CONF-980672--

Measurement of the E1 strength function of ^{11}Be

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AUG 26 1998

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Abstract. We have investigated the E1 strength function of ^{11}Be by Coulomb excitation and measurement of the subsequent projectile photon decay. The photons were measured in a wall of BaF_2 detectors. We have used the virtual photon method to extract the photabsorption cross section and hence the dipole strength function. We compare our findings with sum rule predictions. This is a first example of techniques we will extend to heavier mass nuclei.

INTRODUCTION

An interesting question in the study of radioactive nuclei is how collective excitations, such as the giant dipole resonance (GDR), evolve as one moves away from β -stability. Various models have been used to explore this question. It has been suggested, for example, that the E1 strength of very neutron-rich nuclei could spread over a very wide energy region, and appear at energies lower than expected from the systematics of stable nuclei [1] [2].

The nucleus ^{11}Be is a single-neutron halo nucleus and has been widely studied, particularly its low-lying states and particle decay modes. The E1 strength at $E_x = 0.6 - 4$ MeV has been investigated through kinematic reconstruction following Coulomb dissociation [7]. However, this strength accounts only about 5% of the total TRK sum rule. Most of the E1 strength is expected to be located at higher excitation energies ($E_x > 8$ MeV). We extend the studies of the E1 strength distribution to the higher excitation energies.

Our experiment measures the photabsorption cross section of ^{11}Be by Coulomb excitation followed by photon-decay to the ground state. This process can be thought of as virtual photon scattering [8]. To select Coulomb excitation events, we detect particles only at very forward scattering angles, which selects large impact

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parameters. To identify the ground-state GDR γ -ray decays, we usually deduce the total excitation energy from the kinetic energy of the scattered particle, and match it with the energy of the emitted photon. In this case, simply detecting and identifying the scattered ^{11}Be projectile in coincidence with γ -rays is sufficient. This is because ^{11}Be has a neutron separation energy of only 504 keV, and only two bound states, the $1/2^+$ ground state and the $1/2^-$ 320 keV first excited state. Consequently, detection of scattered ^{11}Be implies that one of these two states was populated directly by photon decay following Coulomb excitation. The contribution of decays to the $1/2^-$ 320 keV state is not expected to be significant since E1 excitation and E1 decay dominate. Contributions from higher multipolarity excitations and decays are much smaller. Photon decays to unbound states will be followed by neutron decays, which will change the identity of the ^{11}Be projectile. Therefore, photons in coincidence with the ^{11}Be projectiles are predominately from ground-state GDR γ -ray decays, and photons from decays to the excited states, whether these states are bound or unbound, are strongly suppressed.

MEASUREMENT

The measurement was performed at the National Superconducting Cyclotron Laboratory of Michigan State University. A 100 MeV/nucleon ^{13}C beam from the K1200 cyclotron was used as a primary beam to produce ^{11}Be in the A1200 fragment separator with an energy of 77 MeV/nucleon, an average intensity of 10^6 pps, and a momentum spread of $\approx 3\%$.

Projectile-like particles, mostly ^{11}Be and ^{10}Be , were detected with the zero-degree detector from the MSU 4π array [10]. This detector consists of 8 E- Δ E plastic scintillators, and was mounted 1.35 meter away from target, subtending polar angles from 1.10° to 3.24° . Photons were measured using the 142 element ORNL-TAMU-MSU joint BaF_2 array, the elements of which were mostly $6.5\text{ cm} \times 20\text{ cm}$ hexagonal BaF_2 scintillators. In order to take advantage of the forward-focusing of the photons emitted from the projectile rest frame, these were arranged as a wall covering the polar angular range of 12° to 45° . An estimate of the ^{208}Pb photon yield was made by detecting photons with a small BaF_2 array at backward angles, where target photons dominate. Target-out yields were measured and subtracted from the data. The photon detectors were calibrated with discrete γ -rays up to 15.11 MeV.

In our analysis, only events with one photon, and no neutron in the BaF_2 array, and one particle detected were accepted. This criterion was chosen to enhance the ground state γ -ray decays from the ^{11}Be nucleus. Random coincidences were corrected by subtracting the data in which particles and γ -rays arose from different beam bursts.

In order to eliminate the background from the ^{10}Be component and continuum we used particle spectra gated by γ -rays with different energies. For the excitation energies below the neutron binding energy of ^{11}Be (504 keV), the separation between ^{10}Be and ^{11}Be is very good, where the 320 keV $1/2^- \rightarrow 1/2^+$ transition

in ^{11}Be dominates. The Coulomb excitation of the $1/2^-$ state has been studied at a range of bombarding energies [5] [6], and is in agreement with the $B(E1)$ from the lifetime measurements [3]. We used this transition to determine the absolute normalization for our data.

