Giant resonance excitation in the ^{27}Al(^{6}Li, ^{6}He)^{27}Si reaction at 93 MeV

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A giant resonance in ^{27}Si is observed in the excitation energy region of 10–18 MeV in the spin-isospin flip ^{27}Al(^{6}Li, ^{6}He)^{27}Si reaction. A microscopic distorted-wave Born approximation analysis using a G-matrix nucleon-nucleon force and a local energy approximation knockout exchange correction indicates multipolarities between $\lambda=3$ and $\lambda=5$ for the giant resonance.

NUCLEAR REACTIONS ^{27}Al(^{6}Li,^{6}He)^{27}Si, $E=93$ MeV; measured $d\sigma/d\Omega(\theta)$, low-lying states, giant resonance; DWBA analysis, deduced λ multipolarity.

The charge exchange reactions at intermediate energies have provided a considerable amount of new information on the isovector modes of excitation in nuclei. Especially noticeable is the progress made lately in understanding the $M1$ and Gamow-Teller giant resonances (GR) with the (p,n) reaction[1] and, to a lesser extent, with the (^{3}He,t) (Ref. 2) and (^{6}Li,^{6}He) (Ref. 3) reactions. Because of the state excitation selectivity associated with the double spin-isospin transfer, one would anticipate that the nuclear continuum should be much reduced in the (^{6}Li,^{6}He) reaction as compared to the (p,n) and (^{3}He,t) reactions. This feature makes this reaction rather appealing for studying new isovector giant resonances at high excitation energies, where the underlying continuum becomes important in the other reactions.

We measured the ^{27}Al(^{6}Li,^{6}He)^{27}Si reaction at the Lawrence Berkeley 88 inch Cyclotron using a beam of 93 MeV ^{6}Li^{++}. The target was a self-supporting aluminum foil of 1.5 mg/cm^2. A magnetic spectrometer was used to detect and identify the emerging particles. The detector arrangement at the focal plane consisted of a plastic scintillator measuring the time of flight and the range parameter of the particles, a position sensitive wire chamber, and an ionization chamber measuring the stopping power. A more detailed description of the magnetic spectrometer and the related detection system can be found elsewhere.[4] Spectra were taken at five angles between 2° and 9° in the laboratory system with an average energy resolution of 0.4 MeV. For all but the 2° data, an external Faraday cup was used for charge collection. To take data at 2°, the Faraday cup had to be removed, and the charge collection was inferred from a solid state monitor mounted inside the scattering chamber. Because of a high singles count rate in the monitor, a systematic error of $\sim\pm 25\%$ was estimated for the data point at 2°.

Figure 1 shows the ^{27}Al(^{6}Li,^{6}He)^{27}Si energy spectrum taken at $\theta_{\rm lab}=3°$. This spectrum is composed of two segments obtained using two different spectrometer settings. A large overlap region between the two segments ensures the proper cross normalization. Besides the low-lying discrete state (or groups of states), a pronounced resonancelike structure is observed. The full width at half maximum (FWHM) of the structure is ~ 10 MeV. Unlike the (p,n) reaction at low energy or the (^{3}He,t) reaction, the continuum is small. In fact, another segment of spectrum taken at a higher excitation energy region having much less statistics showed that the cross section continues to fall, and becomes very small. For this reason, we have not subtracted any background for the cross sections analyzed here.

From the experience of previous studies[3,5] it is known that the (^{6}Li,^{6}He) transitions generally emphasize the lower orbital angular momentum transfers. Our experimental data seem to indicate that the transition to the GR is dominated by a rather large orbital angular momentum transfer. It then appears interesting to investigate whether the GR itself is characterized by a high angular momentum, perhaps larger than that which the sd shells can provide.

