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# Gamma Cascade Transition of $^{51}V(n_{th}, \gamma)^{52}V$ Reaction

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## ABSTRACT

**The thermal neutron capture gamma radiations for $^{51}V(n, \gamma)^{52}V$ reaction have been studied at Dalat Nuclear Research Reactor (DNRR). The gamma two-step cascade transition was measured by event-event coincidence spectrometer. The added-neutron binding energy in $^{52}V$ was measured as 7.31 MeV. Energy and the intensity transition of cascades were consistent with prediction of single particle model. Furthermore, the spin and the parity of levels were confined.**

## KEYWORDS

**Gamma Two-Step Cascade; Neutron Capture Reaction; Coincidence**

## 1. Introduction

The exited states of $^{52}V$ have been studied from 1960s, and the $^{52}V$ level scheme has mainly been performed by means of the $^{51}V(d, p)^{52}V$ and $^{51}V(n, \gamma)^{52}V$ reactions. The energy and the intensity of proton groups in the (d, p) reaction on $^{51}V$ for states in $^{52}V$ up to 3.3 MeV were measured [1-4]. The (d, p) reaction studies were in good agreement with the analysis of the $^{51}V(n, \gamma)^{52}V$ reaction, investigated by single gamma spectra or fast-coincidence gamma spectrometry [1-3,6].

The Ritz-combination principle was used to construct nuclear level scheme from low energy neutron capture gamma ray. The bent crystal spectrometer was reduced by the interference from fortuitous combinations. This technique can be applied to gamma ray energies between 30 keV and several hundred keV. Above 1 MeV, the efficiency and the energy resolution of bent crystal spectrometer were decreased, and other experimental techniques could be used [2,5].

Several studies of the gamma spectrum arising from thermal neutron capture in the $^{51}V(n, \gamma)^{52}V$ reaction have been carried out. The spectrum above 3 MeV was determined by using a pair spectrometer. Groshev *et al*. detected gammas down to 0.4 MeV using a Compton spectrometer, and the resolution at lower ending was relatively poor. The low-lying region has been investigated mostly by interpreting singles spectra from NaI(Tl) and HPGe spectrometers [2]. In Reference [1], the many levels of low energy were found. In this, coincidence and sum-coincidence measurement techniques were used. The coincidence method determines when two events occur within a certain fixed time period which was called coincidence resolving time. This technique can be applied to measurement of events that occurred in two separate detectors within a given time interval, or for the measurement of the delay time between the two events. These two approaches were used in gamma-gamma coincidence or particle-gamma coincidence measurements, positron lifetime studies, decay scheme studies and similar applications, and were titled coincidence or timing measurements. The sum-coincidence method for capture-gamma work was based upon the simple fact that in any nuclear decay scheme caused by gamma de-excitation from a thermal neutron capture state to the ground state, the energy of gamma-rays related in cascade must sum to the neutron binding energy. S. Michaelsen *et al.* studied the level schemes of $^{52}$V with high sensitivity and very good energy resolution, via thermal neutron capture reactions. In $^{52}$V, the excited energy was focused on states between 3.5 and 7 MeV. The populating and decay radiations of most of these states have been established. The densities of states in spin and parity windows were almost completed up to half the binding energies [7].

The nuclear data evaluation of $^{52}$V isotope in library showed the lack of quantum properties of energy levels and the not singular value of spin of some energy levels. The adopted data set looks fairly complete, either missing or being off by about 3%. Energies were probably good to about 0.1 keV. It was hard to assign uncertainties to the intensities, as those of Michaelsen *et al.* were reported as about 10% but the agreements of the sums into and out of various levels were usually better than 10% [8]. Therefore, the $^{52}$V should be more experiment information in order to study nuclear structure.

The nucleus $^{52}$V has three protons and one neutron outside a closed shell core having the structure of the doubly magic $^{48}$Ca. It is in a region where shell model calculations involving the coupling between extra-core nucleons in different shell are known to be particularly appropriate [1,2].

Today, with development of HPGe detector, the sum-coincidence measurement method has been developed to "event-event" coincidence method which was digitalized. In this experiment, the gamma intensities, excited levels of $^{52}$V in energy region below separation neutron energy, were measured by "event-event" coincidence method. The experimental results were compared with prediction of single particle model.

