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Neutron capture experiments with 4π DANCE Calorimeter

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Abstract. In recent years we have performed a series of neutron capture experiments with the DANCE detector array located at the Los Alamos Neutron Science Center. The radiative decay spectrum from the compound nucleus contains important information about nuclear structure and the reaction mechanism. The primary goals of the measurements are to obtain improved capture cross sections, to determine properties of the photon strength function, to improve neutron level densities and strength functions by determining the spin and parity of the capturing states. We shall present examples of our recent results.

1 Introduction

In this paper we present some preliminary results of our recent analysis on neutron capture experiments that have been performed at the Los Alamos Neutron Science Center (LANSCE). The experiments – on all stable Gd isotopes and on ^{151,153}Eu, ^{94,95,97}Mo, ^{87}Sr, ^{117,119}Sn and ^{89}Y – were made on the state-of-the-art Detector for Advanced Neutron Capture Experiments (DANCE).

These measurements provide key information about statistical model parameters for cross section evaluation and for nuclear structure and radiative decay properties at high excitation energies.

By comparing the experimental multistep cascade (MSC) spectra with statistical model simulations, we could test whether the γ-ray cascades could be described by the extreme statistical model and obtain valuable information on the radiative strength functions below the neutron separation energy. The details of the simulations and calculations for ^{94,95}Mo and ^{157}Gd isotopes are given in ref. [1, 4]. The mass and deformation parameter dependence of the scissors mode resonance is being studied on even-even ^{152,154,156,158,160}Gd targets.

The absolute or relative cross sections can be calculated from DANCE time-of-flight spectra. A classic problem in neutron resonance spectroscopy is the difficulty in determining the spin of s-wave neutron resonances on non-zero spin targets. Our initial emphasis on ^{155}Gd has provided new resonance spectroscopic information such as resonance spin, radiative and neutron widths and average quantities such as level density, s-wave neutron strength, etc. (see reference [7]). The most novel feature of these results is the development and application of pattern recognition technique to determine the resonance spin. We shall not discuss this analysis in detail, but instead present sample results.

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2 DANCE Spectra

DANCE is a highly granular (160 crystals) 4π detector which has many advantages for study of MSC spectra in the quasi-continuum region. Some of the experimental spectra observed from recent analysis will be discussed below for various isotopes.

2.1 Total Energy Spectra

DANCE has a very high detection efficiency, since the target is fully surrounded by 160 BaF_2 scintillators – a 4π solid angle. The total γ-ray energy spectra has a peak at the Q-value of the reaction and extends to the low energy side resulting in a triangular shape because of the portion of undetected events. However, the shape of the spectrum is strongly dependent on the γ-ray energy threshold for each individual crystal. As an example Fig. 1 shows a total energy spectrum for ^{97}Mo with 400 keV threshold (and no hardware threshold) for each crystal.

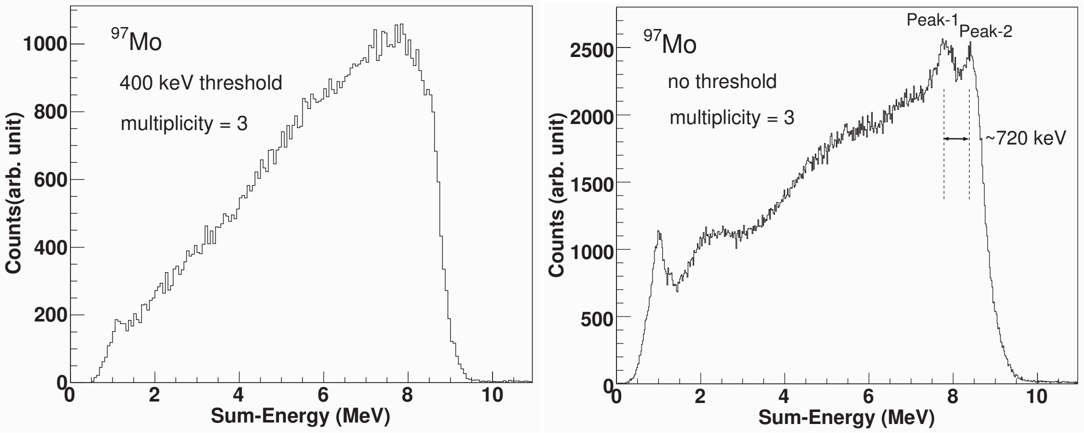

Fig. 1. Total γ-ray energy spectra of ^{97}Mo for experiments with 400 keV and no hardware threshold.

