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APPLICATION OF THE COLLECTIVE MODEL TO DETERMINE SOME VIBRATIONAL BANDS OF ^{140}LA NUCLEUS

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ABSTRACT

^{140}La is created from the thermal neutron capture reaction of ^{139}La, which is the product of the fission reaction. It makes some effects into the components of the nuclear reactor core. Understanding the properties and structure of ^{140}La is important in operating the nuclear reactor. Besides that, nuclear structure models are very effective in explaining the properties of nuclear structure. There are many nuclear structure models to solve those problems, such as Liquid Drop Model, Shell Model, Fermi Model, etc. Among them, the Collective Model has been very successful in describing the variety of nuclear properties, especially energy levels in deformed nuclei that the Shell Model and the Liquid Drop Model does not apply. This paper presents the application of the Collective Model to determine some vibrational bands of ^{140}La nucleus. This experiment is performed at channel No.2 of Dalat Research Reactor (DRR), Prompt gamma neutron activation analysis method (PGNAA) is used. The result has found 8 vibrational bands of ^{140}La nucleus. It's quite relevant to the theoretical calculation. The deviations are less than 1.6 %.

Keywords: Collective model, ^{140}La, vibrational band.

TÓM TẮT

Ứng dụng mẫu hạt nhân suy rộng trong việc xác định một số phổ dao động của hạt nhân ^{140}La

^{140}La được tạo ra từ phản ứng bắt neutron nhiệt của ^{139}La, sản phẩm của phản ứng phân hạch. Nó gây nên nhiều ảnh hưởng đến các thành phần trong lõi lò phản ứng hạt nhân. Việc tìm hiểu tính chất, cấu trúc của ^{140}La là rất quan trọng trong vận hành lò phản ứng. Bên cạnh đó, các mẫu cấu trúc hạt nhân rất hữu hiệu trong việc lí giải tính chất đặc thù của hạt nhân. Có nhiều mẫu cấu trúc hạt nhân khác nhau để giải quyết cho bài toán này, như Mẫu giọt, Mẫu vỏ, Mẫu Fermi, vv. Trong đó, Mẫu suy rộng đã rất thành công trong việc mô tả các đặc tính khác nhau của hạt nhân, đặc biệt là các mức năng lượng của hạt nhân suy biến mà Mẫu giọt và Mẫu vỏ không đáp ứng. Bài báo trình bày ứng dụng Mẫu suy rộng trong việc xác định một số phổ dao động của hạt nhân ^{140}La. Thực nghiệm được tiến hành tại kênh ngang số 2 của Lò phản ứng hạt nhân Đà Lạt (DRR), sử dụng phương pháp phân tích kích hoạt neutron đo gamma tức thời (PGNAA). Kết quả đã xác định được 8 phổ dao động của hạt nhân ^{140}La rất phù hợp với tính toán lí thuyết, với độ lệch nhỏ hơn 1.6 %.

Từ khóa: Mẫu suy rộng, ^{140}La, phổ dao động.

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1. Introduction

In recent years, much progress has been studied about nuclear structure. Because of the defective of the nuclear theory, it is necessary to use different nuclear structure models which have some distinct nuclear properties, but it also has a limitation of these models. The Liquid Drop Model is constructed by the strong interaction between nucleons. The Fermi Model assumes that nucleons in the nucleus is completely not interacting with each other. The Shell Model is considered as the motion of the single-particle, which have the spin interaction. The Collective Model is considered as the motion of single-particle in a potential field, as the collective motion of nucleons [1].

Collective Model was developed in the 1950s by Reynolds, A. Bohr and Mottelson, Hill and Wheele [1]. The Collective Model emphasizes the coherent behavior of all nucleons in heavy nuclei. The spherical symmetric potential of full-shell nucleus is very stable, then it still remains spherical symmetric form. By the increase of external nucleons of full-shell nucleus, the individual motion effect of nucleons on the potential field increases and makes pressure on the nucleus. Collective motion increases rapidly and it impacts the core of full-shell nucleus leading to the spherical asymmetric form of nucleus. One kind of collective motion that can occur in nuclei is vibrational motion. In 1969, Larry Shelton Varnell applied the Collective Model to determine some vibrational bands of some deformed nuclei [2], the result has determined 8 vibrational bands of ^{152}Gd and 9 rotational bands of ^{232}U, etc.

