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Determining Experimental Transition Strengths of ^{52}V by Two-Step Gamma Cascades

Nguyen An Son[1], Pham Dinh Khang[2], Nguyen Duc Hoa[1], Vuong Huu Tan[3], Nguyen Xuan Hai[4], Dang Lanh[4], Pham Ngoc Son[4], Ho Huu Thang[4]
[1]*University of Dalat, 01 Phu Dong Thien Vuong, Dalat, Lamdong, Vietnam*
[2]*Nuclear Training Center, 140 Nguyen Tuan, Hanoi, Vietnam*
[3]*Vietnam Agency for Radiation and Nuclear Safety, 113 Tran Duy Hung, Hanoi, Vietnam*
[4]*Nuclear Research Institute, 01 Nguyen Tu Luc, Dalat, Vietnam*

Abstract: In this paper, the results showed experimental transition strengths of ^{52}V by two-step gamma cascades, lifetime levels, width levels and branch ratio. ^{51}V nucleus was activated by thermal neutron at the 3rd horizontal channel of Dalat nuclear reactor, and the $^{51}V(n_{th}$, 2 gamma$)^{52}V$ reaction was applied in this research. The two-step gamma cascades were collected by event-event gamma coincidence system. The Summation of Amplitude Coincidence Pulses method (SACP) was treated with the experimental data. The results were not affected by background based on SACP method. This method got intensities, energies of two-step cascades directly. The experimental gamma transition strengths were applied to the single particle model. In comparison with the electromagnetic transition probabilities, and rule of multi orders, the spin and parity of intermediate levels were calculated and refreshed.

Keywords: - *Two-step gamma cascade, ^{51}V (n_{th}, 2 gamma)^{52}V, Gamma transition strength, Lifetime, Branch ratio, Spin and parity.*

I. INTRODUCTION

Gamma ray strength functions were important constituents of the compound nucleus model calculations of capture cross sections, gamma ray production spectra, isomeric nucleus, and competition between gamma ray and particle emission. In this paper, relevant multi orders were E1, M1 and E2. The gamma ray strength functions including information on nuclear structure were widely used to study the mechanisms of nuclear reactions. Gamma emission is one of the most importance channels for nuclear de-excitation processes.

The nucleus ^{52}V has three protons and one neutron outside a closed shell core having the structure of the double magic ^{48}Ca. In the region, shell model calculations involving a couple between extra-core nucleons in different layouts were known to be particularly appropriate.

The exited states of ^{52}V have been studied from 60's of the last century. 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 [3,4,5,6,9]. The Ritz algorithm was used to construct nuclear level scheme from low energy neutron capture gamma rays.

The main limitations of previous works of ^{52}V were uncompleted with theoretical and experimental results. The spin and parity of some intermediate levels were determined but uncompleted, some of experimental energy rays could not be arranged in diagram scheme of ^{52}V by Ritz algorithm as well.

Works on two-step gamma cascades intensity and level density of nucleus by the (n, 2γ) reaction have been studied and applied in USA, Dubna, Hungary, Czech, etc. In Vietnam, the method has been studied at Dalat nuclear reactor (500 kW power). The gamma coincidence system is installed on the 3rd horizontal channel neutron beam.

II. THEORY AND CALCULATING METHODS

Experimental data Collecting method

In this principle, the experimental data getting on gamma – gamma coincidences were collected by event – event method, the SACP method was used for treatment of the data. The brief of this method was introduced as follows: when two gamma rays appeared in two detectors (two gamma rays were emitted with two-step gamma cascade), output signals of the detectors had two signals: an energy signal and a timing signal. If those signals were satisfied the obligation conditions, two recorded events were mainly coincidence events. The diagram of algorithm and analysis of spectrum showed in Fig 1. The creation of spectrum of each detector was made by adding all data files. The calibration of energy based on nuclear energies which were known before (using LANL library). The creation of sum spectrum based on the times appearing values of E1 + E2 (E1 is the code of amplitude ADC1; E2 is the code of amplitude ADC2). In the sum spectrum also appeared single escape peaks and double escape peaks. The width of the peaks in the sum spectrum depended on the quality of detectors and the balance of energy conversion factor.