In order to ascertain more quantitatively the mul-

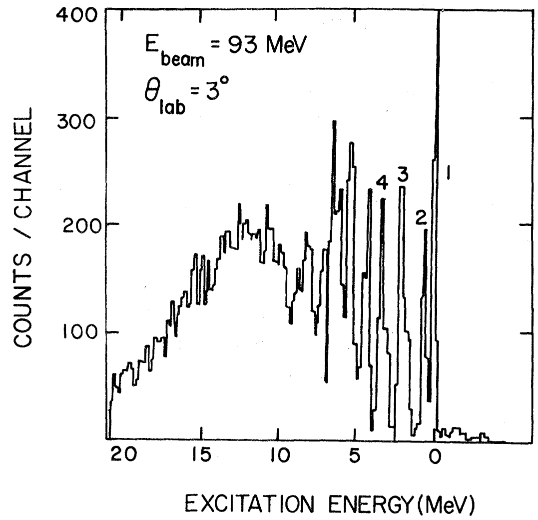

FIG. 1. Energy spectrum of the $^{27}Al(^6Li,^6He)^{27}Si$ reaction at $E(^6Li)=93$ MeV. The figure shows a virtually nonexistent continuum background under the GR situated in the excitation energy region 10–18 MeV.

tipolarity assignment in the GR region, we performed microscopic DWBA calculations for the transitions to several low-lying states of the ^{27}Si nucleus. Although more difficult than for the (p,n) reactions, such calculations can still be done quite comfortably for the $(^6Li,^6He)$ reaction, provided the sequential contributions are small. Since our theoretical framework has been discussed in detail elsewhere,[6] here we will only outline some of the main features of the calculations.

It is known that the ground states of both ^6Li and ^6He nuclei are described by a zero internal orbital angular momentum. This allows a factorization of their wave functions into an $L=0$ spatial part and an $(S,T)=(1,0)$ or $(0,1)$ spin-isospin part. We assume an α-d (nn) clustering of the $^6Li(^6He)$ nuclei for which good wave functions are available in the literature.[7] The alpha cluster is thought of as a spectator during the reaction. This is a rather reasonable assumption if the $(^6Li,^6He)$ reaction proceeds mainly via a quasielastic process. This process has been proven to work rather well in the past.[3,5,6]

The detailed representation of the nucleon-nucleon (N-N) interaction always poses problems in microscopic nuclear studies, bringing along a certain amount of uncertainty. For projectile energies below 65 MeV per nucleon, it has lately become popular to use effective N-N interactions derived from realistic internucleon potentials via the intermediary of the G matrix elements in a harmonic oscillator basis.[8] Although such reaction calculations often need substantial readjustments, they seem more consistent with the spirit of the microscopic analysis than others and therefore will be adopted here.

The N-N interaction which we used, called M3Y by Love,[8] consists of a sum of several Yukawa central and $r^2\cdot$ Yukawa tensor terms. Obviously, since our $(^6Li,^6He)$ transitions are characterized by a double spin-isospin flip, we have only retained the $(\hat{\sigma}\cdot\hat{\sigma})(\hat{\tau}\cdot\hat{\tau})$ central and the $(\hat{\tau}\cdot\hat{\tau})$ tensor components of the M3Y interaction. The spin-orbit interaction component has been dropped since it was not available in the DWUCK4 computer code[9] which we used. Furthermore, previous studies[6] of the $(^6Li,^6He)$ reaction suggest that the spin-orbit interaction may be neglected. The knockout exchange contribution of the central interaction was simulated with a zero-range LEA potential,[10] recalibrated by comparison with plane-wave Born approximation (PWBA) $(^6Li,^6He)$ exact exchange calculations.[11] A serious source of uncertainty is the absence in our calculations of such an exchange correction to the tensor part of the N-N interaction.

The DWBA formalism requires one to fold the N-N interaction into the intrinsic wave functions of the projectile and ejectile nuclei. In our case, this results in a rather complicated pseudopotential acting between the projectile (ejectile) center of mass and the target (residual nucleus) nucleons. In order to reduce the computing time, the exact radial parts of this pseudopotential were conveniently expressed in terms of other functions. Thus, the exact central direct (D) and exchange (E) terms were expanded in the polynomial-Gaussian forms

$$V^{D(E)}(r)=\sum_{m=1}^{2} e^{-A_m^{D(E)}r^2}\sum_{n=0}^{3} B_{mn}^{D(E)}r^{2n} , \quad (1)$$

where $r=|\vec{r}_i-\vec{R}|$ is the distance of a target nucleon i from the c.m. of the projectile. The following χ^2-fitted parameters were obtained with an accuracy better than 2% for values of r up to 17 fm:

$$A_1^D=2.0737\times10^{-1} ,\ A_2^D=4.4057\times10^{-2} ,$$

$$B_{10}^D=1.7295\times10^{0} ,\ B_{11}^D=5.5318\times10^{-1} ,\ B_{12}^D=-1.3583\times10^{-2} ,\ B_{13}^D=7.9935\times10^{-4} ,$$

$$B_{20}^D=2.1817\times10^{-1} ,\ B_{21}^D=-2.8233\times10^{-3} ,\ B_{22}^D=1.5002\times10^{-5} ,\ B_{23}^D=-5.3440\times10^{-12} ,$$

$$A_1^E=2.3940\times10^{-1} ,\ A_2^E=1.2911\times10^{-1} ,$$

$$B_{10}^E=-2.0528\times10^1\ ,\quad B_{11}^E=-1.9936\times10^0\ ,\quad B_{12}^E=-2.5116\times10^{-2}\ ,\quad B_{13}^E=-2.4334\times10^{-3}\ ,$$

$$B_{20}^E=1.9871\times10^1\ ,\quad B_{21}^E=-7.2841\times10^{-1}\ ,\quad B_{22}^E=9.1114\times10^{-3}\ ,\quad B_{23}^E=-4.1819\times10^{-5}\ .$$

Each term in Eq. (1) has the following multipole expansion:

$$\begin{aligned}V_m(r)=4\pi e^{-A_m(r_i^2+R^2)}\sum_\lambda (Y^\lambda(\hat r_i)\cdot Y^\lambda(\hat R))\\
&\times\{i^{-\lambda}j_\lambda(2iA_m r_i R)[B_{m0}-\lambda B_{m1}/A_m+\lambda(\lambda-1)B_{m2}/A_m{}^2-\lambda(\lambda-1)(\lambda-2)B_{m3}/A_m{}^3\\
&\quad+[B_{m1}-2\lambda B_{m2}/A_m+3\lambda(\lambda-1)B_{m3}/A_m{}^2](r_i{}^2+R^2)+(B_{m2}-3\lambda B_{m3}/A_m)(r_i{}^2+R^2)^2\\
&\quad+B_{m3}(r_i{}^2+R^2)^3+3B_{m3}(2r_iR)^2(r_i{}^2+R^2)+[B_{m2}-(\lambda-2)B_{m3}/A_m](2r_iR)^2]\\
&-i^{-\lambda-1}j_{\lambda+1}(2iA_m r_i R)[B_{m3}(2r_iR)^3+[B_{m1}+2B_{m2}/A_m+(\lambda^2+\lambda+6)B_{m3}/A_m{}^2](2r_iR)\\
&\quad+3B_{m3}(2r_iR)(r_i{}^2+R^2)^2+(2B_{m2}+6B_{m3}/A_m)(r_i{}^2+R^2)]\}\ ,\end{aligned}\tag{2}$$

where $i^{-\lambda}j_\lambda(ix)$ is the modified spherical Bessel function of the first kind, which was readily implemented in DWUCK4.

The spatial part of the $r^2\cdot$ Yukawa tensor pseudopotential was expanded in terms of the regularized OPEP tensor forms,

$$V^T(r)=\sum_{m=1}^{2} C_m[h_2^{(1)}(iD_m r)-(E_m/D_m)^3 h_2^{(1)}(iE_m r)]\ ,\tag{3}$$

where $h_2^{(1)}(ix)$ is the modified spherical Bessel function of the third kind, which the code DWUCK4 can handle without any modification. The following χ^2-fitted parameters were obtained with an accuracy better than 7% for interaction radii between $r=3.5$ and 12 fm:

$$C_1=1.427\,37\times10^4\ ,\quad C_2=-2.478\,04\times10^3\ ,$$

$$D_1=9.351\times10^{-1}\ ,\quad D_2=8.855\times10^{-1}\ ,$$

$$E_1=9.653\times10^{-1}\ ,\quad E_2=1.035\times10^0\ .$$

The distorted wave functions were calculated using the optical model parameters from Ref. 12. The same ^{6}Li optical parameters were used for both the entrance and exit channels of the (^{6}Li,^{6}He) reaction. The sensitivity of the calculations to the optical parameters of the outgoing channel was tested. Rather drastic changes in the outgoing channel optical parameters caused just a few percent changes in the cross section.