So far, there are many studies about ^{139}La nucleus. In the 1983s, Yutaka Nakajima et al found the radiative neutron capture in ^{139}La below 2.5 keV [3]. Neutron capture events were detected with a 3500 liters liquid scintillator tank. Individual resonances were analyzed using the area analysis method to obtain the capture widths. Capture areas for 20 resonances and capture widths for 5 resonances were newly obtained. In 2007, the ^{139}La(n_{th}, γ)^{140}La cross section is determined by R. Terlizzi et al [4], the nuclear resonance parameters and the capture cross section of the ^{139}La isotope have been measured relative to ^{197}Au in the energy range of 0.6 eV to 9 keV at the neutron time-of-flight (n_TOF) facility at CERN (Conseil Européen pour la Recherche Nucléaire). These results show sizeable differences with respect to the previous experimental data and allow to extract the related nuclear quantities with improved accuracy. Until now, there aren't any researches about the vibrational band of ^{140}La nucleus.

Prompt gamma neutron activation analysis (PGNAA) is a rapid, nondestructive technique which is used for analysis of various elements [5]. The compound nucleus is created in (n, γ) reaction, it transforms into the stable nucleus or radioactive nucleus for about 10^{-14} seconds and emits prompt gamma-rays. Therefore, the irradiation and the acquisition process must be performed at the same time. ^{139}La exists in nuclear reactor core which is odd-even nucleus which has 57 protons and 82 neutrons. ^{140}La is odd-odd nucleus which has 57 protons and 83 neutrons (1 added neutron by neutron capture reaction). In this experiment, PGNAA method is used to acquire the prompt gamma-rays emitted from ^{139}La(n, γ)^{140}La reaction.

$$^{1}_{0}n + ^{139}_{57}La \rightarrow (^{140}_{57}La)^{*} \rightarrow ^{140}_{57}La + \gamma_{prompt}$$

where $^{1}_{0}n$ is the incident neutron, $^{139}_{57}La$ is the target nucleus, $(^{140}_{57}La)^{*}$ is the compound nucleus, $^{140}_{57}La$ is the product nucleus and γ_{prompt} is the prompt gamma-rays.

2. Theory and equipments

2.1. Theory

The Nilsson model is a Shell Model for a deformed nucleus. It provides the description of single-particle motion in a spherical asymmetric potential. Vibrational bands appear when the external nucleons of full-shell nucleus are not much. If the excitation of the nucleus involves many different single-particle modes *i*, it can be repeated a large number of times, and the resulting set of states can be associated with the Harmonic vibrational motion. Where *i* label is the individual particle-hole configurations. The vibrational energy is given by [1]:

$$E_{vib} = n\hbar\omega \quad (1)$$

where $\hbar\omega$ is the common excitation energy of the degenerate particle-hole *i* state, and *n* is the number of quanta of this mode, *n = 1, 2, 3, ...* Then, the ratio of vibrational energies is given by:

$$E_1 / E_2 / E_3 / E_4 / E_5 / E_6 / ... = 1/2/3/4/5/6/... \quad (2)$$

2.2. Equipments

The experiment is performed at channel No.2 of DRR, using Filtered Thermal Neutron Beam, and HPGe detector with PGNAA method. Configuration of the acquisition system is shown in Fig. 1.

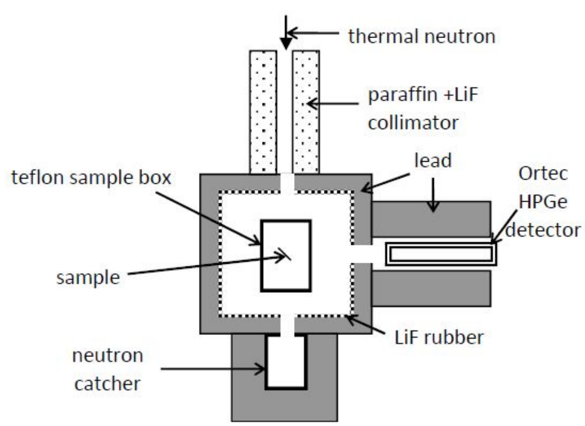


Fig. 1. *Configuration of the acquisition system at channel No.2 of DRR*

The thermal neutron flux at the sample position is 1.6×10^6 n/cm^2/s and the Cd ratio is 420 [6]. A chamber with the internal high density polyethylene (HDPE) is set up, it also has 5% Li to shield the scattered neutrons. Inside the chamber, a holder is made of PTFE (Teflon plastic) material which fixed the sample during the acquisition process. Configuration of the Filtered Thermal Neutron Beam is shown in Fig. 2.

