Soft Dipole Resonance in the Neutron-Skin Nucleus ^{6}He

S. Nakayama,[1,*] T. Yamagata,[2] H. Akimune,[2] I. Daito,[3] H. Fujimura,[3] Y. Fujita,[4] M. Fujiwara,[3,5] K. Fushimi,[1] T. Inomata,[3] H. Kohri,[4] N. Koori,[1] K. Takahisa,[3] A. Tamii,[6] M. Tanaka,[7] and H. Toyokawa[8]

[1]*Department of Physics, University of Tokushima, Tokushima 770-8502, Japan*
[2]*Department of Physics, Konan University, Kobe 658-8501, Japan*
[3]*Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan*
[4]*Department of Physics, Osaka University, Osaka 560-0043, Japan*
[5]*Advanced Science Research Center, JAERI, Tokai, Ibaraki 319-1195, Japan*
[6]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[7]*Kobe Tokiwa Junior College, Kobe 653-0838, Japan*
[8]*SPring-8, Hyogo 678-12, Japan*

(Received 30 November 1999)

A candidate for a soft dipole resonance, a dipole oscillation mode between a core cluster and a neutron skin, was observed at $E_x = 4 \pm 1$ MeV and with a width of 4 ± 1 MeV in ^{6}He via the ^{6}Li(^{7}Li, ^{7}Be) reaction at an incident energy of 65A MeV and forward scattering angles including 0°. Its cross section is deduced to be $\sigma(0°) = 0.9 \pm 0.2$ mb/sr. This value is comparable to that of the giant dipole resonance simultaneously measured.

PACS numbers: 25.70.Kk, 24.30.Cz, 27.20.+n

Neutron-rich light nuclei have loosely bound neutrons outside a core cluster, the so-called "neutron skin or halo" [1]. Such a structure provides a quite new collective motion in nuclei. Indeed, a collective motion in neutron-rich nuclei has been predicted by some cluster models [2,3] in the middle of the 1980s: a dipole oscillation of a core cluster against valence neutrons. This oscillation mode is called a soft dipole resonance (soft DR). Though the exact location of the soft DR is theoretically unestablished, it is expected at a few MeV of excitation energy because its restoring force is weak [2]. The soft DR is a quite different motion from the well-established dipole oscillation. The giant dipole resonance (GDR) is known as a dipole oscillation of protons in opposite phase with respect to neutrons, and the spin-dipole resonance (SDR) as a dipole oscillation of spin-up protons (neutrons) in the opposite phase with respect to spin-down neutrons (protons). Figure 1 shows schematic pictures of the soft DR, the GDR, and the SDR from which their differences are qualitatively explained.

The nucleus ^{6}He is a typical neutron-skin nucleus with a very low separation energy (0.975 MeV) for a neutron pair [4]. Experimental investigations on the soft DR in ^{6}He have been carried out by using various reactions [5–9]. In (n, p)-like charge exchange reactions on ^{6}Li [5–7], a broad resonancelike structure was observed at an excitation energy of $E_x \sim 7$ MeV where an analog of the GDR is expected to be excited. Sakuta *et al.* [5] showed evidence for a resonance with $\Delta L = 1$ at $E_x \sim 6$ MeV in the (^{7}Li, ^{7}Be) reaction at a low incident energy of 82 MeV. Since the reaction at this incident energy predominantly proceeds via the spin-nonflip ($\Delta S = 0$) excitations, the reported resonance is mainly attributed to an excitation of the analog of the GDR as pointed out by Brady *et al.* [6]. Jänecke *et al.* reported that in the (^{7}Li, ^{7}Be) reaction the soft DR was not observed in the low excitation energy region [7]. On the other hand, a large enhancement of an $E1$ transition in the low-excitation energy region has been observed in an electromagnetic dissociation process, which suggested the presence of the soft DR [8]. This work stimulated investigation of the soft DR by scattering a 71A MeV ^{6}He beam in a reaction with kinematics inverse to that of the proton inelastic scattering [9]. However, except for the first excited state (2^+), no resonance was identified in ^{6}He. A recent theoretical investigation suggested that a dipole strength could be concentrated at low-excitation energies not due to the soft DR but only via a final state interaction [10]. The existence of the soft DR is still controversial experimentally as well as theoretically.

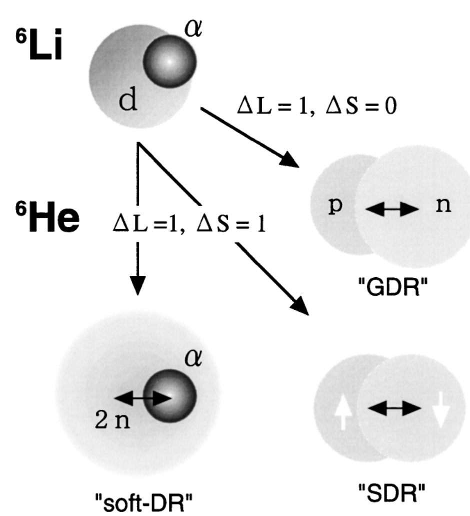

FIG. 1. Schematic picture of the soft dipole (soft DR), the giant dipole (GDR), and the spin-dipole (SDR) resonances excited by the ^{6}Li(^{7}Li, ^{7}Be)^{6}He reaction.