The nucleon orbitals of the target (residual) nucleus were generated in a Woods-Saxon well with a radius $r_0=1.25$ fm, diffuseness $a=0.65$ fm, and a spin orbit coupling constant of 25 times the Thomas term. The Coulomb potential for a uniformly charged sphere of radius $r_C=1.25A^{1/3}$ fm was included for the proton wave functions.

It is known that the simple nuclear models encounter difficulties in describing the properties of the mass $A=27$ nuclei. However, we present here mainly the results assuming a strong coupling Nilsson model since a more sophisticated shell model description[13] based on the sd orbits did not make too much difference.

In order to calibrate our DWBA calculations, we first studied the transitions to the following low-lying states of ^{27}Si shown in Fig. 1:

(1) g.s. $\frac{5}{2}^+$ ($\frac{5}{2}^+$[202]) ,

(2) 0.78 MeV $\frac{1}{2}^+$ plus 0.96 MeV $\frac{3}{2}^+$ ($\frac{1}{2}^+$[211]) ,

(3) 2.16 MeV $\frac{7}{2}^+$ ($\frac{5}{2}^+$[202]) ,

and

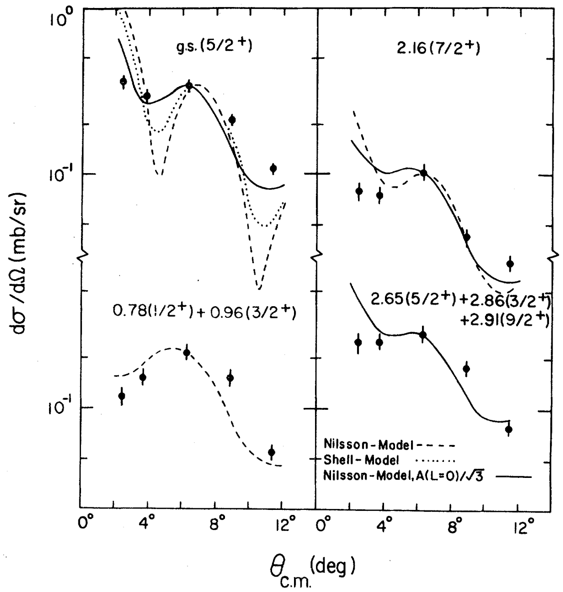

FIG. 2. DWBA microscopic calculations of angular distributions corresponding to (^{6}Li,^{6}He) transitions leading to low-lying states in ^{27}Si. Except for an arbitrary factor of $\sim 1/\sqrt{3}$, necessary to adjust the $L=0$ transition amplitudes, the calculations are parameter-free.

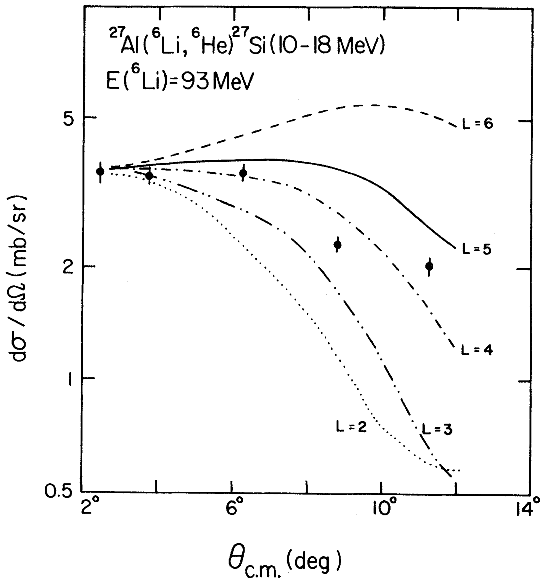

FIG. 3. Comparison of the GR angular distribution with calculations assuming different L-orbital angular momentum transfers.

(4) 2.65 MeV $\frac{5}{2}^+$ ($\frac{1}{2}^+$[211]) plus 2.86 MeV $\frac{3}{2}^+$ ($\frac{3}{2}^+$[202]) plus 2.91 MeV $\frac{9}{2}^+$ ($\frac{5}{2}^+$[202]) .

