Search for a giant resonance built on the 16.6-MeV state in ^{8}Be

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The yield curve for proton capture on ^{7}Li, leading to the region of the isospin-mixed pair of states at $E_x = 16.63$ and 16.92 MeV in ^{8}Be, has been measured as a function of bombarding energy from 4 to 30 MeV. A direct capture model provides a good description of the data.

NUCLEAR REACTIONS ^{7}Li$(p,\gamma)^8$Be$^* \to 2\alpha$; measured $\sigma(E,\theta)$ leading to the 16.6–16.9-MeV states for $E_p = 11.5$ to 30 MeV by γ-ray detection. Measured $\sigma(E)$ for $E_p = 4$ to 13 MeV by detection of 2α. Natural target. Compared to direct capture model.

Proton capture reactions have consistently exhibited a large and broad resonancelike effect in the cross section as a function of energy for nuclei throughout the periodic table. This resonance has been shown to decay by the emission of $E1$ photons and has been identified as the giant dipole resonance (GDR). The peak of the GDR built on the low lying states of light nuclei occurs at an excitation energy of 20–25 MeV above these states. This paper reports the results of a proton capture experiment where the final state in the capture process is itself a highly excited state. In particular, we have measured a yield curve for proton capture on ^{7}Li leading to the region of ^{8}Be which contains the pair of well-known isospin-mixed 2^+ states at 16.63 and 16.92 MeV in ^{8}Be. The resolution of our detector system did not allow a separation of these levels, and we denote this reaction as ^{7}Li$(p,\gamma_{16})^8$Be*.

Related work, initiated by Blatt and co-workers at Ohio State and Indiana University, has been performed for the reaction ^{11}B$(p,\gamma_{19})^{12}$C*, where the final state is a highly excited state, or states, at about 19 MeV in ^{12}C. These states are unbound to single-particle decay. Preliminary results, which suggest a GDR built on the 19-MeV states, have been reported.[1] However, Arnold[2] has suggested that the observed strength leading to the 19-MeV region of ^{12}C might be the result of direct capture to states having the configuration $(d_{5/2}p_{3/2}^{-1})$. Tsai and Londergan[3] performed a direct capture calculation which included effects of residual two-nucleon interactions but treated the final state as a bound state. Following this, Halderson and Philpott[4] performed a direct capture calculation which treated the final state properly as a continuum state. They concluded that direct capture could account for the major features of the data.

The ^{7}Li$(p,\gamma_{16})^8$Be reaction differs from the ^{11}B$(p,\gamma_{19})^{12}$C case in several important respects. First, the final state is bound for proton emission so that the direct capture calculations should be more straightforward. Secondly, as will be seen below, the peak in the yield curve as calculated with the direct capture model is not near the energy at which a GDR built on the final state in ^{8}Be would be expected to occur. The ^{7}Li(p,γ_{16}) reaction therefore appears to be a more favorable case to examine for evidence of a giant resonance built on a highly excited state as well as to test direct capture theory.

The data reported in this paper were obtained with the TUNL NaI spectrometer, which has been described in detail elsewhere.[5] A pulsed beam was used to produce a time-of-flight spectrum for events detected in the NaI spectrometer. A window was set in this spectrum so that only events in the NaI detector which had the proper time relationship, corresponding to prompt γ rays from the target, were accepted. A sample γ-ray spectrum obtained with this system for protons on ^{7}Li is shown in Fig. 1. The spectrum shows capture to the ground and first excited states in ^{8}Be, and also shows a γ-ray peak, labeled ^{7}Li(p,γ_{16}), which corresponds to capture to the isospin-mixed pair at 16.63 and 16.92 MeV. Observation of the "γ_{16}" peak as a function of proton energy indicates that it is indeed a capture peak. The solid curve shown is the result of a γ-ray line shape fitting program,[6] which fitted simultaneously the various peaks shown. The standard γ-ray line shape was obtained from the ^{3}H(p,γ) reaction. For the γ_1 peak, the standard line shape was convoluted with a Lorentzian line shape, since the first excited state in

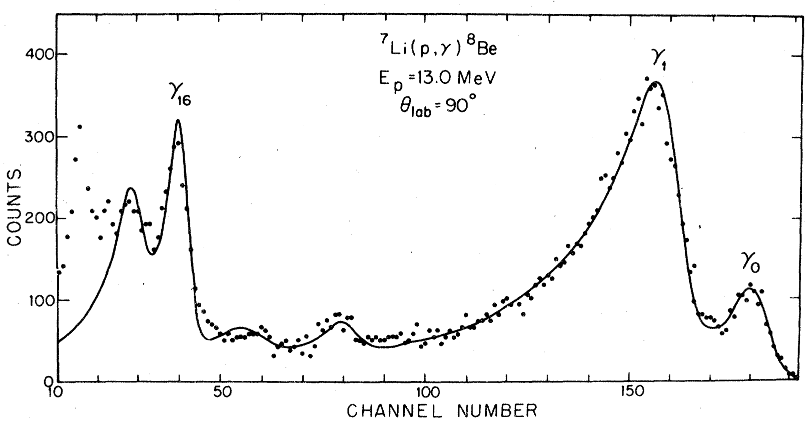

FIG. 1. γ-ray spectrum for proton capture on ^{7}Li. Solid curve is the result of a peak fitting program described in the text. The peak labeled γ_{16} corresponds to γ transitions to the 16.6–16.9-MeV levels of ^{8}Be.