As demonstrated in Fig. 1, the threshold strongly affects the shape of the spectrum as well as the resolution. Of course the dependence should be different from isotope to isotope, but still will affect the efficiency and multiplicity distribution. With a very small value of the threshold, the influence of random background increases. On the other hand a very high threshold blocks real capture event γ-rays. The selection of an appropriate threshold value requires careful consideration.

The double peak near the reaction Q-value shown in Fig. 1 is the result of the 0^+ first excited state at 734.75 keV. This state emits only internal conversion electrons (EC) to the 0^+ ground state in ^{98}Mo. The conversion electrons will be attenuated by the lithium hydrate ball which surrounds the target to reduce the scattering background. The events in the higher energy peak are from transitions that proceed directly to the ground state; the events in the lower energy peaks are the transitions feeding the first excited state (plus some portion of the ground transition events because of the resolution and detector response) . The experiment and the preliminary analysis of the ^{97}Mo data is by C. L Walker. Final calculations are in progress.

As we have learned from the ^{97}Mo preliminary results, one could predict a double peak structure in the total γ-ray energy spectra if there is a low-lying metastable state or a 0^+ first excited state in even-even compound nuclei. The total γ-ray energy spectra for ^{117}Sn is shown in Fig. 2. In these spectra we observe the double peak structure again, but the situation is different from the previous case. As given in nuclear data library [8], there is no metastable or long lifetime first excited state in ^{118}Sn. However, the explanation could be similar to the previous case – that it is because of undetected EC events. As shown in Fig. 2, the ratio of peak-1 to peak-2 at multiplicity 4 is higher than multiplicity 3, indicating that the portion of undetected events increase as cluster multiplicity increase. This behavior was observed almost all other capture experiments, but the peak was so smooth and broad that the effect was weak.

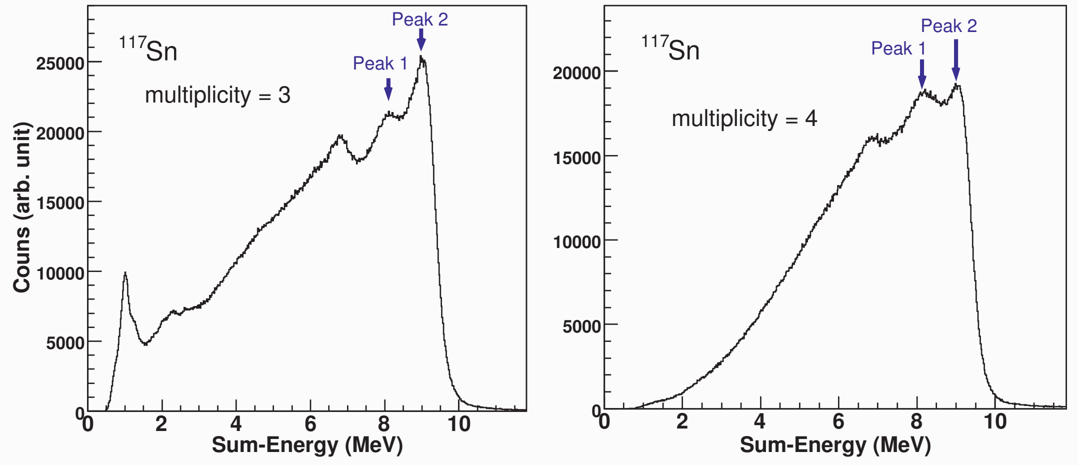

Fig. 2. Total γ-ray energy spectra of ^{117}Sn. The peak around 6.9 MeV is the capture events from ^{116}Sn which is about 7.5% of target contaminations.

2.2 γ-Ray Energy Spectra

The γ-ray energy resolution of the BaF_2 scintillator is not very high, about 10% at 1 MeV. However, the γ-rays from the transitions between the low-lying states can be visible when there is relatively large separation between the levels. This is illustrated in Fig. 3 for ^{87}Sr. This experiment was by G. Rusev *et al*. The shape of γ-ray spectra depends the relative size and strength of the different types of transitions (E1, M1, E2) and is used as important tool for the study of photon strength function.

