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Hybrid random-phase-approximation–cluster model for the dipole strength function of ^{11}Li

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A hybrid random-phase-approximation–cluster model is developed and applied to the calculation of the dipole response of ^{11}Li. A strong collective state at 1.81 MeV is found. Its width is predicted to be ≈ 4.0 MeV. The electromagnetic excitation cross section was found to be 700 mb for ^{11}Li+^{208}Pb (E=800 MeV/nucleon), close to the experimental result.

It is well known that in nuclei with excess neutrons, low excited dipole states might decouple from the giant dipole state while maintaining their appreciable transition strengths.[1] This implies a larger electromagnetic dissociation than in normal stable nuclei. Recently, light neutron-rich nuclei with $N/Z \gtrsim 2.5$ have been produced as secondary beams and their interactions with several targets have been measured at several energies.[2–4] The measured interaction cross section has been reasonably accounted for using Glauber theory with a $t\rho_1\rho_2$ interaction potential constructed from conventional Hartree-Fock densities and from nucleon-nucleon scattering observables.[5] The electromagnetic dissociation cross section of, say, ^{11}Li has been under intensive theoretical scrutiny.[6–8]

A possible model that could account for the measurement is the excitation of a soft giant dipole resonance (SGDR) at very low excitation energies (≈ 0.5 MeV) followed by its decay into ^{9}Li+2n. Whereas the cluster model that mocks up the SGDR can account for the data, conventional random-phase-approximation (RPA) calculation produces very little strength at the required energies, unless a rather unrealistic value of the binding energy of the $P_{1/2}$ orbit (≈ 0.2 MeV) is used.[9] The experimentally known value of the one-neutron separation energy is about 1 MeV and for such a value of $\varepsilon_{P_{1/2}}$ too small a cross section is obtained (≈ 0.25 b versus the experimental value of 0.9 b). It is worth mentioning here that the separation energy of the 2n cluster in ^{11}Li is about 0.2 MeV. Thus the modified RPA calculation of Ref. 9 with $\varepsilon_{P_{1/2}}=0.2$ MeV, mocks up the pairing interaction between the valence neutrons by a rather subtle correction to the mean field.[10]

A more natural treatment, within RPA, is to enlarge the p-h configuration space to accommodate the dineutron-dineutron hole excitations. Thus one ends up treating ^{11}Li as composed of three species of particles: protons, neutrons, and dineutrons (the dineutron is treated as structureless).

The purpose of this paper is to develop the above hybrid RPA–cluster model for ^{11}Li in order to verify the possible enhancement of the low-lying dipole strength.

We choose the Woods-Saxon potential of Bertsch and Foxwell[9] with parameters that result in a $p_{1/2}$ energy of 1.0 MeV. The continuum RPA calculation is done using the complex energy method,[11–13] except for the inclusion of 2n-2n hole excitations. The dineutron potential is chosen such as to produce the correct dineutron separation energy of $\varepsilon=0.2$ MeV. This is done easily by taking a usual shell-model Woods-Saxon interaction with an effective nucleon mass of $2M_N$. The single-particle configurations included in the calculation are shown in Table I with the corresponding energies presented in Table II.

The RPA calculation was then done taking for the residual interaction a Landau-Migdal one (with $g=g'=0$ and $f_0'=1.5$), with $R_0=3.16$ fm and $C=447$ MeV fm^3. The $B(E1)$ strength is found distributed over excitation energy as shown in Fig. 1. Besides the usual GDR at