^{8}Be has a large width (about 1.5 MeV). The γ_{16} yields have been extracted, using the fitting program, at all measured energies and angles from $E_p = 11.5$ to 30 MeV. The two small peaks above γ_{16} and the peak below γ_{16} are contaminant peaks and were fitted only to help construct the background under the γ_{16} peak.

The absolute cross sections were based on the NaI detector efficiency which was determined near 15 MeV by measuring the ^{12}C(p,γ_0) thick target (50 keV for 14.2-MeV protons) yield curve over the 15.07 resonance in ^{13}N and comparing to a previous measurement of the number of γ rays per proton.[7] The extrapolation of the efficiency as a function of energy was obtained as described in Ref. 8. The Li targets used in the present work were made by pressing Li metal. The thicknesses of these targets were determined by measuring the ^{7}Li(p, γ_0) yield relative to that obtained with a thin LiF target, whose thickness was measured by comparing with the proton scattering data of Gleyvod *et al.*[9] Proton monitors were used at all times to measure the stability of the target. The ^{7}Li(p, γ_0) absolute cross sections extracted in this manner are in good agreement with those of the Stanford data.[10] However, the ^{7}Li(p, γ_1) absolute cross section is only about 60% of the Stanford results. The absolute cross section for the ^{7}Li(p, γ_{16}) reaction obtained by the above method is estimated to be uncertain by about 25%. This includes an estimate of the errors introduced by the peak fitting procedure for γ_{16}.

An alternate measure of the ^{7}Li(p, γ_{16}) reaction was provided by an "α-α" coincidence experiment, which involved the observation in coincidence of the decay products of the final state in the capture reaction. This reaction was used to measure the cross section at five energies over the range of 4 to 13 MeV. Since both of the isospin-mixed states decay essentially 100% into two α particles, and since the capture process involving a single γ transition is the only likely way of populating these states, the measurement of the α-decay total cross section should be equal to the total capture cross section. (Feeding through cascades should be negligibly small since all higher levels are particle unstable.) A forward angle detector, set in the laboratory frame to correspond to the zero of $P_2(\cos\theta)$ in the center-of-mass system, observed one of the α particles, and a back angle detector was set at the kinematically determined angle to observe the second α particle in coincidence. Since measurements of polarized and unpolarized (p, γ_{16}) angular distributions for $E_p = 13$–30 MeV indicate that the γ transitions are predominantly $E1$,[11] the angular distribution of the α particles should contain only Legendre polynomials of order 0 and 2.[12] Therefore the differential cross section at the zero of P_2 is equal to the total angle-integrated cross section divided by 4π. Due to the unknown direction of the emitted γ ray, there was a spread in the angle and energy of the α particles, and the back angle detector was therefore provided with a larger solid angle to accept all of the back-scattered α particles. It was necessary to use a thin natural LiF target (250 μg/cm^2) to minimize the energy loss of the α particles, and this led to a rather low count rate. Due in part to poor statistics, the absolute cross section obtained here had an uncertainty of about 20%. More details of this experiment are described elsewhere.[11]

The 90° yield curve for ^{7}Li(p, γ_{16}) from $E_p = 4$–30 MeV is shown in Fig. 2. The $\times$'s represent the results of the α-α experiment, converted to $\sigma(90°)$ using the angular distributions calculated from the direct model. (Based on γ-ray angular distributions measured at higher energies, the direct model is quite reliable.[11,13]) The solid dots represent the (p, γ) data. At 13 MeV, where the data overlap, the cross sections obtained by the two methods differed by slightly more than the estimated errors. The absolute

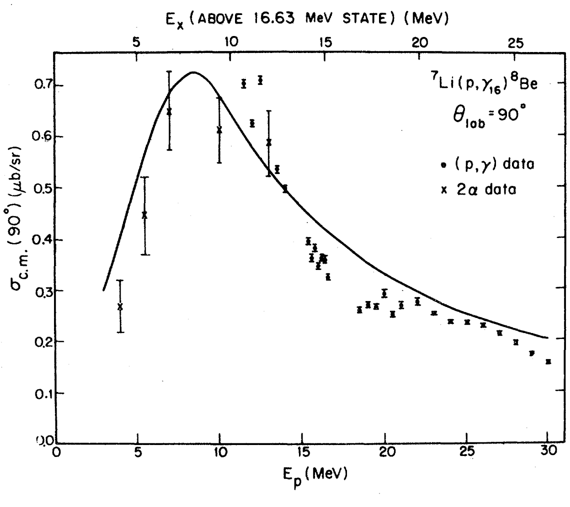

FIG. 2. 90° yield curve for $^7Li(p,\gamma_{16})^8Be^*$. The solid curve is the result of the direct capture calculation. The error bars represent the statistical errors associated with the data points.