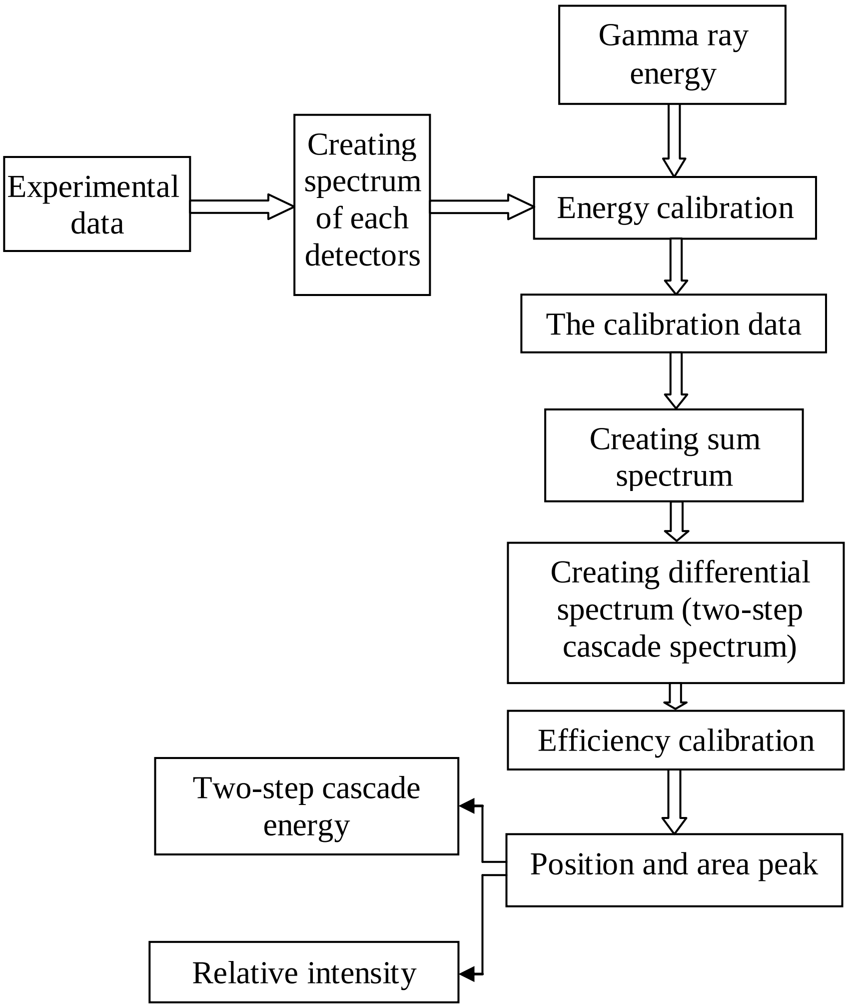

Fig. 1. Diagram of algorithm and analysis of spectrum

To create two-step cascade spectrum (differential spectrum): in the timing window of established coincidence, when two-step gamma cascades have occurred, the event-event coincidence was finally recorded. The gamma ray two-step cascades (having total energy $E_C = E_1 + E_2$) were completely absorbed by two detectors and saved one peak of sum spectrum. Sum spectrum was the sum of real coincidences and the background from which this background was reduced by SACP method. Eventually, the differential spectrum was symmetry mirror.

Thus, the sum spectrum was created by two codes of two detectors that the total code was equal to E_C. In the principle, this spectrum contains only the total absorption peaks and does not contain continuous distribution of energy (by Compton scattering). After efficiency calibration, two spectrums of one detector were created, and by adding two spectrums, differential spectrum (two-step cascade spectrum) was formed. The differential spectrum contained information of gamma rays, such as: relative intensities (proportional the peak areas), energies (proportional the position of peaks), etc.

The transition probabilities and transition strengths depend on relative intensities, spin of levels and multiple orders. The relative intensities of gamma cascade transfer were calculated:

$$I_i^{\gamma\gamma} = \frac{S_i^{\gamma\gamma}}{\sum_1^n S_i^{\gamma\gamma}} \tag{1}$$

$S_i^{\gamma\gamma}$ was the calibrated area of i^{th} peak in the two-step cascades spectrum.