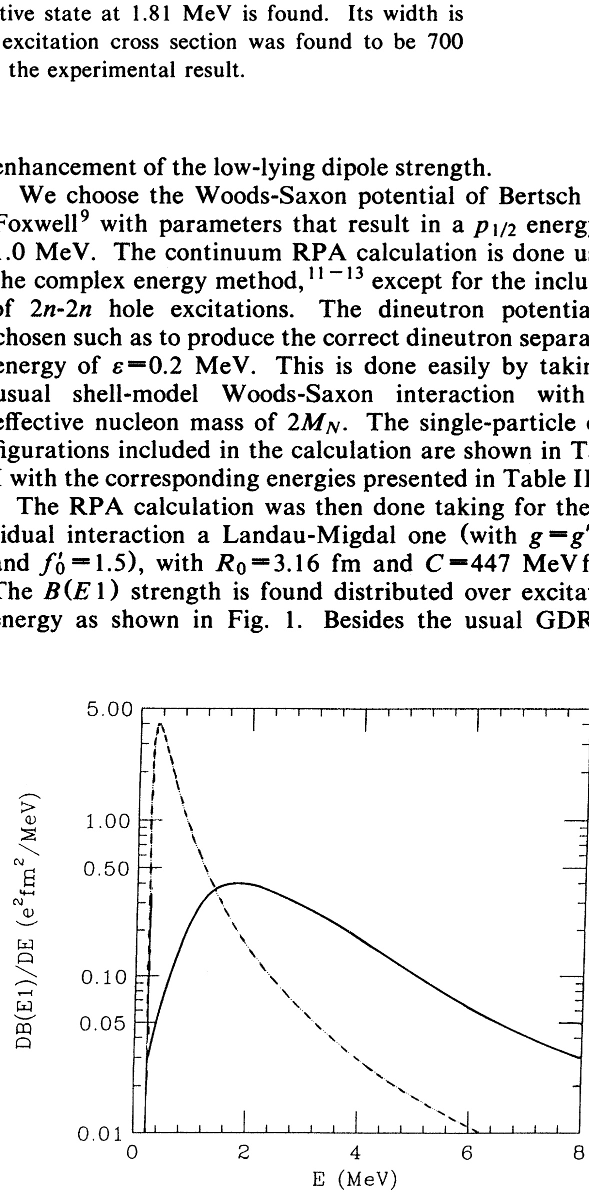

FIG. 1. Calculated dipole strength distribution in the $E<10$ MeV region. Solid curve corresponds to the cluster RPA while the dashed one represents the pure cluster model [Eq. (7)]. See text for details.

$E \approx 16$ MeV, not shown in the figure, we find a strongly collective state, the "soft" GDR, at $E = 1.81$ MeV. Since the width of the $2p_{1/2}$ dineutron single-particle state is found to be about 4 MeV, we conjecture that our soft GDR has a similar width. The $B(E1)$ value of the soft mode is found to be 2.38 $\mathrm{fm}^2 e^2$ which corresponds to $\approx 85\%$ of the dipole cluster sum rule[14] and 8% of the usual energy weighted sum rule. Our findings concerning the soft GDR are in complete accord with the results obtained by Sagawa and Honma[15] using the sum-rule approach.

The cross sections for Coulomb excitation of electric dipole states in the projectile nucleus (which is by far the dominant excitation mode in highly energetic Coulomb collisions) is given by[16]

$$\sigma_c = \int n(\omega)\sigma_{E1}(\omega)\frac{d\omega}{\omega} . \tag{1}$$

In this expression

$$n(\omega) = \frac{2}{\pi} Z_T^2 \alpha \left(\frac{c}{v}\right)^2 \left[\xi K_0 K_1 - \frac{v^2 \xi^2}{2c^2}(K_1^2 - K_0^2)\right] , \tag{2}$$

where $K_0(K_1)$ is the modified Bessel function of zeroth (first) order, as functions of

$$\xi = \frac{\omega b_0}{\gamma v} \tag{3}$$

with $b_0 = R_T + R_{^{11}\mathrm{Li}}$ equal to the sum of the target, R and projectile $R_{^{11}\mathrm{Li}}$, the radii. We use $R_T = 1.2 A_T^{1/3}$ fm and $R_{^{11}\mathrm{Li}} = 3.4$ fm. The radius of ^{11}Li was obtained from the weighted average $R_{^{11}\mathrm{Li}} = \frac{9}{11} R_{^9\mathrm{Li}} + \frac{2}{11} R_{2n}$, where $R_{^9\mathrm{Li}}$ and R_{2n} are given in Table I. In terms of the electric dipole reduced matrix elements $B(E1;\omega)$ of the excited nucleus for the excitation energy $\hbar\omega$, we can write

$$\sigma_{E1}(\omega) = \frac{16\pi^3}{9} \frac{\omega}{c} \frac{dB(E1;\omega)}{d(\hbar\omega)} . \tag{4}$$

The $dB/d(\hbar\omega)$ values were calculated in the RPA method as described above.