yield shown in Fig. 2 was obtained by averaging the results of the two methods and has an estimated uncertainty of ±30%. The energy regions where no (p,γ) data are shown, in the vicinity of 18 and 15 MeV and below 11.5 MeV, were due to the presence of contaminants in the γ-ray spectra which made it impossible to extract the γ_{16} yield. Particular contaminants observed were from $^{12}C(p,p'\gamma)$ reactions giving 15.11- and 12.71-MeV γ rays. The data for $^7Li(p,\gamma_{16})$ show a relatively smooth energy dependence throughout the region measured, with a broad resonancelike peak in the vicinity of $E_p \approx 8 \pm 2$ MeV. However, this peak occurs at an excitation energy of 25 MeV in ^8Be, which is only about 8 MeV above the final states at about 16 MeV. This is not the expected peak position for a GDR. The angle and energy integrated yield, converting to a (γ,p) cross section by detailed balance, exhausts about 8.6% of the classical dipole sum (120 MeV mb for ^8Be) for E_p from 4 to 30 MeV. This is about half of that exhausted by the GDR's built on the ground and first excited states in ^8Be.[10]

The direct capture calculation in the case of electric transitions of multipolarity L involves the computation of radial matrix elements given by

$$\left\langle u(r) \left| \frac{d}{dr}[rj_L(kr)] \right| \chi(r) \right\rangle ,$$

where the electric operators have been written in the form given by employing Siegert's theorem.[14] The radial wave function $u(r)$ represents the final bound state of the captured single particle, while $\chi(r)$ is the radial wave function for a given partial wave of the initial continuum state consisting of an incident nucleon in the optical model potential of the target. The expression used to compute the cross section from the matrix elements was taken from Ref. 13, including the statistical factor necessary to account for the spin of the target.

The final states at 16.63 and 16.92 MeV were described in terms of two single-particle components $p_{3/2}$ and $p_{1/2}$. The radial wave functions for these single-particle states were obtained by adjusting a Woods-Saxon well to place a $p_{3/2}$ proton, and another well to place a $p_{1/2}$ proton, at the proper binding energies. The spectroscopic factors for these states were obtained from the coefficients of fractional parentage (cfp's) used by Sweeney and Marion,[12] as obtained from the shell model calculations of Barker.[15] These cfp's are in agreement with those of Cohen and Kurath.[16] The relationship $S = n\{\text{cfp}\}^2$ was used here, where n is the number of available nucleons in the shell. The values of the two spectroscopic factors for the $p_{3/2}$ and the $p_{1/2}$ components of the 16.63-MeV state, including the isospin Clebsch-Gordon coefficient (C), are $C^2S_{3/2} = 0.826$ and $C^2S_{1/2} = 0.114$, respectively. Since the proton spectroscopic factors for the 16.92-MeV state are negligibly small by comparison (this is a neutron state), they were set to zero. The energy dependent optical model potential of Watson *et al.*[17] was used to generate the incident radial wave functions.

The results of our $E1$ plus $E2$ direct calculation, normalized by a factor of 1.3, are shown as the solid curve in Fig. 2. The effect of including the direct $E2$ term is quite small. The agreement in shape is quite remarkable. In particular, the broad peak near 8 MeV is well described by the calculation. Furthermore,the absolute cross section of the calculation lies within the estimated error in the absolute cross section of the experimental data. This result is in marked contrast with direct calculations in a typical ground state GDR region, which normally give a cross section about 5–10 times smaller than the data.

We therefore conclude that a simple direct capture model is quite sufficient to describe the data for the $^7Li(p,\gamma_{16})$ reaction. Additionally, a strong peak in the yield curve is not seen at the expected position of a GDR. The absence of a GDR, if true, would be in violation of the Brink hypothesis,[18] which states that a GDR should be formed on every state (with some single-particle strength) regardless of its detailed nature. The yield curve does, in fact, give some suggestion of a weak, broad peak from 20–30 MeV, sitting on the direct background. We have performed direct-semidirect (DSD) calculations,[19] which indicate that if a peak is present at 25 MeV, it must have a width of at least 20 MeV to be consistent with the data. The single-particle escape mechanisms should give the largest contribution to the GDR width in light nuclei.[20] Since d-wave capture dominates in these light nuclei,[12,21] the energy dependence of the d-wave proton penetrabilities should give a rough estimate of the energy dependence of this width. This suggests a width of about 40 MeV for a GDR built on a state near 16 MeV in ^{8}Be. The DSD calculations indicate that such a broad resonance would be difficult to establish experimentally, both in the yield curve and in the angular distributions. In any case, there would seem to be little utility in calling such a broad effect a giant dipole resonance.

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