Theory

The intensity of gamma cascade was a function which depended on gamma width level:

$$I_{\gamma\gamma} = \sum \frac{\Gamma_{\lambda i} \times \Gamma_{if}}{\Gamma_i \times \Gamma_\lambda} \tag{2}$$

where $\Gamma_{\lambda i}$ and Γ_{if} were the partial widths of the transitions connecting the levels $\lambda \rightarrow i \rightarrow f$; Γ_i and Γ_λ were the total width levels of the decaying states λ and i, respectively.

If J^π was spin and parity of the ground state of nucleus, the spin and the parity of the compound nucleus as capturing neutron (s-wave neutron capture) were ability $J^\pi \pm 1/2$. Because the lifetime of nuclei at excited states was very short, gamma radiations emitted from compound nuclei were usually electric dipole (E1), magnetic dipole (M1), electric quadruple (E2) or a mixture of M1 + E2. Selection rules for the multiple order of radiation were identified by:

$$|J_i - J_f| \leq L \leq J_i + J_f \tag{3}$$

where, L was multiple orders, J_i was the spin of the initial state, J_f was the spin of the final state.

When the electromagnetic transfer, the parity was conservative:

$$\pi_i \pi_\gamma \pi_f = 1 \tag{4}$$

π_i was the parity of initial level, π_f was the parity of final level π_γ was the parity of gamma ray.

For electric transfer:

$$\pi_\gamma = (-1)^L \tag{5}$$

For magnetic transfer:

$$\pi_\gamma = (-1)^{L+1} \tag{6}$$

The total gamma width (Γ_γ) of an excited state of a certain mean lifetime (τ_m) was given by:

$$\Gamma_\gamma = \frac{\hbar}{\tau_m} = \frac{\hbar \times \ln 2}{t_{1/2}} \tag{7}$$

where ħ was the Dirac constant = 0.658212×10^{-15} eV.s and $t_{1/2}$ was lifetime of level.

If two or more γ-rays de-excited from the same state, the partial gamma width of i^{th} gamma transition ($\Gamma_{\gamma i}$) was:

$$\Gamma_{\gamma i} = \Gamma_\gamma \times B_{\gamma i} \tag{8}$$

where $B_{\gamma i}$ was the branching ratio of i^{th} gamma ray, and it was obtained from the following equation:

$$B_{\gamma i} = \frac{I_{\gamma\gamma i}}{I_{tot}} \times 100\% \tag{9}$$

here, $I_{\gamma\gamma i}$ was the intensity of i^{th} gamma transition and I_{tot} was the total intensity.

According to the single particle, half-life of level can be calculated for electric transitions and magnetic transitions with [7]:

$$t_{1/2}(EL) = \frac{\ln 2 L[(2L+1)!!]^2 \hbar}{2(L+1)e^2 R^{2L}} \left(\frac{3+L}{3}\right)^2 \left(\frac{\hbar c}{E_\gamma}\right)^{2L+1} \tag{10}$$

$$t_{1/2}(ML) = \frac{\ln 2 L[(2L+1)!!]^2 \hbar}{80(L+1)\mu_N^2 R^{2L-2}} \left(\frac{3+L}{3}\right)^2 \left(\frac{\hbar c}{E_\gamma}\right)^{2L+1} \tag{11}$$

where: $e^2=1.440\times10^{-10}$keV.cm, $\mu_N^2=1.5922\times10^{-23}$keV.cm^3.
From the total gamma width, we can calculate the transition strengths of *E1*, *M1* and *E2*.
Components of the gamma rays were defined by the following [7]:

$$|M(E,M(L)|^2 = \frac{\Gamma(E,M(L))}{\Gamma_{\gamma wu}(E,M(L))} \tag{12}$$

where, $\Gamma(E,M(L))$ was the partial gamma width of electric transfer, magnetic transfer. Applying for ^{52}V, in Weisskopf units can be obtained from the following relations in equations:

$$\Gamma_{\gamma wu}(E1) = 6.7492\times10^{-11} A^{2/3} E_\gamma^3 \tag{13}$$

$$\Gamma_{\gamma wu}(E2) = 4.7925\times10^{-23} A^{4/3} E_\gamma^5 \tag{14}$$

$$\Gamma_{\gamma wu}(M1) = 2.0734\times10^{-11} E_\gamma^3 \tag{15}$$

where, *A* represents the mass number of the nucleus and E_γ was the energy of the gamma transitions in keV units.