Unfortunately, at excitation energies between the thresholds of (γ, n) (504 keV) and $(\gamma, 2n)$ (8.73 MeV), photon spectra are dominated by the γ -rays from the daughter nucleus ^{10}Be . After being excited, almost all the ^{11}Be projectiles emit a neutron, and populate the bound states in ^{10}Be . The yield of photons from these states is much stronger than the yield of single photon decays to the ground state of ^{11}Be . It is very difficult to resolve ^{11}Be from ^{10}Be with the resolution of the present plastic scintillators.

At excitation energies well above the $(\gamma, 2n)$ threshold (8.73 MeV), the γ -ray branching ratio of ^{11}Be and ^{10}Be will be comparable. Therefore, compared to the lower excitation energy, the photon yields of ^{11}Be will increase relative to that of ^{10}Be .

The photon yields were unfolded from the data, using the simulated response of the BaF_2 detector array. The acceptance of the particle detector array was taken into account in the response calculation.

The absolute differential cross section is shown in Fig. 1a. The uncertainties shown are statistical.

We have estimated the ground-state decay contributions of the isoscalar GQR. It is at least one order of magnitude smaller than the contribution from the GDR. The results are shown in Fig. 1a. We have also studied contributions from hadronic excitation by comparing the cross sections for inelastic excitation with and without the nuclear interaction. Within the acceptance of our detector, the differences between the integrated cross sections of these calculations from 8 to 25 MeV are less than 1%.

PHOTO-ABSORPTION CROSS SECTIONS

Bertulani and Nathan [11] have related ground state γ -ray decays from the GDR following the Coulomb excitation to the elastic photon scattering with

$$\frac{d^2\sigma_\gamma}{d\Omega dE_\gamma}(E_\gamma) = \frac{1}{E_\gamma} \frac{dN_{E1}}{d\Omega}(E_\gamma) \sigma_{\gamma\gamma}(E_\gamma) \quad (1)$$

where N_{E1} is the $E1$ virtual photon number, and $\sigma_{\gamma\gamma}$ is the cross section of elastic photon scattering, which can be expressed in terms of the photo-absorption cross section $\sigma_{abs}(E_\gamma)$ as [12]

$$\sigma_{\gamma\gamma}(E_\gamma) = \frac{8\pi}{3} \left[\left| \frac{E_\gamma \sigma_{abs}(E_\gamma)}{4\pi\hbar c} \right|^2 + \left| \frac{E_\gamma^2}{2\pi^2\hbar c} P \int_0^\infty \frac{\sigma_{abs}(E'_\gamma) dE'_\gamma}{E_\gamma'^2 - E_\gamma^2} \right|^2 \right]. \quad (2)$$

FIGURE 1. Photon cross-sections of ^{11}Be . a) Cross section for ground state γ -decay following Coulomb excitation. The line is a calculation of the GQR contribution. b) The deduced cross section of photon elastic scattering. The line is the fitted result using Eq. 2. c) The unfolded photoabsorption cross section. The dashed lines are uncertainties.

The cross section $\sigma_{\gamma\gamma}$ of the elastic photon scattering is deduced from the measured yields of ground-state γ -ray decay according to the Eq. (1). Fig. 1b presents results for $\sigma_{\gamma\gamma}$.

Extracting the photo-absorption cross sections σ_{abs} from the $\sigma_{\gamma\gamma}$ requires us to invert Eq. (2). This is difficult, because of the infinite range of the integral in Eq. (2), and the finite energy range and discrete nature of the experimental data. We have developed a numerical procedure to solve this problem, in which we approximate $\sigma_{\gamma\gamma}$, the estimate σ_{abs} using on the first term of Eq. (2). Then the integral was evaluated, and used to make correction for the new guess. The procedure was repeated until the differences between the calculated and measured $\sigma_{\gamma\gamma}$ were small.

The solid line in Fig. 1c is the extracted photoabsorption cross section σ_{abs} . The dashed lines in Fig. 1c are an estimate of the uncertainties generated by a Monte Carlo technique.

We estimated that the effect of the low energy dipole strength [7] and the quasi-deuteron [13] above 30 MeV is small ($< 5\%$).