## 2. Experiment

### 2.1. The Experimental Arrangement

The experimental system has been installed at the tangential beam port of the DNRR. The thermal neutron beam was filtered by S, Pb and Si. The neutron flux, the cadmium ratio was 900 (1 cm thinness of cadmium) and the neutron beam at the target position was $1.02 \times 10^6$ n·cm$^{-2}$s$^{-1}$. The collimator was made a mixture of paraffin and boron. The distance from the endcap of detectors to the neutron beam center was 4 cm; lead bricks of 10 cm thickness were used to surround the detectors as gamma shields which the background count rate in the 0.2 ÷ 8 MeV range was guaranteed less than 400 counts per second (cps). Two plates of 2 mm thick lead were placed between the detectors and target to decrease the number of backscattered gamma rays and to filter out X-ray. The electronics configuration was used in those gamma-gamma coincidence experiments are shown in **Figure 1**, the parameters of system were setup by method in Reference [9]. The detector signals are amplified with 572 amplifier (AMP) modules with a shaping time of 3.0 µs and about 1 keV per channel. Output signals of the amplifiers are digitized by 7072 analog-to-digital converter (ADC) modules. The timing signals of both detectors are put through 474 timing filter amplifier (TFA) modules. The shaped and amplified timing signals by 474 TFA are plugged into 584 CFD modules, which are used in slow rise time rejection option (SRT) mode. The CFD output signal of the first channel (using GPC20 detector) is used as 556 time-to-amplitude converter (TAC) start signal. The CFD output signal of the second channel (using GC2018 detector) is delayed 100 ns and served as a TAC

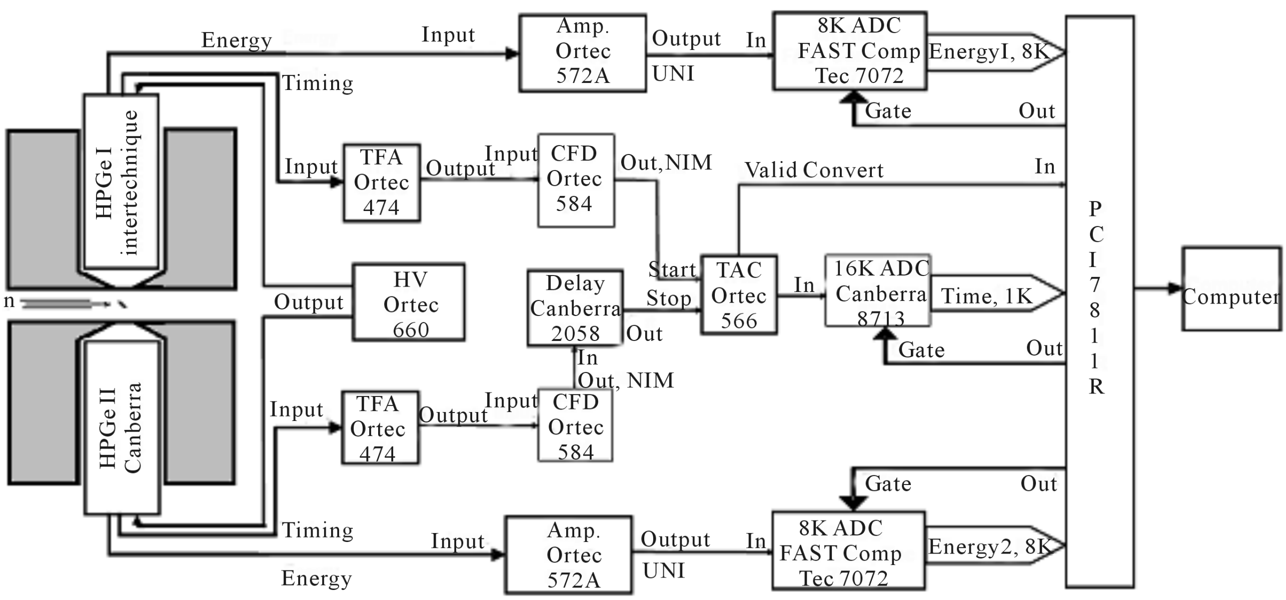


**Figure 1. The electronics configuration.**

stop signal. The full scale of TAC is set at 500 ns, and output signal is digitized in 8713 ADC with selection of 1024 channels for a 10 V input pulse. The TAC ''Valid Convert'' signal is used to gate 7072 ADC, and the delay or synchronizing with AMP output signal is implemented by interface software. Recorded coincident events have three values, including coincidence gamma-ray energies from detector 1, detector 2 and time interval between two $\gamma$-rays in one detection of pair event.

