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EVIDENCE FOR A SECONDARY DOORWAY STATE
IN A = 13 NUCLEI FROM UNPOLARIZED AND
POLARIZED CAPTURE MEASUREMENTS

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ABSTRACT

Cross section, angular distribution, and analyzing-power measurements show structure and interference effects in neutron, proton, and deuteron capture into the $A=13$ system at about 20-MeV excitation energy. By introducing a secondary doorway state at 20.6 MeV with a 0.5-MeV width it is possible to explain the shape of the $^{12}\text{C}(n,\gamma_0)^{13}\text{C}$ and $^{12}\text{C}(p,\gamma_0)^{13}\text{N}$ cross sections as well as the fluctuations observed in the experimental angular distributions and analyzing powers.

1. INTRODUCTION

Angular distributions of nucleon capture gamma rays typically vary slowly with energy throughout the region of the Giant Dipole Resonance (GDR). A simple model, known as the Direct Semidirect (DSD) Model, is generally successful in predicting angular distributions for a wide variety of nucleon capture situations ranging from ground state capture to capture to highly excited states. This has led to the conclusion that the angular distributions--fixed by the complex s-to-d-wave ratio--are determined mainly by the geometry of the nuclear potential.

Structures a few hundred kilovolts wide have been observed superimposed on the primary GDR states. These structures have been observed to be correlated with resonances in the photoreaction cross sections of more complex particles--such as those for (d,γ_0) or (α,γ_0) --and there is evidence that these more complex secondary doorways can interfere with

the primary doorway to produce structure observed in the cross sections, angular distributions and analyzing powers.¹

We have observed an excursion in the a_2 Legendre coefficient (defined below) from the DSD value to near zero and back in the excitation energy region about ~ 20 MeV in both the $^{12}\text{C}(p, \gamma_0)^{13}\text{N}$ and mirror $^{12}\text{C}(n, \gamma_0)^{13}\text{C}$ reactions.² The case for the neutron reaction is shown in Fig. 1. Correlation of this effect with structure in the $^{11}\text{B}(d, \gamma_0)^{13}\text{C}$ excitation function, also shown in Fig. 1, has led us to infer the presence of a primary-secondary doorway state interference and subsequent measurement of the analyzing powers for the $^{12}\text{C}(n, \gamma_0)^{13}\text{C}$ reaction have substantiated this interpretation.

2. EXPERIMENTAL DETAILS AND DATA ANALYSIS

The polarized neutron capture measurements reported here were made using the Triangle Universities Nuclear Laboratory (TUNL) polarized neutron capture facility. A published account describing this facility is pending³ so only the briefest account of the analyzing power measurement will be given. A pulsed beam of deuterons polarized in the $M=1$ ($P_z = P_{zz} = 0.7$) state was incident upon a cell containing deuterium gas. The polarization of the deuteron beam was transferred to the neutrons via the $^2\text{H}(d, n)^3\text{He}$ reaction to produce the polarized neutron beam. The normalization from run to run was made using charge collected in the gas cell and checked using a proton recoil monitor located at 0° .

The gamma rays from the $^{12}\text{C}(n, \gamma_0)^{13}\text{C}$ reaction were detected in two 25.4×25.4 cm NaI spectrometers employing plastic anticoincidence shields. The resolution was better than 3% for 20 MeV gamma rays. Background was reduced further by demanding a ~ 2 ns-wide time correlation with the pulsed incident beam. Systematic errors in beam polarization were reduced by locating the 2 spectrometers at $\pm \theta$ with respect to the beam. The gamma ray spectra were reduced using standard computer techniques and the resulting angular distributions and analyzing powers were fit to the following equations:

$$\sigma(\theta) = A_0 [1 + a_1 P_1(\cos\theta) + a_2 P_2(\cos\theta)] \quad (1)$$

for angular distributions, and

$$\frac{\sigma(\theta) A_y(\sigma)}{A_0} = b_1 P_1^1(\cos\theta) + b_2 P_2^1(\cos\theta) \quad (2)$$

for analyzing powers.

The coefficients a_1 and b_1 are expected to be small for neutron capture in this energy range and this was corroborated by measurements at several energies. For energies where not enough data were taken to determine a_1 and b_1 they were assumed to be zero.

3. DISCUSSION

In the context of the nuclear shell model, where the ^{13}C ground state $|0\rangle$ is $|1p-0h\rangle$, the giant dipole resonance primary states $|1\rangle$ will be $|2p-1h\rangle$ in character. We have assumed the existence of a secondary doorway state, $|2\rangle$, which has a large $|3p-2h\rangle$ component [because of its propensity to emit deuterons, e.g. Fig. 1 (a)]. Furthermore, we have assumed that this secondary state has no photon width of its own. Thus, the state $|2\rangle$ photon decays through the primary state $|1\rangle$ via a coupling interaction V . In this case, the correlation is seen between isospin-allowed reactions and so the coupling interaction between these primary and secondary doorways of the same isospin will be dominated by the strong force. The proximity of

Fig. 1 (a) The $^{11}\text{B}(d,\gamma_0)^{13}\text{C}$ 90° cross section from Ref. 4. (b) The $4\pi A_0$ cross section for the $^{13}\text{C}(\gamma,n_0)^{12}\text{C}$ reaction of Ref. 5 is shown with bars, where the values of Ref. 5 have been multiplied by 0.7 (see Ref. 3). The solid points with error bars are the cross sections obtained using time-reversal invariance from the present $^{12}\text{C}(n,\gamma_0)^{13}\text{C}$ measurement. The dashed line is a background subtracted from the data before fitting. (c) The a_2 coefficient from Ref. 5 is shown with bars. The solid dots with error bars are from the present measurement. (d) The b_2 coefficient from the present $^{12}\text{C}(n,\gamma_0)^{13}\text{C}$ analyzing power measurements are shown.