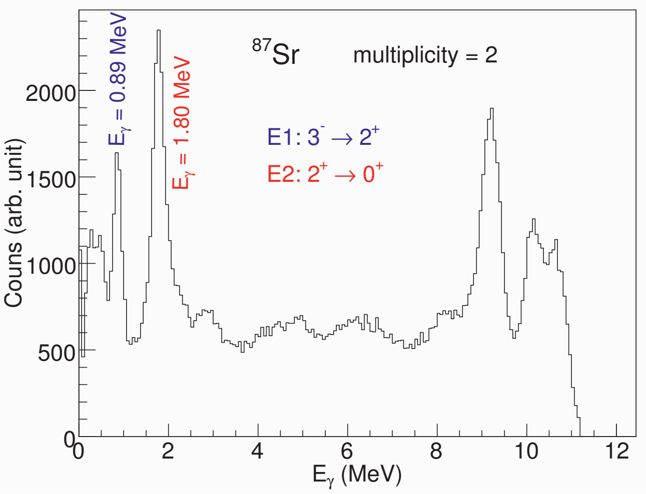

Fig. 3. Capture γ-Ray Energy Spectra for ^{87}Sr.

2.3 Multiplicity Distribution and Spin Assignment

The multiplicity distribution is the relative probability of the number of steps to when the compound nucleus decays to its ground state from the highly excited capture state. We have demonstrated that the multiplicity distribution contains information about the spin and parity of the initial state. In favorable cases the average multiplicity is sufficient to determine the spin. In general, one needs more detailed analysis of the multiplicity distribution to determine the spin. We have produced several techniques to assign spin of the neutron resonances. The advanced methods give an ability to assign spin of the resonances consitently [6,7]. However, for some isotopes such as ^{151,153}Eu, the radiative decay patterns are nearly identical for the cascades initiated from different spin states. As a result, using the multiplicity distribution for spin assignment become very difficult. Fig. 4 shows the γ-ray spectra and average multiplicities for stronger neutron resonances in ^{153}Eu.

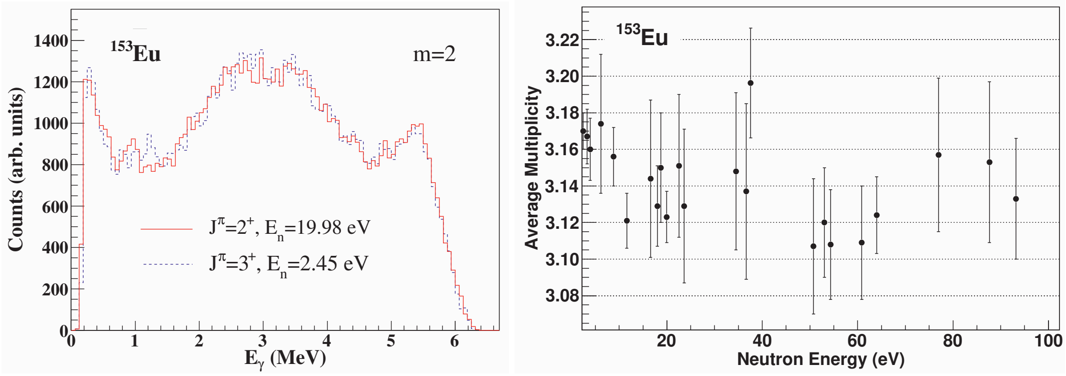

Fig. 4. Capture γ-Ray Energy Spectra and Average Multiplicities for ^{153}Eu.

3 Differential Spectra

The integrated spectra shown in previous spectra may not contain detailed information about the transitions multipolarities. However, the angular correlation between the sequential radiations could provide more information about the radiative transitions. In other words, the sequences of different multipole orders (D)ipole-(Q)uadrupole, Q-Q and D-D will have different correlations. Clearly the correlation also depends on the spin and parity of the states involved in the transitions. Since we are not using the polarized neutrons the γ-ray emission by the compound nucleus will be isotropic. However, two successive γ-ray from the compound nuclear cascade will have a directional correlation.

3.1 Theoretical Assumption

The relative probability that the second γ-ray will be emitted at an angle θ with the first, $W(\theta)$, depends on the angular momenta of the states involved in the transition and the multipole order of the radiation [9].

$$W(\theta) = \sum_k A_k P_k(cos(\theta)) \tag{1}$$

The polynomial coefficient are constants depending from transition multipole order and the spin and parity of the states. The theoretical calculation of the coefficients are tabulated in various textbooks and papers (see reference [9]).

3.2 Correlation spectra for DANCE

To confirm if the correlation spectra could be extracted from DANCE experiments, we measured ^{60}Co spectra. Through β^- emission, the cobalt nucleus decays into an excited state of nickel at 2505 keV with spin 4^+. This state then decays to the 0^+ ground state though an intermediate state with spin 2^+ and energy 1333 keV. The correlation spectra between the two γ-rays are shown in Fig. 5. Dashed blue line is the theoretical predictions for the cascade and the red line is the fit of experimental points. As we seen from the figure, the DANCE spectra nicely agrees with theoretical curve.