The target was natural Vanadium which the rich of $^{51}V$ was 99.75%, the thermal neutron capture cross section of $^{51}V$ was $\sigma$ = 4.9 barn [10]. The target was placed between two detectors. Experimental data collected 280 hours total. The coincidence count rate was about 34 cps. The programming interface was set up in event-event coincidence mode. The data on the deposited gamma ray energies and time intervals were recoded and processed off-line by summation of amplitude method.

## 2.2. Data Analysis

From the recorded information a set of gamma rays spectra were obtained that belong to all tow step cascades that end at preselected final levels in $^{52}V$. We call these spectra two-step gamma cascades (TSC) spectra and the corresponding TSC final level. Each of these spectra were constructed from deposited energy in one of the detectors under condition that the gamma ray energy sum from both detectors fell within the region of full energy line corresponding to a preselected level. The energies and $J^{\pi}$ of these final levels are listed in **Table 1**. Note, that in one case two of the levels were not resolved.

While constructing the TSC spectra, the background due to accidental coincidences and Compton scattering was subtracted: Compton background was subtracted by choosing background regions on two sides of peak in the spectrum of energy sums; and choosing time windows, selecting three intervals of detection-time difference, was adjusted to isolate the net signal from the background due to accidental coincidences.

The constructed TSC spectra were corrected for the energy dependence of the full energy line efficiencies of both detectors. In addition, corrections for the vetoing effects caused by the detection of gamma rays following the decay of the TSC final level and for the effects of gamma-gamma angular correlations were applied. After these corrections the TSC spectra were converted into spectra expressed in absolute TSC intensities. This conversion requires knowledge of the TSC intensity of at least one TSC and it was performed with data from library.

The **Figure 2** was a part of spectrum of gamma ray energy sums accumulated from the event-event mode data obtained from the coincidence neutron capture $^{51}V$. The **Figure 3** was TSC spectrum of $^{52}V$ belong to final level at 0 and 18 keV.

**Table 1. The energies and $J^{\pi}$ of these final levels.**

| $N^0$ | Final level (keV) | Spin ($J^{\pi}$) | N° | Final level (keV) | Spin ($J^{\pi}$) |
|---|---|---|---|---|---|
| 1 | 0.00 | $3^+$ | 4 | 147.85 | $4^+$ |
| 2 | 17.16 | $2^+$ | 5 | 436.30 | $2^+, 3^+$ |
| 3 | 22.29 | $5^+$ | 6 | 793.34 | $2^+, 3^+$ |