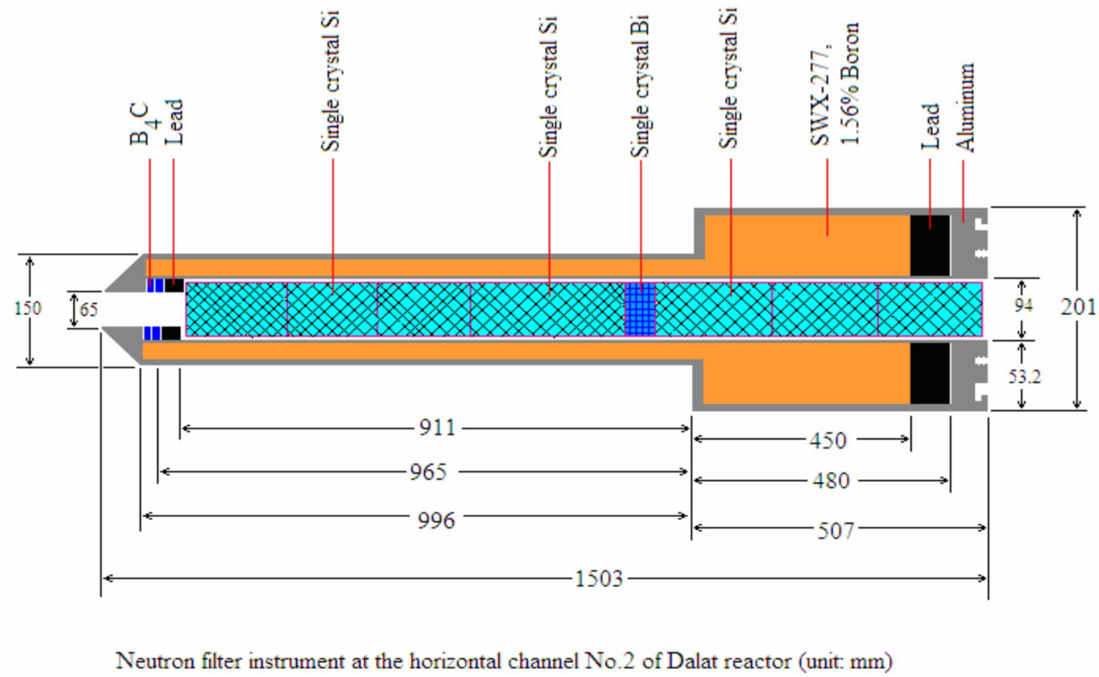


Fig. 2. *Configuration of the Filtered Thermal Neutron Beam at channel No.2 of DRR (unit: mm)*

Due to the large number of gamma-rays incident on the main detector, the Compton continuum makes the difficult search of low-intensity peaks and increases the uncertainty of the measured activities. Therefore, a Compton suppression spectroscopy has been set-up and installed at DRR for neutron activation analysis and nuclear data measurement. The central detector is a GR7023 Canberra n-type coaxial HPGe detector. There are 12 Bismuth Germanium (BGO) guard detectors shielded by lead of 10 cm thickness. The reduction of the Compton continuum has been achieved by surrounding the HPGe detector with the BGO detectors whose signals are used for the anti-coincidence gating in the analog-to-digital converter (ADC). The Compton continuum is reduced about 1.5 to 2 times, up to 1 MeV region of energy [7]. The electronic modules are manufactured by Canberra except the high voltage module for BGO detectors, which were produced by Fast Comptec. They include 2026 main amplifier (AMP), 3106D high voltage power supply, multiport II with ADC 16K and multichannel analyzer (MCA), using the Genie 2000 software. Its configuration is shown in Fig. 3.

