough information the collection time was set at 2.5 sec. After the collection period, the beam was deflected from the tape of the MTC through use of a high voltage. The daughter analysis system which controls the MTC was set for a total data accumulation time of 6.4 sec which was broken up into 16 time bins 0.4 sec long. After the observation period, the remaining activities were carried away by moving the tape and the cycle was repeated. An analyzer with a memory of 16384 channels was divided into a 1024 X 16 array in order to store the decay information. An energy range from

Figure 5. Block diagram of multi-scale electronics

500 keV to 1200 keV was spanned in 16 successive 1024-channel spectra. A block diagram of the equipment is shown in Figure 5.

D. Coincidence Measurement

A coincidence occurs if two events occur whose time difference is less than or of the order of the resolving time of the coincidence circuit. In nuclear studies, if cascading gamma rays emitted from different levels arrive at the detector within the resolving time of the system they are called in coincidence. The gamma-gamma coincidence measurements provide additional information for level scheme construction. They are useful because they determine which gamma rays are in cascade. A block diagram in Figure 6 shows the equipment set up for this measurement. Two Ge(Li) detectors were placed at an angle of 180° about 10 cm apart. In order to get an amplitude and rise-time compensated timing signal, constant-fraction timing discriminators (CFD) were used. Since a coincidence event is determined by the timing between signals from the two detectors the pulses from one detector were used as a start signal for the time-to-pulse-height converter (TPHC) and the pulses from the other detector which were used as a stop signal were delayed about 40 nanoseconds. The single channel analyzer (SCA) then selected a region of pulse heights which

Figure 6. Block diagram of gamma coincidence electronics

corresponded to coincidence events. If the output of the TPHC fell within this selected pulse-height region, then the output pulse from the SCA was used to gate open the ADC's. The ADC's were used in the 4K mode to register each pair of events (channel number) coming from detectors A and B. A buffer system having a capacity of 2048 events was used to store each coincidence pair. After the buffer was filled with 2048 events it was dumped onto the magnetic tape and the process repeated.

III. DATA ANALYSIS AND RESULTS

Data analysis was undertaken with the aid of computer programs which have been developed previously. The programs used for each measurement are discussed in the next few pages and the experimental results obtained for ^{122}Ag decay are summarized in the figures and tables.

A. Transition Energies and Intensities

The gamma-ray spectra stored on magnetic tape were transferred to disk storage by the program DISKRITE. This program also provides a listing of the data. The transition energies and intensities were determined from the centroids and areas of the peaks which in turn were obtained by fitting the peaks to a skewed Gaussian. Two programs, PEAKFIND (8) and SKEWGAUS (9) are available for the peak fitting. PEAKFIND makes initial peak identification and provides preliminary fits. SKEWGAUS utilizes the PEAKFIND output and makes available additional parameters when necessary to obtain a better fit.

The determination of the unknown gamma energies is a three step process involving a calibration, calibration plus unknown and unknown run. The calibration run was used to measure the non-linearity in the relationship between the energy and channel number. Gamma rays from ^{56}Co , ^{182}Ta and

^{226}Ra were used as standards. The calibration plus unknown run was used to determine the energies of the intense unknown peaks using the calibration peaks as an internal calibration. The unknown run was used to determine the energies of the remaining unknown peaks. Many of these peaks were very weak, therefore an accumulation time for the unknown run of 12 hours was required in order to get statistically satisfying data. The computer program used to determine the energies and intensities was DRUDGE (10). The procedure for obtaining the gamma-ray energies is described below.

A weighted least-squares straight line was fitted to the standard energies in the calibration spectra. The non-linearity of the electronics was derived relative to the least squares line by subtracting the computed "least squares energy" from the standard energy. It was assumed to be the same for the calibration plus unknown and unknown spectra. A second least squares line was fit to the same standard calibration energies in the calibration plus unknown spectrum. The energies of the strong ^{122}Ag gamma rays were obtained from the calibration after correction for non-linearities. In the calibration plus unknown spectrum, the energies of strong peaks from both ^{122}Ag and ^{122}In were determined for use as secondary standards to determine the energies of the weak ^{122}Ag gamma rays in the unknown

spectrum.