For $\omega \leq 1$, which is the case for the most relevant part ($\hbar\omega < 40$ MeV) of the RPA response function (see Fig. 1) one can use

$$\xi K_0 K_1 - \frac{v^2\xi^2}{2c^2}(K_1^2 - K_0^2) \approx \tfrac{1}{2} \ln\left[\left(\frac{0.681}{\xi}\right)^2 + 1\right] . \tag{5}$$

For states with energy $\hbar\omega = 1$ MeV one finds that the above expression [Eq. (5)] results in the value 2.95 for $^{11}\mathrm{Li} + ^{208}\mathrm{Pb}$ collisions. However, for $\hbar\omega = 20$ MeV one obtains the value 0.32. That is, $B(E1;\omega)$—values with low energy (≈ 1 MeV) are weighted by a factor 9 times larger in the integral (1) than states with large energies (≈ 20 MeV). In conclusion, a small enhancement of the $B(E1;\omega)$—values at low energies may increase the cross section (1) considerably. Inserting (4) and (5) in (1) we obtain, with $E \equiv \hbar\omega$

$$\sigma_c \approx 1.3 \times 10^{-3} Z_T^2 \int \left(\frac{dB/dE}{e^2}\right) \ln\left[\left(\frac{210}{E b_0}\right)^2 + 1\right] dE \quad [\mathrm{fm}^2] , \tag{6}$$

which is a good approximation to determine the Coulomb excitation cross sections of ^{11}Li projectiles incident with 800 MeV/nucleon on a target (Z_T, A_T).

For Cu and Pb targets, with RPA-response calculated above, we obtain

$$\sigma_c = 130 \text{ mb} \quad ^{11}\mathrm{Li} + \mathrm{Cu} ,$$

$$\sigma_c = 682 \text{ mb} \quad ^{11}\mathrm{Li} + \mathrm{Pb} .$$

These values of σ_c are to be compared to the experimentally extracted values of $\sigma_c = 210 \pm 40$ mb and $\sigma_c = 890 \pm 100$ mb, respectively.

The cross section for ^{11}Li+Pb given above is almost identical to the value obtained by Bertsch and Foxwell[9] using a different model. The contribution to the cross section of the excitations at $E > 10$ MeV is about 65 mb. We also find a strong linear dependence of σ_c on the width of the resonance. Allowing a variation of $\Gamma^\uparrow$, we obtain for ^{11}Li+Pb $\sigma_c = \sigma_c^0(1 + 0.84\Gamma^\uparrow)$, where σ_c^0 is the cross section with $\Gamma^\uparrow = 0$.

It is interesting to mention at this point that a pure cluster model does generate a large dipole strength at low excitation energies. In fact, the expression for dB/dE one obtains in this case is given by[8]

$$\frac{dB}{dE} = \frac{3\hbar^2}{\pi^2 \mu_{bx}} \left(\frac{Z_x m_b - Z_b m_x}{m_a}\right)^2 \sqrt{\varepsilon} \frac{(E - \varepsilon)^{3/2}}{E^4} \quad (\mathrm{fm}^2 e^2/\mathrm{MeV}) , \tag{7}$$

which, for the ^{11}Li nucleus, with ε, the separation energy of the dineutron, equal to 0.2 MeV, peaks at $E = \frac{8}{5}\varepsilon$

TABLE I. The parameters of the Woods-Saxon well used in the calculation.

$U_{n,p}(r) = V_{n,p} f(r) + 1\sigma V_{ls} f'(r)$
$f(r) = 1/\{1 + \exp[(r - R)/a]\}$

Protons neutrons	Dineutron
$V_n = -40.99$ MeV	$V_{2n} = -8.61$ MeV
$V_p = -59.82$ MeV	
$V_{ls} = -15.5$ MeV fm	$V_{ls} = 0.0$
$a = 0.65$ fm	$a = 0.65$ fm
$R = 2.78$ fm	$R = 6.2$ fm

TABLE II. Calculated single-particle energies [MeV] and widths [MeV] for neutrons, protons, and dineutron, using the code TABOO [A.F.R. de Toledo Piza, University of São Paulo, Internal Report (unpublished)].