The solid curves in (b), (c) and (d) represent the fit to Eq. (3).

Figure 1.

these states to each other allows them to interfere thereby giving rise to the asymmetry in the $^{13}\text{C}(\gamma, n_0)^{12}\text{C}$ cross section peak at ~ 20.5 MeV and the structure in the a_2 and b_2 coefficients. The following analysis, which allows for determination of the interaction strength V between doorway states of different orders, should therefore provide insight into the nuclear potential of a complex nucleus.

To test the hypothesis that a secondary doorway state was responsible for the observed structure in a_2 , we used the form for the T-matrix¹:

$$T_L = \frac{\exp(i\phi_1^L) g_1^\gamma g_1^L (E - E_2 + i\frac{\Gamma_2}{2}) + g_1^\gamma g_2^L \exp(-i\eta^L) V}{(E - E_1 + i\frac{\Gamma_1}{2}) (E - E_2 + i\frac{\Gamma_2}{2}) - V^2} \quad (3)$$

where

- $(g_1^\gamma)^2$ = gamma-decay width for the primary state
- $(g_1^L)^2$ = neutron-decay width for the primary state
- $(g_2^L)^2$ = neutron-decay width for the secondary state

This equation can be derived from the two level formula for interfering Breit-Wigner resonances assuming that $g_2^\gamma = 0$ and that V is real.

In terms of these T-matrices, the A_0 , a_2 and b_2 coefficients of Eqs. (1) and (2) are

$$4\pi A_0 = s^2 + d^2 \quad (4)$$

$$A_0 a_2 = \frac{-d^2}{2} - \sqrt{2} \, sd \cos(\phi_d - \phi_s) \quad (5)$$

$$A_0 b_2 = \frac{sd}{\sqrt{2}} \sin(\phi_d - \phi_s) \quad (6)$$

with

$$se^{i\phi_s} = \frac{\sqrt{\pi}}{k_n^2} T_s$$

and

$$de^{i\phi_d} = \frac{\sqrt{\pi}}{k_n^2} 2 T_d$$

The equation for the T-matrix was used to fit the data of Fig. 1 using a least-squares criterion. The resulting fits are shown by the solid lines. An excellent description of the data was obtained.

The parameters of Eq. (3) obtained in the fit are given in Table I. These are quite consistent with the positions of the structures seen in the cross sections--particularly if allowance is made for the proximity of the resonance in the (d, γ_0) reaction resonance to the Coulomb barrier. It is observed that not all the parameters are independent.^{1,3}

Table I. Parameters for the $^{13}\text{C}(\gamma, n_0)^{12}\text{C}$ reaction determined by least-squares fitting of experimental data shown in Fig. 1 with Eq. (3).

	Primary Doorway	Secondary Doorway
E_i	21.05 MeV	20.52 MeV
Γ_i	4.2 MeV	.51 MeV
$g_i^\gamma g_i^s$	5.9 keV	8.6 keV
$g_i^\gamma g_i^d$	12.8 keV	26.9 keV
ϕ_s	0.°	118.0°
ϕ_d	341.°	342.2°
$V = 720 \text{ keV}$		

To see if our value for V was reasonable, we calculated typical values for the coupling matrix between $|2p-1h\rangle$ and $|3p-2h\rangle$ states. For example

$$\langle p_{1/2} d_{5/2} (J_1) p_{3/2}^{-1} (1/2) | V | [p_{1/2}^2 (J_2) d_{3/2}]^J p_{3/2}^{-2} (J_h) (1/2) \rangle = 910 \text{ keV},$$

where two-particle shell-model matrix elements from Kuo and Brown based on the Hamada-Johnston nucleon-nucleon potential were used. In general, the value for all relevant configurations is of order 1.0 MeV. Thus, we see that the data appear consistent with what one would expect for a typical $2p1h-3p2h$ matrix element as a result of the strong force.

4. CONCLUSIONS

From the present work we have concluded that 1) inclusion of a secondary doorway accounts for the features in the $^{12}\text{C}(n,\gamma_0)^{13}\text{C}$ cross section and angular distribution. The same model with only slightly different nucleon decay widths (but all other parameters as for the neutron case) describes the $^{12}\text{C}(p,\gamma_0)^{13}\text{N}$ data; 2) Analyzing powers measured for the $^{12}\text{C}(n,\gamma_0)$ reaction are also well described. $^{12}\text{C}(p,\gamma_0)$ measurements have not been performed for this energy range; 3) The coupling interaction between these two states is (720 ± 200) keV; 4) Measurements of the $^{11}\text{B}(d,\gamma_0)^{13}\text{C}$ reaction would allow further development of this picture.

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