The energy resolution of these data prevent us from studying detailed structures in the GDR region, but the results show that the E1 strength distribution is spread from 8 MeV to 26 MeV, and shows few prominent features except a broad peak near the energy of the 10.59 MeV state in ^{11}Be and a rise near 14.5 MeV. This is qualitatively consistent with the Hartree-Fock calculations for neutron rich nuclei [1] [2]. Unfortunately, we know of no theoretical calculations for the GDR region of ^{11}Be .

Oscillator sum rules allow us to connect the observed strength distribution of col-

lective excitations with bulk and surface parameters of the nuclear medium (nucleus radius, symmetry energy, incompressibility etc.) [14]. Energy weighted moments of the photonuclear cross section defined by

$$\sigma_k = \int_0^\infty \sigma_{abs} E^k dE. \quad (3)$$

can be related to these sum rules [14]. We consider the moments σ_0 , σ_{-1} , σ_{-2} . The Thomas-Reiche-Kuhn (TRK) sum rule limits the integrated total cross section σ_0 , while the "bremsstrahlung weighted" cross section integral σ_{-1} can be related to a sum rule expression proportioned to the mean square charge radius of the nucleus [14]. The sum rule for the σ_{-2} moment can be shown to be proportional to the dipole polarizability of the nucleus [14]. Table 1 shows experimental values for the cross section moments integrated from 8 to 25 MeV compared with the sum rule limits evaluated [14] using experimental values [15] charge radius (assumed to be the same as ^9Be), and experimental constraints on the matter density distribution [16].

Our results shows that the total strength between 8 and 25 MeV exhausts 120% of the TRK sum rule. The total strength at 1 - 4 MeV in ref. [7] shown in Table 1 is only about 5% of the TRK sum rule. The E1 strength of halo nuclei at low excitation is presumably related to the extended distribution of the valence neutron. The observed low energy strength exhausts about 80% of the "cluster sum rule" [17] expected for a neutron weakly coupled to a ^{10}Be core.

The experimental value of the σ_{-1} is consistent with the corresponding sum rule [14] using the experimental [15] RMS charge radius $\sqrt{\langle r^2 \rangle} = 2.52$ fm. This suggests that the charge distribution for the ^{11}Be nucleus is similar to the one for the ^{10}Be core, and is consistent with the picture that ^{11}Be consists of a core plus a valence neutron.

The σ_{-2} moment should be particularly interesting in this case, since the corresponding sum rule is proportional to the nuclear dipole polarizability, which is extremely sensitive to nuclear surface properties. The Migdal estimate of the σ_{-2} sum rule, which ignores surface effects is [14] 0.11 mb MeV^{-1} . The sum rule limit given in Table 1 improves on the Migdal value by including surface effects in a leptodermous approximation using droplet model expressions [14]. This can be seen to increase the Migdal sum rule value by almost a factor of 5. It should not be expected that the leptodermous approximation would treat surface effects in a halo nucleus adequately. In fact, even the data integrated from 8-25 MeV exceeds the

TABLE 1. Comparison between the sum rules and the experimental values.

Moment	Calculated Sum Rule Limit	Experimental value	E=1-4MeV
σ_0 (MeV-mb)	152	$181 \pm (+23 -35)$	6.7
σ_{-1} (mb)	15.49	$11.4 \pm (+1.4 -2.2)$	4.7
σ_{-2} (MeV $^{-1}$ -mb)	0.484	$0.784 \pm (+0.095 -0.162)$	3.8

droplet model sum rule limit by 607. If the low energy contribution is added in, the data is almost an order of magnitude larger than the sum rule value!

SUMMARY

We have measured the E1 strength of ^{11}Be from 8.5 MeV to 25 MeV. The energy distribution is relatively flat, which is consistent with the theoretical expectation from the Hartree Fock calculations. The total cross section has exhausted ≈ 1.2 TRK sum rule. The experimental value of the σ_{-1} moment of the the distribution is about equal to the bremsstrahlung weighted sum rule when the low energy contributions are included. The measured σ_{-2} is much higher than corresponding sum rule estimates.

This measurement illustrates the potential usefulness of ground state γ -ray decay following projectile Coulomb excitation as a tool for study of the GDR of radioactive nuclei. More precise measurements could be made with more intense radioactive beams, using a high resolution spectrograph to identify and detect the scattered projectile. We believe it will be possible to apply this technique to systematically study the isospin dependence of the GDR strength distribution in unstable nuclei.

ACKNOWLEDGEMENTS

Research at the Oak Ridge National Laboratory is supported by the U.S. Department of Energy under contract number DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp This research was supported in part by an appointment to the Oak Ridge National Laboratory Postdoctoral Research Associates Program administrated jointly by the Oak Ridge National Laboratory and the Oak Ridge Institute for Science and Education.

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