The energy contains the uncertainty of the non-linearity plus the uncertainty in the position of the peak centroid. The relative intensity of the gamma transitions is determined from the area of the gamma peak corrected for the relative efficiency as a function of energy for the Ge(Li) detector. The area of the peak is determined after subtraction of Compton background counts from higher energy gamma rays. The strongest ^{122}Ag peak in the unknown run was normalized to 1000. The other unknown peaks were calculated relative to the strongest peak. The gamma energies and intensities are summarized in Table II.

Table II. Gamma transitions observed in the decay of ^{122}Ag

Energy (keV) this work	Relative ¹ intensity	Energy (keV) Ref. (3)	Placement (keV)
569.45 $\pm$ 0.08	1000	570	569-0
650.20 $\pm$ 0.12	215 $\pm$ 32		1979-1329
759.70 $\pm$ 0.08	335 $\pm$ 30	760	1329-569
798.4 $\pm$ 0.3	130 $\pm$ 46		1368-569
1367.8 $\pm$ 0.5	43 $\pm$ 19		1368-0
1423.0 $\pm$ 0.9	32 $\pm$ 25		

¹Intensities normalized to 1000 for the 569-keV gamma ray.

Only the gamma rays at 569- and 760-keV were seen in earlier work and no intensities were given. The relative efficiency for our Ge(Li) detector was determined using standard gamma rays from ^{56}Co , ^{182}Ta and ^{226}Ra (11). The gamma-ray spectrum (parent run) from the decay of ^{122}Ag is shown in Figure 7. The energies of ^{122}Ag gamma rays are given on the figure in keV. Other activities observed in this spectrum included ^{122}In , ^{132}I , ^{60}Co and Ge neutron-capture gamma rays produced by the interaction of fast neutrons with the Ge(Li) detector.

A spectrum taken using a LEPS detector is shown in Figure 8. The purpose of this run was to detect X-rays and gamma rays with energies less than 100 keV. Activities observed in this spectrum included X-rays from In and Pb, and low energy gamma rays from ^{122}In decay. No ^{122}Ag gamma rays with energies less than 100 keV were found. The conditions for the LEPS run were almost the same as for the parent ^{122}Ag run. The only difference was that the gamma calibration standards used were ^{57}Co and ^{182}Ta .

B. Half-life

The multi-scale data for ^{122}Ag were stored temporarily on magnetic tape, then transferred to a private disk pack for computer analysis. The spectra plots from each time bin

Figure 7. Gamma-ray parent spectrum from the decay of ^{122}Ag

Figure 8. Low-energy gamma-ray spectrum from the A=122 decay chain

were obtained from the output of the ICPEAK (12) program which also provides the centroid, area, height and width of the peaks. These plots consisted of 16 successive gamma-ray spectra which included transitions that were prominent in the activity of interest. In Figure 9 gamma-ray spectra from the 1st, 3rd and 5th time bins are shown. Each segment represents a time interval of 0.4 sec. From the peak area of the 569-keV gamma ray in each segment, a rough decay curve was obtained. To improve the accuracy of the half-life result, the decay curve was fit by the method of least-squares weighted by the uncertainty of the area (13).

The half-life of the 569-keV transition from ^{122}Ag decay was determined to be 0.48 ± 0.08 sec. The other gamma transitions (760-keV, 650-keV and 798-keV) in Figure 9 were also examined. They decayed very fast which is consistent with the short half-life result. Figure 10 shows the decay curves for the 569-keV gamma-ray from ^{122}Ag decay and for comparison the 1002-keV gamma-ray from ^{122}In decay. The known half-life from the ^{122}In 1002-keV transition was used to check the accuracy of the measurement. From Nuclear Data Sheets (14) the ^{122}In half-life was reported to be 10.0 ± 0.5 sec in good agreement with our result of 10.4 ± 0.5 sec. It is thus reasonable to have confidence in the 0.48 sec result, even though it is much less than either the value of 1.5 ± 0.5 sec obtained at OSIRIS (3) by gamma-ray meas-

Figure 9. Multi-scale gamma-ray spectra

Figure 10. Decay curve for ^{122}Ag

urement or the value of about 1 sec obtained by delayed-neutron measurements (4).

C. Coincidences

The ^{122}Ag activity was very weak, therefore the coincidence data was taken under equilibrium conditions (moving tape at rest) in order to maximize the ^{122}Ag coincidence counting rate. After the run, gates were chosen for the ^{122}Ag gamma rays of interest. In order to eliminate those events in coincidence due to the Compton background under a given transition, two gates were chosen. One was the coincidence gate on the peak of interest, and the other was a Compton gate of the same channel width placed immediately above or below the peak.

