Proton Capture on ^{48}Ti

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The ^{48}Ti(p,γ)^{49}V reaction was studied in the energy range E_p = 2.0-2.7 MeV with a Compton-suppressed HPGe detector. Capture spectra were obtained for 27 compound nuclear resonances whose resonance parameters (energy, spin, parity, and particle widths) had been determined in earlier measurements by our group. A total of ten $1/2^+$ resonances, nine $1/2^-$ resonances and eight $3/2^-$ resonances were studied. The primary motivation for these measurements was to provide a data set suitable for testing the applicability of conventional statistical models in this mass region. The relative populations of 10 of the first 12 excited states of ^{49}V were determined (γ-ray detector resolution prevented the determination of the populations for two low-lying states). The experimental relative populations were compared with calculations performed with the statistical model code DICEBOX, which has proven very successful in describing neutron capture spectra in heavy nuclei. Here the simulations provide a reasonable qualitative description of the relative population of the low-lying states of ^{49}V but not a quantitatively correct description.

I. INTRODUCTION

Since the early days of nuclear physics, the study of neutron capture has been an important and integral part of nuclear research. Historically neutron capture played a key role in reactor development, in the understanding of nucleosynthesis, and in nuclear structure in general. Present emphases include a focus on reaction networks for stewardship science and on better understanding of the radiative strength function. The high level of interest is illustrated by a long running conference devoted specifically to capture γ-ray spectroscopy – see the proceedings of the most recent conference in this series [1]. Although the Brink-Axel hypothesis [2, 3] works reasonably well in general, the characteristics of the low energy tail of the giant resonances are poorly understood. At present the standard prescription is by Kadminskij *et al.* [4]. However, recent measurements [5] suggest anomalous behavior for soft transitions between highly excited states. Other interesting issues include the origin of the "pygmy resonances" – the resonant-like structures observed at low photon energies. For a recent summary on more exotic aspects of these resonances, see von Neumann-Cosel [6].

However, one characteristic of resonance neutron capture in heavy nuclei is well accepted. Since there are so many decay channels available, the capture process is predominantly statistical. In fact, purely statistical models such as the approach formulated by Bečvář [7] in the program DICEBOX, work extremely well for the description of neutron capture in heavy nuclei. Interesting applications include using this approach to predict the population of low-lying levels and thus to infer resonance spins [8, 9].

In the present work we consider the range of applicability of this general statistical approach – that is, over what mass numbers and excitation energies does the method apply? At some value of the mass number and at some excitation energy, nuclear structure efforts should dominate, and the statistical approach should no longer be valid. However, the lines of demarcation are very poorly defined; in addition they may depend on the specific observables. Proton resonances in the nuclear $1f$-$2p$ shell behave statistically in the sense that the level statistics agree well with the predictions of Random Matrix Theory (RMT) [10]. For some lighter nuclei such as ^{26}Al and ^{30}P, even the low-lying levels obey RMT [11–14]. Therefore, it seemed valuable to address experimentally the issue of the range of applicability of statistical descriptions.

In earlier measurements in our laboratory, we had performed high resolution studies of proton resonances in the ^{48}Ti(p,p) and ^{48}Ti(p,p$_1$) reactions [15] and therefore knew the quantum numbers of many resonances. We chose a limited but substantial subset of these known resonances for detailed study. The resonances were chosen based on the reliability of the quantum number assignments and on their relative isolation from other resonances. One difficulty in the study of capture reactions in lighter nuclei is the reduced level density, which increases the importance of Porter-Thomas fluctuations. As a result the study of the decay of an individual resonance provides relatively little information. In the present work we study a number of resonances and average in order to minimize the effect of statistical fluctuations. In addition we consider resonances with three different spin-parity combinations.

We studied detailed capture spectra for 27 compound nuclear resonances in ^{49}V whose resonance parameters (energy, spin, parity, and particle widths) had been determined previously. The γ rays were measured with a Compton-suppressed HPGe detector. In Section II the experimental method is briefly described. The results are presented in Section III and compared with the predictions of the statistical model program DICEBOX. The final section provides a brief summary and conclusions.