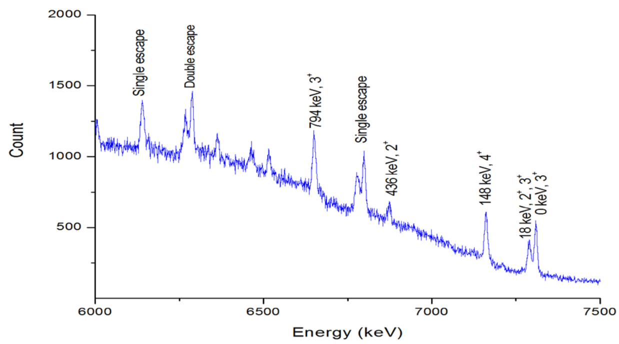


**Figure 2. A part in gamma ray energy sums of spectrum.**

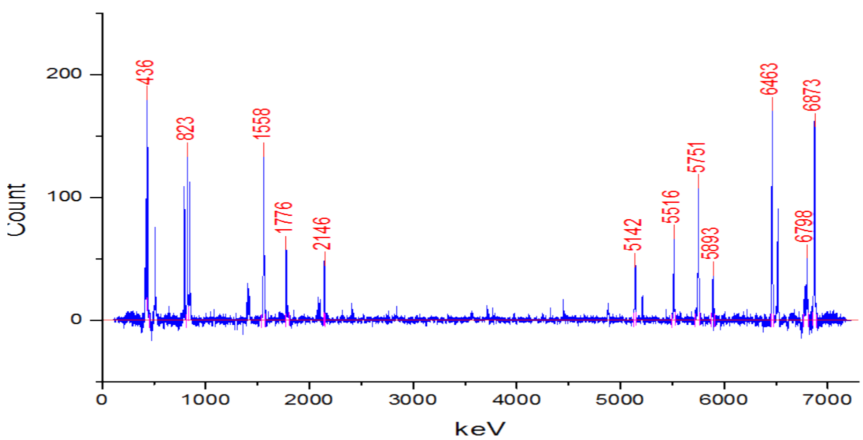


**Figure 3. TSC spectrum of $^{52}V$ belong to final level at 0 and 18 keV.**

### 2.3. Spin Assignment and Theoretical Investigation of the $^{52}V$ Levels

In neutron capture reaction, if $J^{\pi}$ was spin of target then $J^{\pi} \pm 1/2$ were probability spins of compound nuclear. The emitted gamma rays were E1, M1, E2 or M1 + E2 which are called the multi-polarity orders of the radiation. The multi-polarity orders of the radiation were determined:

$$\left|J_i - J_f\right| \le L \le J_i + J_f \quad (1)$$

$L = 1$ was electric dipole (E1) and magnetic dipole (M1), $L = 2$ was electric quadruple (E2) and magnetic quadruple (M2). The parity was $(-1)^{L}$ for electric transition, and $(-1)^{L+1}$ for magnetic transition [11].

According to the single particle model, the $\gamma$-ray transition probability was predicted by Equation 2 [12].

$$\begin{aligned} T_{\gamma}^{EL} &= \frac{8\pi(L+1)e^2b^L}{L\left[(2L+1)!!\right]^2 h}\left(\frac{E_{\gamma}}{hc}\right)^{2L+1} B(EL)\downarrow \\ T_{\gamma}^{ML} &= \frac{8\pi(L+1)\mu_N^2 b^{L-1}}{L\left[(2L+1)!!\right]^2 h}\left(\frac{E_{\gamma}}{hc}\right)^{2L+1} B(ML)\downarrow \end{aligned} \quad (2)$$

where: $hc = 197.327\times10^{-10}$ keV·cm,
$e^2 = 1.440 \times 10^{-10}$ keV·cm,
$\mu_N^2 = 1.5922\times10^{-23}$ keV·cm$^3$, and $b = 10^{-24}$ cm$^2$ .

Both $B(EL)\downarrow$ and $B(ML)\downarrow$ were the reduced downward probabilities for electric and magnetic transition respectively. Using the Weisskopf derived for the single particle estimates for these matrix elements based on the shell model in Equation 3 [12]:

$$\begin{aligned} B(EL) &= \frac{1}{4\pi b^L}\left(\frac{3}{3+L}\right)^2 R^{2L} \\ B(ML) &= \frac{10}{\pi b^{L-1}}\left(\frac{3}{3+L}\right)^2 R^{2L-2} \end{aligned} \quad (3)$$

$R = 1.2 \times 10^{-13} A^{1/3}$ cm.

From Equations 2 and 3, the transition probabilities of $^{52}V$ could be calculated by Equation 4.

$$\left.\begin{aligned} T_{\gamma}^{E1} &= 1.4280\times10^{6} E_{\gamma}^3 \\ T_{\gamma}^{E2} &= 1.4127\times10^{-5} E_{\gamma}^5 \\ T_{\gamma}^{M1} &= 3.1483\times10^{4} E_{\gamma}^3 \\ T_{\gamma}^{M2} &= 3.1143\times10^{-7} E_{\gamma}^5 \end{aligned}\right\} \quad (4)$$

The Equation 4 can be predicted the gamma transitions probabilities of exited nuclei with average mass range.

## 3. Result and Discussion

### 3.1. The Gamma Two-Step Cascade Energies, Intensities and Intermediate Levels

By this work, the 36 pairs of gamma two-step cascades were recorded, the results are shown in Table 2.