These Nilsson orbitals are linear combinations of *sd*-shell model orbitals, therefore the allowed orbital angular momentum transfers in the reaction process are $L=0$, 2, and 4. Since several L's may contribute to a given transition, inadequate handling of the various L components will cause poor fitting of the angular distribution shapes, as well as inconsistent interaction strengths. Thus, as previously remarked,[5] a (^{6}Li,^{6}He) reaction with an odd A target nucleus represents a more stringent test for the theoretical assumptions than with an even A target nucleus where practically a single L transfer dominates.

The results of our calculations, which are compared with the data in Fig. 2, have met with mixed success. The transitions which do not contain an $L=0$ transfer compare well with the data, both in shape and in magnitude. Whenever an $L=0$ is allowed by the angular momentum selection rules, the calculation overestimates its contribution. Only when dividing the $L=0$ spectroscopic amplitude by an arbitrary factor of $\sqrt{3}$ does the fit with the data become acceptable. Unfortunately, our data do not allow us to verify whether this situation still persists at larger detection angles.

The very complicated nature of the GR region precludes a detailed study using a conventional analysis such as ours. Instead, we proposed to only

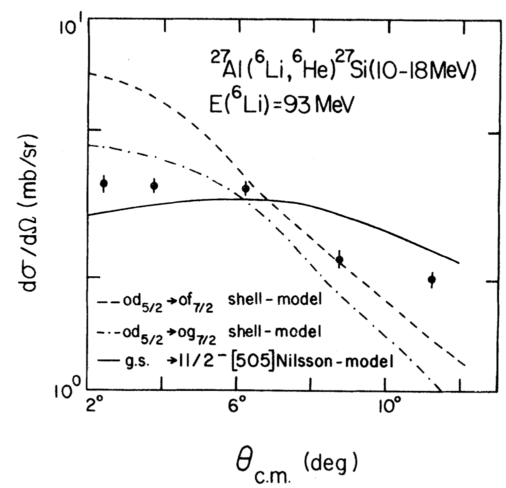

FIG. 4. Comparison of the GR angular distribution with calculations assuming different particle-hole excitations as explained in the text.

make an estimation of the dominant GR multipolarity. The experimental angular distribution shown in Fig. 3 indicates that the transition to the GR is concentrated around high L transfers to a degree which, according to our previous calibration calculations, cannot be ensured by the *sd*-shell L mixing. Thus, we surmise that a major component of the GR might correspond to a promotion of one nucleon of the ^{27}Si nucleus to a level above the *sd* shells. The comparisons made in Fig. 4 seem to favor such a promotion to the $\frac{11}{2}^{-}[505]$ Nilsson orbit rather than to the $0f_{7/2}$ or $0g_{7/2}$ shell model orbits. This would correspond to a GR-component multipole assignment of $\lambda=5$ and a particle-hole excitation energy of about $2\hbar\omega_0$ (if we assume a negative deformation for the mass-27 nuclei) which exhausts some 80% of the total GR strength. We mention that a recent study[14] of the ^{208}Pb(p,p') reaction at 201 MeV also reports a high multipole resonance with a $\lambda=3$ or a sum of $\lambda=3$ and $\lambda=4$ multipolarities in the excitation region between 16 and 27 MeV. Furthermore, the existence of such multipolarities has also been observed[15] in the GR excited by the ^{92}Zr$(p,p')^{92}$Zr reaction at 115 MeV.

In conclusion, in this work we have analyzed the results of the ^{27}Al(^{6}Li,^{6}He)^{27}Si reaction measurements at 93 MeV. The microscopic DWBA calculation of the transitions to the low-lying states of ^{27}Si is quite successful except for the cases where an $L=0$ orbital angular momentum transfer is involved. A GR is observed in the excitation energy region of 10—18 MeV with practically no continuum background. The GR angular distribution suggests the existence of a dominant component characterized by a large λ multipole. Our DWBA calculation accommodates a rather large $\frac{11}{2}^{-}[505]$ Nilsson component which would indicate a multipolarity $\lambda=5$. However, the comparison made in Fig. 4 shows that a safer conclusion would be that the GR data are compatible with a mixing of multipolarities between $\lambda=3$ and $\lambda=5$.

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