III. EXPERIMENTAL SYSTEM

The experimental target was natural vanadium which the rich of ^{51}V was 99.75%, the thermal neutron capture cross section of ^{51}V was σ = 4.9 barn [1].
The neutron beam, sample and detector were set up for maximum efficiency of gamma detection. In this experiment the sample was set at 45^o from neutron beam, two detectors were placed opposite (180^o) with each other. The thermal neutron flux at sample position was about 10^6 n/cm^2/s. Cadmium coefficient was 900 (1 mm in thickness).
The experimental system was a gamma – gamma coincidence showed in Fig. 2, and the operating principle was described [8].

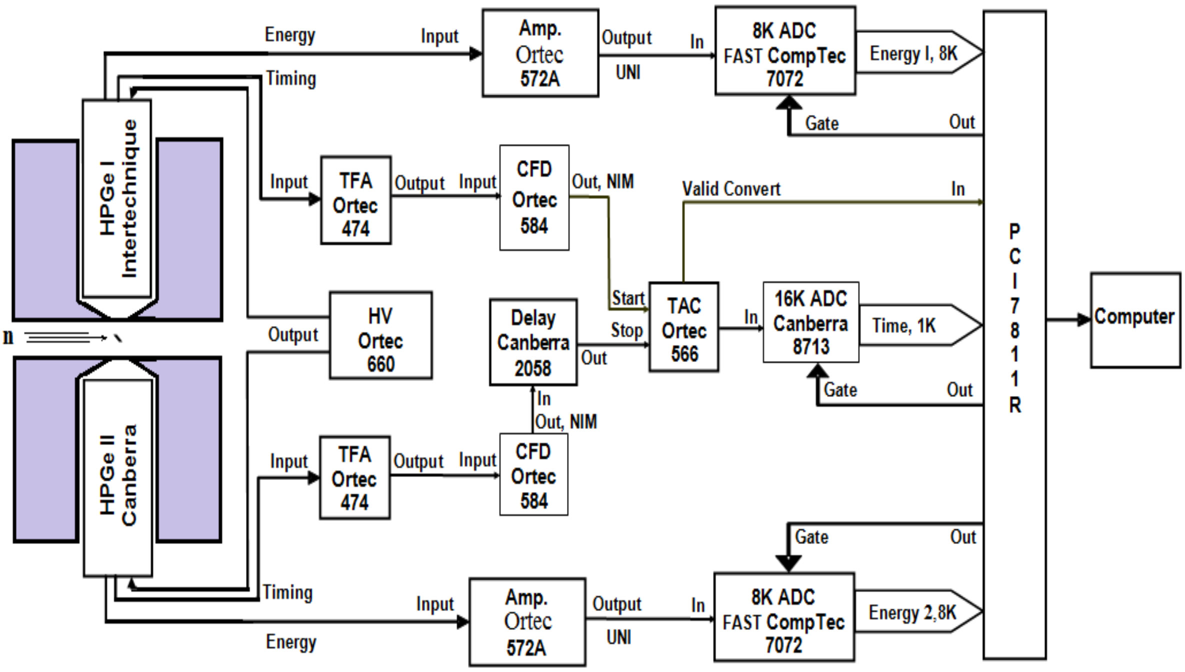

Fig. 2. The experimental system for gamma-gamma coincidence measurement [8]

IV. RESULTS AND DISCUSSION

The experimental timing was about 280 hours. The numbers of event – event coincidence were about 55×10^6 events, the statistic counts of sum peak at B_n (B_n: neutron binding energy) were about 6000. Table 1 showed some information of sum peaks. Table 2 showed some levels, energy gamma rays, spin, parity, branch ratio of level and transition strength of ^{52}V.