**Table 2. The gamma two-step cascade energies and intensities of $^{52}V$ in $^{51}V(n_{th}, \gamma)^{52}V$ reaction.**

| N° | $E_1$ (keV) | $E_2$ (keV) | $E_L$ (keV) | $I_{\gamma-\gamma}$ (%) |
|---|---|---|---|---|
| $E_1 + E_2$ = 7310.68 keV, $E_f$ = 0 keV | | | | |
| 1 | 6875.09(102) | 436.30(52) | 436.34 | 2.913(24) |
| 2 | 6518.05(94) | 793.34(62) | 793.34 | 3.700(27) |
| 3 | 6465.04(98) | 845.35(64) | 845.64 | 4.324(45) |
| 4 | 5892.97(142) | 1418.42(77) | 1418.42 | 2.511(22) |
| 5 | 5752.96(123) | 1558.44(88) | 1558.44 | 9.461(67) |
| 6 | 5578.93(104) | 1732.46(89) | 1732.46 | 0.487(65) |
| 7 | 5516.93(76) | 1795.47(92) | 1795.47 | 0.855(11) |
| 8 | 5211.89(89) | 2101.51(114) | 2101.51 | 0.974(23) |
| 9 | 5142.88(98) | 2169.51(121) | 2167.80 | 0.540(14) |
| 10 | 4993.86(102) | 2317.53(124) | 2316.82 | 0.294(12) |
| 11 | 4884.85(114) | 2427.55(146) | 2427.55 | 0.435(09) |
| $E_1 + E_2$ = 7293.52 keV, $E_f$ = 17.16 keV, 22.29 keV | | | | |
| 12 | 6875.09(102) | 419.30(52) | 436.34 | 1.849(24) |
| 13 | 6465.04(98) | 823.35(63) | 845.64 | 4.433(34) |
| 14 | 5892.97(142) | 1401.42(77) | 1418.42 | 1.317(26) |
| 15 | 5516.93(76) | 1778.47(89) | 1795.47 | 3.776(27) |
| 16 | 5211.89(89) | 2083.50(112) | 2098.79 | 0.837(11) |
| 17 | 5142.88(98) | 2146.51(121) | 2167.80 | 3.382(32) |
| 18 | 4884.85(114) | 2410.54(132) | 2427.55 | 0.802(14) |
| 19 | 4452.80(146) | 2842.60(145) | 2857.88 | 0.871(17) |
| 20 | 3579.69(165) | 3716.71(168) | 3730.99 | 0.625(13) |
| $E_1 + E_2$ = 7162.83 keV, $E_f$ = 147.85 keV | | | | |
| 21 | 6875.09(102) | 295.28(49) | 436.34 | 1.130(22) |
| 22 | 6518.05(94) | 645.33(60) | 792.63 | 7.957(58) |
| 23 | 6465.04(98) | 698.33(59) | 845.64 | 1.229(23) |
| 24 | 5752.96(123) | 1410.42(78) | 1557.72 | 1.569(64) |
| 25 | 5551.93(68) | 1612.45(54) | 1758.75 | 0.732(20) |
| 26 | 5211.89(89) | 1953.49(95) | 2098.79 | 1.780((54) |
| 27 | 5142.88(98) | 2021.50(102) | 2167.80 | 0.949((43) |
| 28 | 4452.80(146) | 2710.58(165) | 2857.88 | 0.581(24) |
| $E_1 + E_2$ = 6874.51 keV, $E_f$ = 436.34 keV | | | | |
| 29 | 5892.97(142) | 982.37(66) | 1417.71 | 0.539(44) |
| 30 | 5516.93(76) | 1358.41(73) | 1793.75 | 4.012(68) |
| 31 | 5211.89(89) | 1664.45(54) | 2098.79 | 1.669(51) |
| $E_1 + E_2$ = 6517.34 keV, $E_f$ = 793.34 keV | | | | |
| 32 | 5516.93(76) | 1002.37(70) | 1793.75 | 1.654(60) |
| 33 | 5211.89(89) | 1307.41(72) | 2098.79 | 1.262(51) |
| 34 | 4884.85(114) | 1634.45(56) | 2425.83 | 0.954(30) |
| $E_1 + E_2$ = 1793.38 keV, $E_f$ = 5516.62 keV | | | | |
| 35 | 1358.4(73) | 436.30(55) | 436.34 | 0.018(14) |
| 36 | 1002.37(70) | 793.34(62) | 793.63 | 0.025(12) |

The **Figure 4** was the distribution of gamma transition intensities to energy.