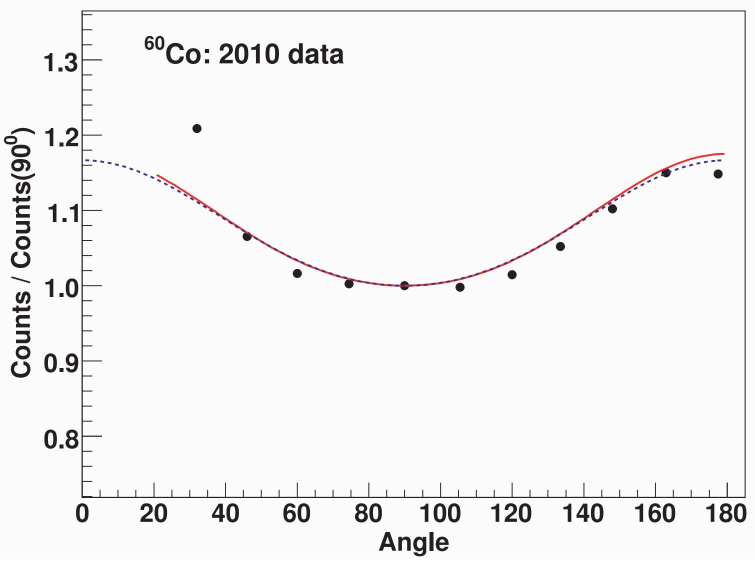

Fig. 5. Gamma ray energy and correlation spectra between the two gamma transitions.

The correlation spectra for capture gamma rays should be very complicated because of the poor energy resolution of the detector and the large number of possible transitions. The angular correlation between two clusters (which assumes a cluster represents a single γ-ray) for ^{155}Gd is shown in Fig. 6. This shows the correlation spectra for 2 different neutron resonances with spin $j = 1$ and $J = 2$.

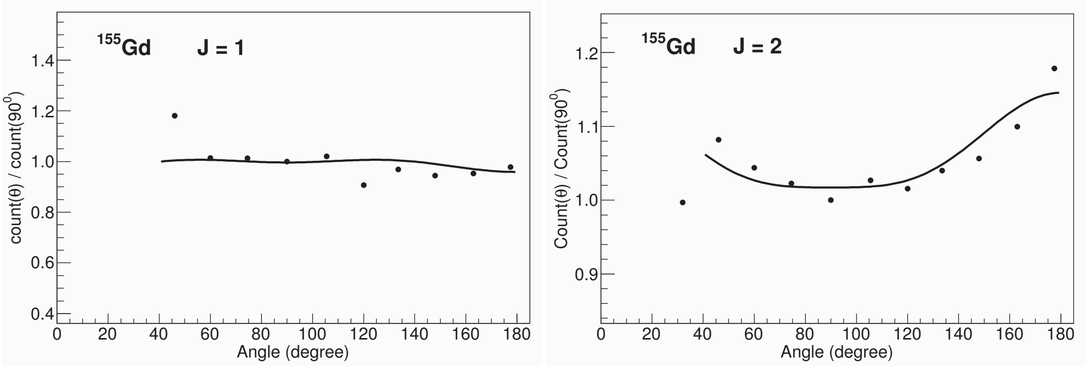

Fig. 6. γ-ray correlation spectra for transitions between ^{156}Gd states.

As shown in Fig. 6 there is a relatively small difference in correlation spectra for the cascades with different initial states ($J_1 = 1$ and $J_2 = 2$). Calculation of the theoretical coefficients is very complicated because of the mixture of different types of transitions. Although quantitative comparison is very complicated, the correlation spectra may used as qualitative estimates for the resonance spins.

4 Conclusion

Understanding the DANCE detector responses for different types of experiments is important. Most of the spectra shown in this paper is from preliminary analysis. However, we have already established the applicability of the extreme statistical model, made clear that the scissors mode resonance is essential to fit the energy spectra in the gadolinium and europium isotopes, and developed a new pattern recognition method to determine the spin of neutron resonances. The DANCE array will be upgraded next year – 1 or 2 crystals will be replaced with high-resolution detectors such as the new BrilLanCe 380$^{\mathrm{TM}}$(St. Gobain) and/or a HPGe solid-state detector; a new range of scientific problems will be addressed.

5 Acknowledgment

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