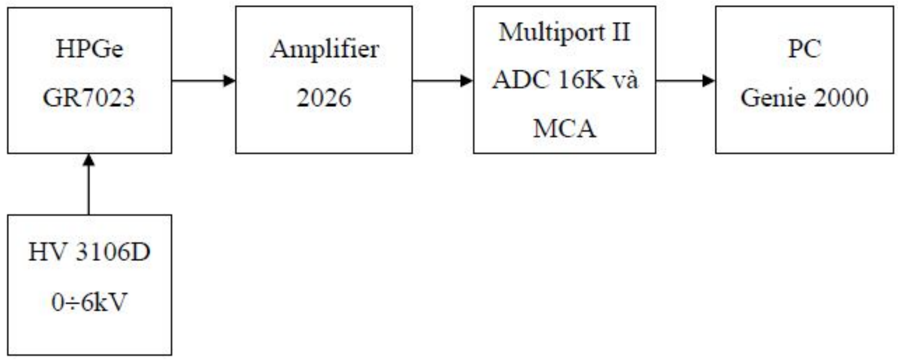


Fig. 3. *The block schema of the gamma acquisition system*

^{139}La powder sample is used. Its diameter, thickness and weight are 1.2 cm, 1.2 cm and 1.53101 g respectively. Geometric form of ^{139}La sample is cylinder form, which is shown in Fig. 4.

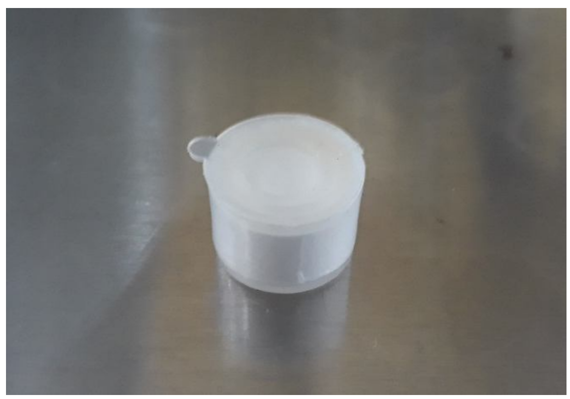


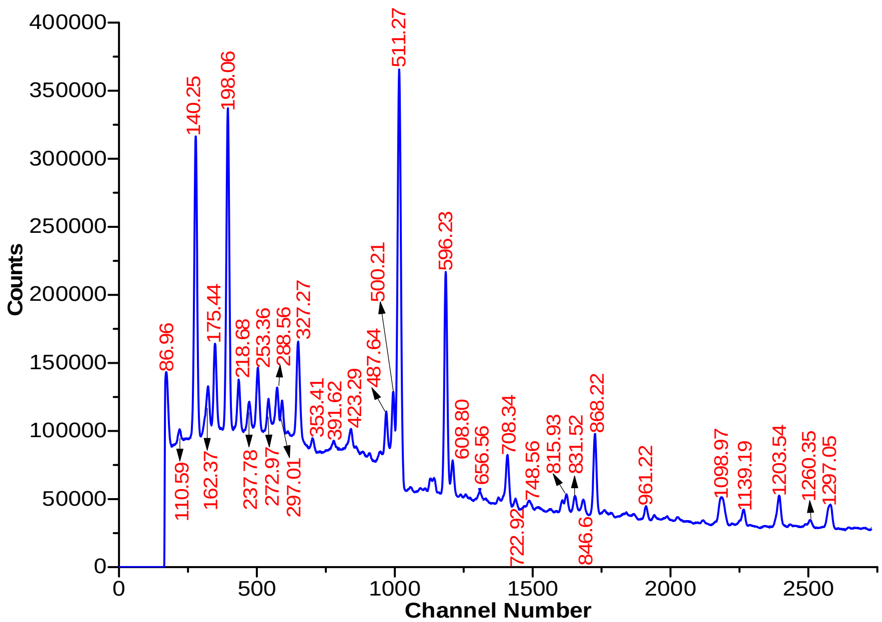
Fig. 4. *Geometric form of ^{139}La*

The ^{139}La sample is placed in the holder at the irradiation position, the angle between the neutron flux and the sample is 45°, the distance from the sample to the detector is 38.5 cm.

3. Results and discussions

The acquisition time of background spectrum is 62,465 seconds and ^{140}La spectrum is 106,846 seconds.

Prompt gamma spectrum of ^{140}La acquired at channel No.2 of DRR is shown in Fig. 5. The statistical count of the spectrum is 1.66×10^{8} counts.