### 3.2. Parities, Spin Assignments and Transition Probabilities

According to the shell model of nucleus, the structure of $^{51}V$ is $1s_{1/2}^4 1p_{3/2}^8 1p_{1/2}^4 1d_{5/2}^{12} 2s_{1/2}^4 1d_{3/2}^8 1f_{7/2}^{11}$, so the $j^\pi$ of $^{51}V$ in ground state is $7/2^-$. The $j^\pi$ of the state formed on neutron capture by $^{51}V$ may have the value of $3^-$ or $4^-$ (an s-wave neutron could be captured). The $j^\pi$ of $^{52}V$ in ground state is $3^+$ [1-4]. The parity of the $^{52}V$ excited state is opposite to the ground state, and the directly gamma emitted compound to ground sate, so transition between these states (the first order transition) must be of the E1 type.

Further more, refer to the word of Schwager [1], the possibilities $j^\pi$ of $^{52}V^*$ in intermediate state are $0^+$, $1^+$, $2^+$, $3^+$, $4^+$, $5^+$, $6^+$, $7^+$, $8^+$ and $9^+$. According to single particle model nuclear structure, applying condition (1), and Equation (4), the possibilities spins, parities of levels and transition probabilities of $^{52}V$ exciting in thermal neutron capture reaction, are shown in **Table 3**.

## 4. Discussion

In this work the final state 17 keV and 22 keV appeared in one peak of the summation spectrum at 18 keV. It was

**Table 3. The spins, parities of levels, and transition probabilities of $^{52}V$ exciting in thermal neutron capture reaction.**

| Level (keV) | E (keV) | $j_f^\pi$ (This work) | $j_f^\pi$ ([2-7]) | $T_\gamma^{M1}$ (Exp.) | $T_\gamma^{M1}$ (Model) | $\frac{(\text{Model} - \text{Exp.})}{\text{Model}}$ |
|---|---|---|---|---|---|---|
| $(2^+, 3^+)$ 436.30 | 436.30 | $3^+$ | $3^+$ | 0.494 | 0.455 | 0.09 |
| | 419.30 | $2^+$ | $2^+$ | 0.314 | 0.404 | −0.22 |
| | 295.28 | $1^+$ | $1^+$ | 0.192 | 0.141 | 0.36 |
| $(2^+, 3^+)$ 793.34 | 793.34 | $3^+$ | $3^+$ | 0.293 | 0.614 | −0.52 |
| | 645.33 | $4^+$ | $4^+$ | 0.630 | 0.330 | 0.91 |
| | 356.29 | $2^+, 3^+$ | $2^+$ | 0.077 | 0.056 | 0.38 |
| $(3^+, 4^+)$ 845.35 | 845.35 | $3^+$ | $3^+$ | 0.433 | 0.402 | 0.08 |
| | 823.35 | $5^+$ | $5^+$ | 0.444 | 0.371 | 0.20 |
| | 698.33 | $4^+$ | $4^+$ | 0.123 | 0.227 | −0.46 |
| $(2^+, 3^+)$ 1417.71 | 1418.42 | $3^+$ | $3^+$ | 0.575 | 0.435 | 0.32 |
| | 1401.42 | $2^+$ | $2^+$ | 0.302 | 0.420 | −0.28 |
| | 982.37 | $2^+, 3^+$ | $2^+$ | 0.123 | 0.145 | −0.15 |
| $(3^+, 4^+)$ 1557.72 | 1558.44 | $3^+$ | $3^+$ | 0.858 | 0.574 | 0.49 |
| | 1410.42 | $4^+$ | $4^+$ | 0.142 | 0.425 | −0.67 |
| $(2^+, 3^+)$ 1793.75 | 1795.47 | $3^+$ | $3^+$ | 0.083 | 0.387 | −0.79 |
| | 1778.47 | $2^+$ | $2^+$ | 0.367 | 0.376 | −0.02 |
| | 1358.41 | $2^+, 3^+$ | $2^+$ | 0.390 | 0.168 | 1.32 |
| | 1002.37 | $2^+, 3^+$ | $3^+$ | 0.161 | 0.067 | 1.40 |
| $(2^+, 3^+)$ 2101.51 | 2101.51 | $3^+$ | $3^+$ | 0.149 | 0.284 | −0.48 |
| | 2083.50 | $2^+$ | $2^+$ | 0.128 | 0.277 | −0.54 |
| | 1953.49 | $4^+$ | $4^+$ | 0.273 | 0.228 | 0.20 |
| | 1664.45 | $2^+, 3^+$ | $2^+$ | 0.256 | 0.141 | 0.82 |
| | 1307.41 | $2^+, 3^+$ | $3^+$ | 0.193 | 0.068 | 1.84 |
| $(3^+, 4^+)$ 2169.51 | 2169.51 | $3^+$ | $3^+$ | 0.111 | 0.359 | −0.69 |
| | 2146.51 | $5^+$ | $5^+$ | 0.694 | 0.348 | 0.99 |
| | 2021.50 | $4^+$ | $4^+$ | 0.195 | 0.291 | −0.33 |
| $(2^+, 3^+)$ 2427.55 | 2427.55 | $3^+$ | $3^+$ | 0.199 | 0.437 | −0.54 |
| | 2410.54 | $2^+$ | $2^+$ | 0.366 | 0.428 | −0.14 |
| | 1634.45 | $2^+, 3^+$ | $3^+$ | 0.435 | 0.133 | 2.27 |
| $(3^+, 4^+)$ 2857.88 | 2842.60 | $2^+$ | $2^+$ | 0.600 | 0.534 | 0.12 |
| | 2710.58 | $4^+$ | $4^+$ | 0.400 | 0.463 | −0.14 |