Orbit	Neutron	Proton	Dineutron
$1s_{1/2}$	− 17.74	−30.5	
$1p_{3/2}$	−5.15	−14.55	
$1p_{1/2}$	−0.96	−6.95	
$1d_{5/2}$	1.83−i0.17	−0.34	
$2s_{1/2}$	6.1−i6.5	−0.14	−0.20
$2d_{3/2}$	18.8−i6.0	10.05−i2.7	
$2p_{1/2}$			2.0−i2.0

$=0.32$ MeV and has a peak value of $0.163/\varepsilon^2=4.1$ $e^2\text{fm}^2$. Notice that the photonuclear cross section $\sigma_{E1}(E)$ of Eq. (4) with the above cluster model $dB(E1)/dE$, peaks at $E=2\varepsilon=0.4$ MeV and has a peak value of $0.645/2\varepsilon=1.61$ fm^2. The dashed curve in Fig. 1 corresponds to Eq. (7). With the above distribution the cross section σ_c [Eq. (1)] comes out close to our cluster-RPA calculation if $\Gamma^{\uparrow}$ is taken to be 5 MeV.

Finally, it is worth mentioning that the experimental data for the electromagnetic dissociation of 800 MeV/ nucleon ^{11}Li projectiles on Pb are 1.72 ± 0.65 b for the total cross Coulomb section and 0.89 ± 0.1 b for the $2n$-removal channel.[4] It is by no means clear to which extent the RPA response function includes other decay channels beside the two-neutron emission. This fact actually may set an additional difficulty in relating the Coulomb excitation cross section obtained with the RPA approach and the experimental two-neutron removal cross sections.

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[1]M. Harvey and F. K. Khanna, Nucl. Phys. **221**, 77 (1974); R. Mohan, M. Damos, and W. C. Biedenharn, Phys. Rev. C **3**, 1740 (1971); Y. Suzuky, K. Ikeda, and H. Sato, Prog. Theor. Phys. **83**, 180 (1990).

[2]I. Tanihata *et al.*, Phys. Lett. **B160**, 380 (1985); Phys. Rev. Lett. **55**, 2676 (1985); Phys. Lett. B **206**, 592 (1988).

[3]W. Mittig *et al.*, Phys. Rev. Lett. **59**, 1889 (1987).

[4]T. Kobayashi *et al.*, Phys. Lett. B **232**, 51 (1989).

[5]G. F. Bertsch, B. A. Brown, and H. Sagawa, Phys. Rev. C **39**, 1154 (1989).

[6]C. A. Bertulani and M. S. Hussein, Phys. Rev. Lett. **64**, 1099 (1990).

[7]G. F. Bertsch, H. Esbensen, and A. Sustich, Phys. Rev. C **42**, 754 (1990).

[8]C. A. Bertulani, G. Baur, and M. S. Hussein, Nucl. Phys. A (to be published).

[9]G. F. Bertsch and J. Foxwell, Phys. Rev. C **41**, 1300 (1990); **42**, 1159(E) 1990.

[10]G. F. Bertsch and H. Esbensen (unpublished).

[11]N. Van Giai *et al.*, Phys. Lett. B **199**, 155 (1987).

[12]A. F. R. de Toledo Piza, Rev. Bras. Fis. **17**, 195 (1987).

[13]N. Teruya, H. Dias, and A. F. R. de Toledo Piza (unpublished).

[14]Y. Alhassid, M. Gai, and G. F. Bertsch, Phys. Rev. Lett. **49**, 1482 (1982).

[15]H. Sagawa and M. Honma, Phys. Lett. B **234**, 534 (1990).

[16]C. A. Bertulani and G. Baur, Phys. Rep. **163**, 299 (1988).