Every pair of coincidence events from the ADC's were recorded on a buffer tape. In this study, each pair of events consisted of channel numbers corresponding to the gamma-ray energies registered by detectors A and B respectively. In order to reconstruct the 4K spectra in coincidence with each gamma-ray, the coincidence pairs in the appropriate gate were assembled by the computer program BUFPTAPE (15) and recorded on another magnetic tape. The coincidence spectra on this tape were then written on a private disk using the program BUFFREAD. Later both the coincidence gate and Compton gate spectra were plotted using

the program UPLT (10). These two plots were examined visually and valid coincidences were recorded. Because both the coincidence and Compton gates were of equal size, it was possible to do a point-by-point subtraction of the background from the coincidence spectrum. If the peak in the coincidence gate was statistically significant when compared to the same peak or region in the background gate it was called a definite coincidence. If it was slightly larger or had poor statistics it was called a possible coincidence. The spectra of gamma rays in coincidence with the 569-keV and 760-keV photopeak from ^{122}Ag decay are shown in Figure 11. The results from the coincidence measurements are summarized in Table III.

Table III. Coincidences observed in the decay of ^{122}Ag

Gating transition (keV)	Coincident gamma rays (keV)
569	650, 760, 798
650	569, 760
760	569, 650
798	569

Figure 11. Gamma spectrum in coincidence with the (a) 569-, and (b) 760-keV gamma rays from ^{122}Ag

IV. DECAY SCHEME

A. Level Scheme Construction

Using results from the singles and coincidence measurements, a decay scheme for ^{122}Ag was constructed. The resulting level energies, β feedings, and $\log ft$ s are given in Table IV, and the decay scheme is shown in Figure 12. In the figure a solid dot indicates a definite coincidence.

Table IV. Beta branchings and $\log ft$ values for ^{122}Ag decay

Level energy (keV)	Beta branching ¹ (percent)	$\log ft$
0	0	
569.45 $\pm$ 0.08	51.2 $\pm$ 8.6	5.30 $\pm$ 0.12
1329.15 $\pm$ 0.12	11.6 $\pm$ 4.2	5.77 $\pm$ 0.19
1367.8 $\pm$ 0.5	16.6 $\pm$ 4.9	5.60 $\pm$ 0.17
1979.4 $\pm$ 0.4	20.6 $\pm$ 3.3	5.35 $\pm$ 0.13

¹ β branching to the ground state is assumed to be zero, because β^- feeding to the 4^+ level in ^{122}Cd was observed.

The most intense gamma ray from ^{122}Ag decay at 569 keV was postulated to depopulate the first excited state. The

Figure 12. ^{122}Ag decay scheme

1368-keV level was established using the energy sum of the two gamma rays at 798- and 569-keV. This level was also confirmed by the coincidence between the 798-keV and 569-keV gamma rays. The three gamma rays at 569-, 760-, and 650-keV were all in coincidence with each other indicating a three level cascade. The reason for placing the 760-keV gamma ray between the 569- and 650-keV gamma rays was due to the fact that the intensity of the 760-keV gamma-ray was stronger than that of the one at 650 keV. Levels at 1329 and 1979 keV were therefore established. The gamma-ray at 1423 keV was not placed, since it was not observed in any of the coincidence spectra. It was also the weakest of the gamma rays from ^{122}Ag .

B. Beta Branchings and $\log ft$ Values

The percentage of total beta feeding to a level is required to calculate the $\log ft$ value for that level. The $\log ft$ values are useful in limiting the spin and parity assignments for levels of interest.

The computer program LEAF(10) calculated the relative beta branchings to all excited states. We assumed a ground-state beta branching of zero, since the beta-transition intensities to the first and second excited states in ^{122}Cd are strong. The beta branching of the excited states was

obtained by calculating the difference between the gamma transition intensities into and out of each level of the daughter nucleus (Cd). Corrections for internal conversion were not made due to the fact that the corrections are small for gamma-ray energies greater than 500 keV. The $\log ft$ values were calculated using the program LOGFT(10).

C. Spin and Parity Assignments

The spin and parity assignments for levels in ^{122}Ag and ^{122}Cd were made on the basis of the $\log ft$ values, observed gamma transitions and systematics of neighboring even-even Cd nuclei. A discussion of our spin and parity assignments is given below.