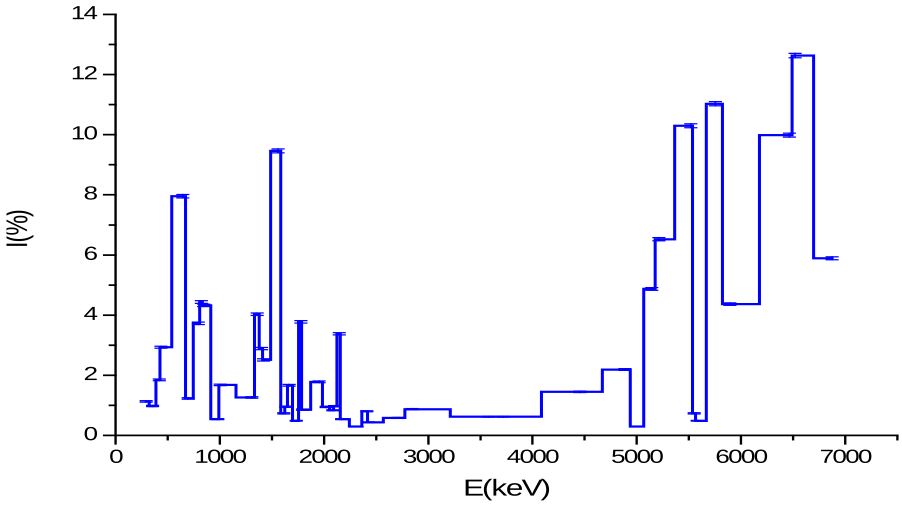


**Figure 4. The distribution of gamma transition intensities to energy.**

not solved in summation spectrum but in TSC corresponding this peak, the gamma ray energies were separated in two groups, one had summation energies of 7.31 - 0.17 MeV and other had summation energy of 7.31 - 0.22 MeV.

The neutron binding energy of $^{52}V$ appeared in summation spectrum at 7.31 MeV that was consisted with previous research. The spin of gamma ray energies of 356.29 keV, 1002.37 keV, 1307.41 keV, 1358.41 keV, 1634.45 keV and 1664.45 keV were not singular and could be accepted $2^+$ and $3^+$.

The transition probabilities of $^{52}V$ were rather consisted with the prediction of single particle model. The difference of experimental and calculation results were about 2% to 22%, it was in range of experiment errors.

## 5. Conclusion

In this work, the 36 pairs of gamma two-step cascades were recorded, and the results were consisted with prediction of single particle model. The event-event coincidence method was very useful for research of gamma cascade transition which could separate unresolved levels by detectors.

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