Energy Calibration: $y = 0.5101x - 0.354$

where x is the channel number and y is the gamma energy (keV)

Fig. 5. *Prompt gamma spectrum of ^{140}La*

Experimental data are shown in Table 1. 36 prompt gamma-rays are emitted from ^{139}La(n, γ)^{140}La reaction. Especially, the 140.25 keV and 198.06 keV peaks have the count quite high but their intensity are low, because those two peaks are overlapped by some elements exist in the background spectrum (those elements are the fission products which are created from the nuclear reactor, they continuous emit into the background spectrum). The 140.25 keV peak is overlapped by ^{99m}Tc nucleus, while the 198.06 keV peak is overlapped by ^{169}Yb nucleus. Use Equation (1) and (2) to calculate the vibrational band of ^{140}La. Results compared between experimental data and theoretical calculation are shown in Table 2.

Table 1. *Energy and Intensity of prompt gamma-rays emitted from ^{139}La(n, γ)^{140}La reaction*

No.	**Energy (keV)**	**Intensity (%)**		**No.**	**Energy (keV)**	**Intensity (%)**		**No.**	**Energy (keV)**	**Intensity (%)**
1	86.96	0.21		*13*	327.27	2.00		*25*	722.92	2.88
2	110.59	0.19		*14*	353.41	1.15		*26*	748.56	2.39
3	140.25	0.82		*15*	391.62	1.31		*27*	815.93	4.41
4	162.37	0.63		*16*	423.29	2.15		*28*	831.52	2.89
5	175.44	0.62		*17*	487.64	3.99		*29*	846.60	2.84
6	198.06	1.37		*18*	500.21	2.71		*30*	868.22	5.79
7	218.68	1.24		*19*	511.27	7.99		*31*	961.22	3.39

8	237.78	1.06		*20*	568.58	2.54		*32*	1098.97	4.86
9	253.36	1.01		*21*	596.23	5.80		*33*	1139.19	4.24
10	272.97	1.42		*22*	608.80	2.31		*34*	1203.54	5.72
11	288.56	1.79		*23*	656.56	3.41		*35*	1260.35	4.64
12	297.10	1.09		*24*	708.34	3.61		*36*	1297.05	5.50

Table 2. *Results compared between experimental data and theoretical calculation*

No.	**E_γ experiment (keV)**	**E_γ theory (keV)**	**(E_i/E_1) experiment (keV)**	**(E_i/E_1) theory (keV)**	**Deviation (%)**
1	162.37	*162.66*	1.00	1.00	0.18
2	327.27	325.32	2.02	2.00	0.60
3	487.64	487.98	3.00	3.00	0.07
4	656.56	650.64	4.04	4.00	0.91
5	815.93	813.30	5.03	5.00	0.32
6	961.22	975.96	5.92	6.00	1.51
7	1139.19	1138.62	7.02	7.00	0.05
8	1297.05	1301.28	7.99	8.00	0.33

**Note: (162.66) keV is taken from Nuclear Data Services [8]*

The result in Table 2 shows that the ^{140}La nucleus has 8 vibrational bands E_1, E_2, E_3, E_4, E_5, E_6, E_7, E_8, which are 162.37 keV; 327.27 keV; 487.64 keV; 656.56 keV; 815.93 keV; 961.22 keV; 1139.19 keV and 1297.05 keV respectively, among 36 energy peaks from the prompt gamma spectrum acquired at the channel No.2 of DRR. 28 another peaks are from the ^{140}Ce daughter nucleus (created form the β^- decay of ^{140}La nucleus) of ^{140}La nucleus. Determination of the vibration band of the ^{140}La nucleus has been calculated, where the vibrational energies are multiple of first excitation energy (according to the number of quanta *n*). In this research, the experimental result is similar to theoretical result. The deviations are less than 1.6 %.

4. Conclusion

Besides many studies about the vibrational band of the even-even nuclei before, this is the new research about the vibrational band of the odd-odd ^{140}La nucleus, which is the product of fission reaction in the nuclear reactor core. It's the important work in the research of the nuclear reactor.

From prompt gamma spectra acquired at channel No.2 of DRR using application of Collective Model in nuclear structure research, 8 vibrational bands the ^{140}La nucleus are identified. The result is quite relevant to the theory of the Collective Model when studying about the nucleus which has the different between the neutron and proton numbers. The ^{140}La is the nucleus which has the deformed structure, it definitely has the spherical asymmetric shape.

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