II. EXPERIMENTAL METHOD AND PROCEDURE

The experiment was performed at the High Resolution Laboratory of the Triangle Universities Nuclear Laboratory. The high resolution system [16] provides proton beams in the range E$_p$ = 1-4 MeV, with proton beam energy resolution in the range of 250-300 eV. For this experiment the energy range covered was about 2.0-2.7 MeV. (Below about 2.0 MeV there were relatively few resonances available for study; at higher energies the γ-ray background increased rapidly.) The targets were thin films of highly enriched titanium (99.81% ^{48}Ti) evaporated onto 5-μg/cm^2 carbon foils. Typical targets were about 1.4-μg/cm^2 thick, corresponding to an energy loss of about 100 eV in the target.

The experiments were performed in a special chamber [17] which allows both NaI(Tl) and Ge detectors for γ-ray detection and a silicon surface barrier detector for particle detection. In the first phase of the experiment, known resonances [15] (from the early elastic and inelastic scattering measurements) were located and evaluated as possible candidates for detailed study. This initial experiment was performed with a charged particle detector at 165°, four 7.62 cm × 7.62 cm NaI(Tl) detectors at ±55°, 125°, and 135°, and one unsuppressed HPGe detector at 90°.

The capture excitation function was measured from $E_p = 1.97$ MeV to 2.80 MeV in 100-eV beam energy steps. Since the ambiguities in assigning quantum numbers was largest for the *d*- and *f*-wave resonances, we chose to restrict further detailed measurements to *s*- and *p*-wave resonances. We also focused on resonances with well determined total angular momentum. We chose 27 resonances (ten $1/2^+$ resonances, nine $1/2^-$ resonances and eight $3/2^-$ resonances) for detailed study.

Measurement of the γ-ray spectra was performed with two 60% HPGe detectors: one unshielded detector was located at 90°, and the BGO-suppressed detector was located at 55°. The particle detector and one NaI(Tl) detector were used to locate the resonance of interest. The HPGe detectors have a measured energy resolution of about 2.0 keV at 1333 keV. The gains were set so that ^{49}V transitions from 152 keV to 9.1 MeV were observed. Energy and efficiency calibrations were performed using a ^{152}Eu source and the well studied resonance in ^{27}Al(p,γ) at $E_p = 991.86$ keV [18].

For each resonance studied in depth, the resonance was first located with the particle and NaI(Tl) detectors, and then spectra were measured with the HPGe detectors – first on resonance and then at a nearby energy that was clearly off resonance. Both of these measurements were performed for an accumulated charge of 30,000 μC. The resonance was then relocated with the higher efficiency detectors and the process repeated. A typical cumulative charge of 240,000 μC was collected for both the on- and off-resonance measurements.

III. RESULTS

A. Experimental Results

The γ-ray decay of 27 ^{49}V resonances was studied. Table I lists the low-lying levels whose populations were measured. Initially we attempted to study the populations of the first 12 excited low-lying levels in ^{49}V. Due to detector resolution issues, results were not obtained for two of these states, the 90.64-keV level and the 1643.2-keV level. The 90.64-keV level has only the single γ-ray to the ground state depopulating it, and that relatively low-energy γ ray was not observed in our experiment. The 1643.2-keV level has two γ rays depopulating it with energies of 1490.24 keV and 1553 keV and branching ratios of 97.7% and 2.3%, respectively. The weaker γ ray was not observed, and the stronger γ ray could not be cleanly resolved from the 1493.6 keV γ-ray emitted from the 1646.4-keV level. (For the 1646.4-keV level there were other branches that could be used to determine its population).

The relative populations of the remaining 10 states were determined using the observed intensities of depopulating γ-rays and known branching ratios from earlier experiments [19]. The average values of the measured branching ratios agreed well for all states that were strongly populated. We utilized the previously measured values for the branching ratios throughout our analyses. The experimental relative populations are also listed in Table I. Because significant variations in relative population are observed from resonance to resonance (as expected), a standard weighted mean does not seem an ideal choice of statistic in this case because it tends to weight the smaller values more strongly. Instead we quote the unweighted mean and standard deviation to provide a better description of

TABLE I: Average relative populations of low-lying states in ^{49}V. For each state, the average experimental values are listed next to the state's energy, and the predictions of the DICEBOX code for those same values are listed in parentheses below the experimental values.