Table 1. The information of sum peaks

No	Sum peak energy (keV)	Final level (keV)	Spin and parity of final level
1	7310.68	0	3^+
2	7293.52	17.16	2^+
3	7162.83	147.85	4^+
4	6874.51	436.34	2^+, 3^+
5	6517.34	793.34	2^+,3^+
6	1793.38	0	3^+

Table 2. Levels, lifetime levels, width levels, spins, branch ratio and transition strengths of ^{52}V

Level (keV)	($t_{1/2}$) (s)	Γ_γ (eV)	E_γ (keV)	$J_i \to J_f$	$J_i \to J_f$ [2]	$B_{\gamma i}$ (%)	Transition Strength		
							$\lvert M(E(1)\rvert^2$	$\lvert M(M(1)\rvert^2$	$\lvert M(E(2)\rvert^2$
7310.68	3.5638E-18	18.695	6875.09	$3^-,4^-\to 2^+,3^+$	$3^-,4^-\to 2^+$	8.255(84)	12.04	--	--
			6518.05	$3^-,4^-\to 2^+,3^+$	$3^-,4^-\to 3^+$	17.701(122)	5.65	--	--
			6465.04	$3^-,4^-\to 3^+,4^+$	$3^-,4^-\to 4^+$	13.990(109)	7.14	--	--
			5892.97	$3^-,4^-\to 2^+,3^+$	$3^-,4^-\to 3^+$	6.118(72)	16.39	--	--
			5578.93	$3^-,4^-\to 2^+,4^+$	$3^-,4^-\to ?$	15.453(128)	142.81	--	--
			5516.93	3-,4-$\to 2^+,3^+$	$3^-,4^-\to 3^+$	14.425(115)	6.94	--	--
			5211.89	$3^-,4^-\to 2^+,3^+$	$3^-,4^-\to 4^+$	9.136(84)	10.99	--	--
			5142.88	$3^-,4^-\to 2^+,3^+$	$3^-,4^-\to 3^+$	6.823(76)	14.70	--	--
			4884.85	$3^-,4^-\to 2^+,3^+$	$3^-,4^-\to ?$	3.069(51)	32.25	--	--
			4452.80	$3^-,4^-\to 3^+$	$3^-,4^-\to ?$	2.033(60)	49.98	--	--
			3579.69	$3^-,4^-\to 3^+$	$3^-,4^-\to 3^+$	0.875(27)	111.08	--	--
			5752.96	$3^-,4^-\to 2^-,3^-$	$3^-,4^-\to 4^+$	15.453(128)	--	6.45	--
			5551.93	$3^-,4^-\to 3^-,5^-$	$3^-,4^-\to 2^+$	1.026(29)	--	99.96	--
			4993.86	$3^-,4^-\to 2^-,4^-$	$3^-,4^-\to ?$	0.412(19)	--	24.92	--
2857.88	1.4678E-15	0.448	2842.60	$3^+\to 2^+$	$? \to 2^+$	60.006(551)	--	1.67	--
			2710.58	$3^+\to 4^+$	$? \to 4^+$	39.994(449)	--	2.50	--
2425.83	4.4473E-15	0.148	2427.55	$2^+,3^+\to 3^+$	$? \to 3^+$	19.877(261)	--	5.02	--
			2410.54	$2^+,3^+\to 2^+$	$? \to 2^+$	36.593(354)	--	2.73	--
			1634.45	$2^+,3^+\to 2^+,3^+$	$? \to 3^+$	43.530(386)	--	2.29	--
2167.80	3.3262E-15	0.198	2169.51	$2^+,3^+\to 3^+$	$4^+\to 3^+$	11.084(207)	--	9.02	--
			2146.51	$2^+,3^+\to 5^+$	$4^+\to 5^+$	69.442(518)	--	1.44	--
			2021.50	$2^+,3^+\to 4^+$	$4^+\to 4^+$	19.474(275)	--	5.12	--
2098.79	6.6423E-15	0.099	2101.51	$3^+,4^+\to 3^+$	$3^+\to 3^+$	14.937(175)	--	6.70	--
			2083.50	$2^+,3^+\to 2^+$	$3^+\to 2^+$	12.831(162)	--	7.82	--
			1953.49	$2^+,3^+\to 4^+$	$3^+\to 4^+$	27.300(236)	--	3.67	--
			1664.45	$2^+,3^+\to 2^+,3^+$	$3^+\to 2^+$	25.586(229)	--	3.90	--
			1307.41	$2^+,3^+\to 2^+,3^+$	$3^+\to 3^+$	19.346(199)	--	5.15	--
1793.75	1.2572E-14	0.052	1795.47	$2^+,3^+\to 3^+$	$2^+\to 3^+$	38.970(41)	--	12.03	--
			1778.47	$2^+,3^+\to 2^+$	$2^+\to 2^+$	16.247(65)	--	2.74	--
			1358.41	$2^+,3^+\to 2^+,3^+$	$2^+\to 2^+$	8.269(288)	--	2.56	--
			1002.37	$2^+,3^+\to 2^+,3^+$	$2^+\to 3^+$	36.514(606)	--	6.17	--
1557.72	8.8182E-15	0.075	1558.44	$2^-,3^-\to 3^+$	$4^+\to 3^+$	85.774(711)	1.16		--
			1410.42	$2^+,3^+\to 4^+$	$4^+\to 4^+$	14.226(289)	--	7.04	--
1417.71	1.3370E-14	0.049	1418.42	$2^+,3^+\to 3^+$	$3^+\to 3^+$	57.508(457)	--	2.36	--
			1401.42	$2^+,3^+\to 2^+$	$3^+\to 2^+$	30.149(331)	--	2.06	--
			982.37	$2^+,3^+\to 2^+,3^+$	$3^+\to 2^+$	12.343(348)	--	10.97	--
845.64	5.9512E-14	0.011	845.35	$3^+,4^+\to 3^+$	$4^+\to 3^+$	43.296(393)	--	2.31	--
			823.35	$3^+,4^+\to 5^+$	$4^+\to 5^+$	44.394(398)	--	0.96	--