Ground state. The spin and parity for the ^{122}Cd ground state was assumed to be 0^+ since this is the J^π for the ground states of all even-even nuclei (16).

569.45 $\pm$ 0.16-keV level. This well-established level has been accepted as a 2^+ state as reported in Nuclear Data Sheets (14). This is probably true since almost all even-even nuclei have first excited states which are 2^+ with only a few exceptions which are mostly doubly-magic nuclei. Also all other known even-even Cd nuclei have a 2^+ J^π for the first excited state.

1367.8 $\pm$ 0.5-keV level. This level was assigned a J^π

of 2^+ . This was based on the observation of gamma transitions to both the ground and first-excited states. Even-even nuclei in the Cd region display vibrational-type spectra. For the ^{122}Cd nucleus, one therefore expects to find a $0^+-2^+-4^+$ triplet at roughly twice the energy of the first excited state. The 0^+ to ground state (0^+) transition is absolutely forbidden since the phonon has spin 1. According to parity and angular momentum selection rules for gamma-ray transitions, E2 and E4 transitions involve no parity change, but E4 is forbidden relative to E2 since its angular momentum is two units greater. Therefore, the 4^+ to ground state (0^+) transition was impossible to see. Thus only the 2^+ member of the triplet could decay to the ground state.

1329.15 ± 0.12 keV. This level was assigned a J^π of 4^+ . For ^{118}Cd and ^{120}Cd the 4^+ state is lower in energy than the 2^+ member of the vibrational triplet thus from systematics we favor 4^+ for this level. The gamma transition at 760 keV was found to be the second strongest peak in the ^{122}Ag decay spectrum which is typical for the 4^+ to 2^+ transition.

^{122}Ag ground state. Rules for limits on spin and parity assignments based on $\log ft$ values were suggested by Raman and Gove (17). One rule states that for nuclei with $Z < 80$ and $\log ft \leq 5.9$, $\Delta J=0,1$ and $\Delta\pi=\text{no.}$ The $\log ft$ values

for the 569-keV and 1329-keV levels are 5.3 and 5.8 respectively. From the selection rule above and the 2^+ character of the 569-keV level, we can limit the ^{122}Ag ground state assignment to 1^+ , 2^+ or 3^+ . Based on the same argument for the 4^+ state at 1329-keV, the ^{122}Ag ground state J^π is limited to 3^+ , 4^+ or 5^+ . Only one J^π satisfied the above conditions. Therefore, the ^{122}Ag ground state was determined to be 3^+ .

1979.4 $\pm$ 0.4 keV level. The $\log ft$ value for this level is 5.35. According to the $\log ft$ rule, the spin is limited to 2^+ , 3^+ and 4^+ . A spin of 3^+ or 4^+ is favored for this level on the basis of the absence of a gamma transition to both the first excited 2^+ state and the ground state.

V. DISCUSSION

A. Comparison with Previous Work

The levels proposed in this study were compared in Figure 13 to the beta decay results of B. Fogelberg et al. (3). Four new gamma-ray transitions with energies at 650-, 798-, 1368- and 1423-keV were found. Three of them were used to extend the level scheme. The new levels at 1329- and 1979-keV were confirmed by coincidence results, gamma-ray intensities, and energy sums. The two energies from previous work (3) were in agreement with our results within the quoted error. We can't compare the intensities, since they were not given in the previous work.

B. ^{122}Ag Ground State Configuration

^{122}Ag ($Z=47$, $N=75$) is an odd-odd nucleus which consists of three proton holes and seven neutron holes below the $Z=50$ and $N=82$ magic numbers respectively. In the single-particle model the spin of the ^{122}Ag ground state is determined by the sum of the angular momenta of the odd-neutron and odd-proton. Often some of the shell-model states inside a major closed shell are quite close in energy, therefore the odd proton can be either $g_{9/2}$ or $p_{1/2}$. The same reasoning implies that the odd neutron can be $s_{1/2}$, $d_{3/2}$ or $h_{11/2}$.