Level E_x (keV)	J^π	Average Experimental Relative Populations (DICEBOX Predictions)		
		$1/2^+$	$1/2^-$	$3/2^-$
152.9	$3/2^-$	0.31±0.08 (0.52±0.03)	0.3±0.1 (0.54±0.04)	0.3±0.2 (0.51±0.05)
748.3	$3/2^+$	0.20±0.07 (0.22±0.03)	0.2±0.1 (0.18±0.03)	0.17±0.05 (0.18±0.03)
1021.6	$11/2^-$	0.003±0.006 (< 0.0001)	0.005±0.007 (< 0.0001)	0.03±0.04 (< 0.0001)
1140.5	$5/2^+$	0.09±0.03 (0.041±0.07)	0.07±0.03 (0.035±0.006)	0.12±0.04 (0.09±0.02)
1155.3	$9/2^-$	0.02±0.02 (< 0.0001)	0.01±0.01 (< 0.0001)	0.04±0.03 (0.0030±0.0004)
1514.5	$5/2^-$	0.05±0.02 (0.011±0.001)	0.05±0.03 (0.015±0.003)	0.07±0.04 (0.06±0.02)
1602.7	$7/2^+$	0.05±0.04 (0.0010±0.0004)	0.02±0.02 (0.0010±0.0003)	0.03±0.03 (0.0060±0.0008)
1646.4	$(1/2^+)$	0.07±0.07 (0.07±0.02)	0.13±0.09 (0.08±0.03)	0.07±0.05 (0.05±0.02)
1661.4	$3/2^-$	0.15±0.09 (0.07±0.02)	0.10±0.04 (0.07±0.02)	0.10±0.04 (0.06±0.02)
1994.7	$3/2^{(+)}$	0.07±0.03 (0.06±0.02)	0.05±0.02 (0.06±0.02)	0.07±0.03 (0.05±0.01)

the spread in values of the relative populations.

The first major result is that the relative populations for decay from resonances with the three different spins are very similar. We made an effort to utilize the relative population of low-lying states with rather different spin-parity combinations in order to infer the spin of the resonance state. Contrary to the success of this method in heavy nuclei, the low-level population method was at best marginally successful. It certainly was not a reliable indicator of the resonance spins in ^{49}V. The relative populations are compared with statistical model calculations in the next section.

B. Comparison with Statistical Model Calculations

The experimental populations of the low-lying states in ^{49}V were compared with predictions of the statistical model code DICEBOX [7]. This code simulates the γ-ray cascade following resonance capture. The approach is to use the experimental information available for the low-lying states (up to some excitation energy), and to treat the higher energy region (up to the resonance energy) in a purely statistical manner using Monte Carlo techniques.

The basic assumptions of the model may be summarized. (1) Below some critical energy E_c there is a full set of experimentally measured levels, including energy E, spin and parity J^π, and all branching ratios. (2) The energy levels above E_c follow a known level density $\rho(E,J^\pi)$. (3) In the energy region above E_c the partial radiation width Γ_{ab} for transitions from a to b is a random quantity

$$\Gamma_{ab} = \sum_{XL} y_{XL}^2 \, (E_a - E_b)^{2L+1} \, \frac{S_\gamma^{XL}(E_a - E_b)}{\rho(E_a, J_a^{\pi_a})}. \tag{1}$$

$S_\gamma^{XL}(E_\gamma)$ is the radiative strength function for a class X (electric or magnetic) and multipolarity L. The summation is over the relevant contributing terms. In practice these are $E1$, $M1$, and $E2$ in order of (generally) very rapidly decreasing importance. (At low photon energies – on the tails of the giant resonances – there may be exceptions to this general rule.) The quantity y_{XL} is a random number obeying a standard normal distribution; this provides the Porter-Thomas fluctuations for the partial widths. (4) The partial widths are not correlated. (5) Each decay starts from one initial level with known energy, spin, and parity.

The actual procedure is governed by an algorithm that uses a Monte-Carlo procedure to generate a complete description of one cascade. This process is then repeated many times. The average relative populations of the low-lying levels are determined. Other interesting quantities such as the multiplicity are also calculated.

Of course the results (such as the relative population of low-lying levels that is immediate interest here) depend on the assumed level density models and on the models for the radiative strength functions. Space limitations prevent a detailed description of these models. All of the standard models are available. The parameters that we adopted were chosen to agree with the best available information for this mass region.

In Figure 1 the measured relative populations of the low-lying levels are compared with DICEBOX predictions. It is evident that there is no quantitative agreement. However, the model predictions are correct in a qualitative sense – the states that are strongly (weakly) populated experimentally are predicted to be strongly (weakly) populated by the model. Attempts were made to adjust the relative populations by varying the input parameters such as the radiative strength functions. Even large variations lead to rather small changes in the relative populations. This was disappointing, since one motivation for such measurements is to provide information concerning the radiative strength functions. It is also somewhat surprising since in heavier nuclei the capture spectra show more sensitivity to changes in the radiative strength functions. The model calculations did show significant variation in the relative populations of the low-lying states with changes in resonance spin, but this was not observed in the experimental data.