			698.33	$3^+,4^+\to4^+$	$4^+\to4^+$	12.310(209)	--	1.57	--
792.63	1.4730E-13	0.004	793.34	$2^+,3^+\to3^+$	$3^+\to3^+$	29.426(40)	--	3.40	--
			645.33	$2^+,3^+\to4^+$	$3^+\to4^+$	62.846(711)	--	1.59	--
			356.29	$2^+,3^+\to2^+,3^+$	$3^+\to2^+$	7.729(249)	--	12.94	--
435.59	5.6046E-13	0.001	436.30	$2^+,3^+\to2^+$	$2^+\to2^+$	49.587(52)	--	2.01	--
			419.30	$2^+,3^+\to1^+$	$2^+\to1^+$	31.289(532)	--	3.19	--
			295.28	$2^+,3^+\to3^+$	$2^+\to3^+$	19.124(416)	--	5.24	--

In the results, there were 37 two-step gamma cascades obtained, spins and parities of levels of ^{52}V were refreshed, including of levels: 2858.88 keV (3^+); 2425.83 keV ($2^+,3^+$); 2316.82 keV ($2^-,4^-$); 1731.75 keV ($2^+,4^+$). Comparing with electromagnetic transition probability of the single particle model, two gamma rays: 5551.93 keV emitted from B_n to 1758.75 keV level, and 5752.96 keV emitted from B_n to 1557.72 keV level were magnetic dipole; therefore, the spins and parities of those levels must be: 1758.75 keV ($3^-,5^-$); 1557.72 keV ($2^-,3^-$).

The single particle model was comfortable with experimental data. From rule of multi orders and electromagnetic transition probabilities, the uncompleted spins and parities of levels were determined.

V. CONCLUSIONS

This experimental result obtained by the ^{51}V(n, 2γ)^{52}V reaction at Dalat nuclear reactor. These were determined 37 two-step gamma cascades pairs. The single particle model was used to calculate and compare with experimental data. The parities and spins were determined by multi orders and electromagnetic transition probabilities. This paper delivered spins and parities of some incomplete levels according to LANL library. The spins, the parities were up to dated for unsuitable levels. The results also showed lifetime level, width level and gamma transition strength of some levels. Unfortunately, the experimental system was not able to get directly three or more gamma cascades, therefore; in this result, the three-step cascade was incomplete in any decay scheme.

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