Figure 13. Comparison of ^{122}Cd levels with those from previous work
 (a) This work (b) Ref. (3)

By coupling the odd proton to the odd neutron states, six combinations were possible and are given below:

Configuration	J^π
$\pi (g_{9/2}) \nu (s_{1/2})$	$5^+, 4^+$
$\pi (g_{9/2}) \nu (d_{3/2})$	$6^+, 5^+, 4^+, 3^+$
$\pi (g_{9/2}) \nu (h_{11/2})$	$10^-, 9^-, 8^-, 7^-, 6^-$ $5^-, 4^-, 3^-, 2^-, 1^-$
$\pi (p_{1/2}) \nu (s_{1/2})$	$1^-, 0^-$
$\pi (p_{1/2}) \nu (d_{3/2})$	$2^-, 1^-$
$\pi (p_{1/2}) \nu (h_{11/2})$	$6^+, 5^+$

From the states listed above, one can see that only one configuration satisfies the condition that the ^{122}Ag ground state is 3^+ . So, the configuration for ^{122}Ag ground state should be $\pi (g_{9/2}) \nu (d_{3/2})$.

C. ^{122}Cd and the Vibration Model

Vibrational and rotational motion are classified as collective motions, since both involve orderly displacement of many nucleons. The ratio of the energies of the first excited 4^+ and 2^+ states is quite informative. For example, in the pure vibration picture, the two-phonon state is a degenerate triplet and the energy ratio of the two phonon to the one phonon state is two. For pure rotational motion the

energy ratio of the second to first excited state is given by the equation:

$$\frac{E(J_2)}{E(J_1)} = \frac{J_2(J_2 + 1)}{J_1(J_1 + 1)}$$

Therefore for a pure vibrator $E(4+)/E(2+)=2.0$ whereas for a pure rotator $E(4+)/E(2+)=3.33$. From the experimental results for ^{122}Cd , the $E(4+)/E(2+)$ ratio is 2.33. Therefore, ^{122}Cd is more like a vibrator than a rotator. This is not surprising since $\text{Cd}(Z=48)$ is only two protons away from the magic number ($Z=50$).

D. Systematics

Figure 14 gives a comparison between the ^{122}Cd level scheme described in this work and those for other even-even Cd isotopes. An interesting relationship may be noted between the isotopes with $N < 68$ and those with $N > 72$ in the first excited state. ^{120}Cd , with $N = 72$, has a first excited state whose energy is close to that of the first excited state of ^{116}Cd with $N = 68$. Likewise, the first excited state of ^{114}Cd and ^{122}Cd are at about the same energy difference. It is as if the addition of one neutron pair to the ^{118}Cd nucleus is equivalent to the removal of one neutron pair, at least insofar as the energy of the first excited state is concerned. The energy for the first excited state in even-even Cd nuclei reaches a minimum

$\frac{4^+}{2^+}$	1285.5	$\frac{4^+}{2^+}$	1220.2	$\frac{2^+}{4^+}$	1269.7	$\frac{2^+}{4^+}$	1323.0	$\frac{2^+}{4^+}$	1367.8
$\frac{2^+}{2^+}$	1209.3	$\frac{2^+}{2^+}$	1213.6	$\frac{4^+}{4^+}$	1164.9	$\frac{4^+}{4^+}$	1203.7	$\frac{4^+}{4^+}$	1329.2

$\frac{2^+}{2^+}$	558.3	$\frac{2^+}{2^+}$	513.9	$\frac{2^+}{2^+}$	487.8	$\frac{2^+}{2^+}$	505.9	$\frac{2^+}{2^+}$	569.4
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$\frac{0^+}{0^+}$	0.0	$\frac{0^+}{0^+}$	0.0	$\frac{0^+}{0^+}$	0.0	$\frac{0^+}{0^+}$	0.0	$\frac{0^+}{0^+}$	0.0
^{114}Cd		^{116}Cd		^{118}Cd		^{120}Cd		^{122}Cd	

Figure 14. Systematics of even-even Cd isotopes

at ^{118}Cd . One might expect this minimum to occur at ^{114}Cd midway between the $N=50$ and $N=82$ closed shells but we see it to be slightly displaced to the neutron-rich side. The similarity in level structure for ^{114}Cd and ^{122}Cd clearly extends to the 4^+ levels as well, but the second-excited 2^+ level has a different behavior, since the energy increases from ^{114}Cd all the way to ^{122}Cd . In ^{118}Cd the 2^+ state crosses 4^+ state. It would be of great interest to see if these trends continue in the manner indicated above as additional neutron pairs are added and the magic neutron number 82 is approached. Later at the TRISTAN facility a search will be made for ^{124}Ag with the purpose of extending the systematics of even-even Cd nuclei.

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