IV. SUMMARY AND CONCLUSIONS

Capture spectra were measured with a Compton-suppressed HPGe detector for 27 compound nuclear resonances in ^{49}V with known spin and parity. A total of ten $1/2^+$ resonances, nine $1/2^-$ resonances, and eight $3/2^-$ resonances were studied. The relative populations of 10 of the first 12 excited states were measured. To reduce the effects of statistical fluctuations, the average relative populations were determined for each of the

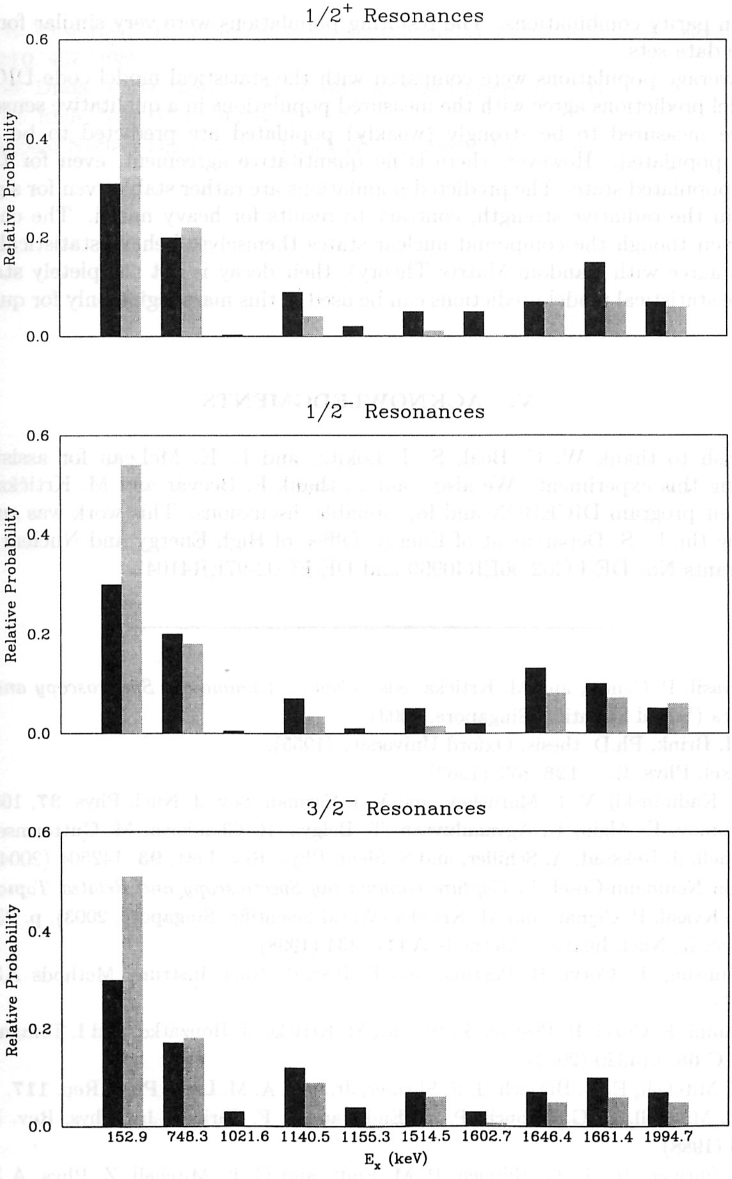

FIG. 1: Experimental relative probabilities (black) and DICEBOX predictions (gray) for ten low-lying levels in ^{49}V.

three spin-parity combinations. The resulting populations were very similar for each of the three data sets.

The average populations were compared with the statistical model code DICEBOX. The model predictions agree with the measured populations in a qualitative sense: states that were measured to be strongly (weakly) populated are predicted to be strongly (weakly) populated. However, there is no quantitative agreement, even for the most strongly populated state. The predicted populations are rather stable even for significant changes in the radiative strength, contrary to results for heavy nuclei. The conclusion is that even though the compound nuclear states themselves behave statistically (level statistics agree with Random Matrix Theory), their decay is not completely statistical. Therefore statistical model predictions can be used in this mass region only for qualitative purposes.

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