 0031-9007/00/85(2)/262(4)$15.00

In the present work, a dipole strength at excitation energies lower than the GDR or SDR in ^{6}He was investigated via the ^{6}Li(^{7}Li, ^{7}Be) reaction at an incident energy of 65*A* MeV. The (^{7}Li, ^{7}Be) reaction at 65*A* MeV is a probe which distinguishes the spin-flip ($\Delta S = 1$) and spin-nonflip ($\Delta S = 0$) isovector excitations by measuring ^{7}Be ejectiles in coincidence with ejectile-deexcitation γ rays [11]. The ground state of ^{6}Li has a cluster structure, $d + \alpha$, with a large spectroscopic factor of 0.85 [4]. If the soft DR in ^{6}He exists, it could be excited, remaining an α cluster as a spectator, by transferring a deuteron cluster (1^+) in ^{6}Li to a $2n$ cluster (singlet S state, 0^+); i.e., the $\Delta S = 1$ transition. This is schematically shown in Fig. 1. The soft DR is expected to be identified by observing the $\Delta S = 1$ isovector excitations. This is the reason why the ^{6}Li target was chosen for the present study.

The SDR is also excited via the $\Delta S = 1$ excitations. This contribution should be removed from the $\Delta S = 1$ spectrum to isolate the possible soft DR. Hoshino *et al.* performed a shell model calculation for dipole excitations via a charge exchange reaction from a ^{11}B target to a neutron-rich nucleus ^{11}Be [12]. They predicted that the $\Delta S = 0$ and $\Delta S = 1$ dipole excitations have very similar strength distributions. Actually, the strength distribution of the SDR in light nuclei was observed to be similar to that of the GDR [6,13]. The strength of the SDR in the $\Delta S = 1$ spectrum would be estimated by assuming that it has the same strength distribution as the GDR in the $\Delta S = 0$ spectrum. Here the GDR is well established by various nuclear reactions with the $\Delta S = 0$ selectivity, e.g., (γ, n) [14], (^{7}Li, ^{7}Be) reaction [13,15], etc. Thus, for identification of the soft DR, it is necessary to simultaneously measure the $\Delta S = 0$ and $\Delta S = 1$ spectra in the transition of $^6\text{Li} \rightarrow {}^6\text{He}$.

A 65*A*-MeV $^7\text{Li}^{3+}$ beam was provided from the Ring Cyclotron of the Research Center for Nuclear Physics, Osaka University. The target used was a self-supporting foil of a separated ^{6}Li isotope (96.5%) with a thickness of 2.5 mg/cm^2. Details of the experimental setup have been described in Ref. [11]. The ^{7}Be ejectiles were analyzed using the magnetic spectrometer "Grand RAIDEN" [16] set at $\theta_L = 0.3°$. The aperture of the entrance slit of the Grand RAIDEN was ± 20 mrad horizontally and ± 15 mrad vertically. The scattering angles θ_L for the ^{7}Be ejectiles were determined by tracing back their positions and incident angles at the focal plane of the Grand RAIDEN. Energy spectra were obtained with an energy resolution of about 500 keV which was mainly due to the energy spread of the incident beam. The 0.43-MeV γ ray from ^{7}Be ejectiles was measured with the γ detector system "NYMPHS" [11] surrounding the target chamber. The 0.43-MeV γ ray was clearly observed as a prominent peak in the coincident γ spectra. The ratio of the peak to the Compton continuum was about 10. Separation of the $\Delta S = 0$ and $\Delta S = 1$ spectra is performed by the procedure described in Ref. [15]. A peak due to hydrogen contamination in the target was used as a calibration for the relative contributions of the $\Delta S = 0$ and $\Delta S = 1$ spectra. Here the $\Delta S = 0$ and $\Delta S = 1$ transition strengths used for the H(^{7}Li, ^{7}Be) reaction, $B_{\text{F}} = 1$ and $B_{\text{GT}} = 3$, are taken from the neutron β-decay data [17]. This results in $\sigma(\Delta S = 1) = 3\sigma(\Delta S = 0)$ for the H(^{7}Li, ^{7}Be) reaction.

Figure 2(a) shows the $\Delta S = 1$ spectrum obtained in the ^{6}Li(^{7}Li, ^{7}Be)^{6}He reaction at 65*A* MeV and $\theta_L \leq 1.5°$. The ground state (0^+) of ^{6}He is dominantly observed [inset in Fig. 2(a)]. Its transition strength has been discussed in Ref. [13]. In a low-excitation energy region, besides a weak excitation of the first excited state of 2^+,

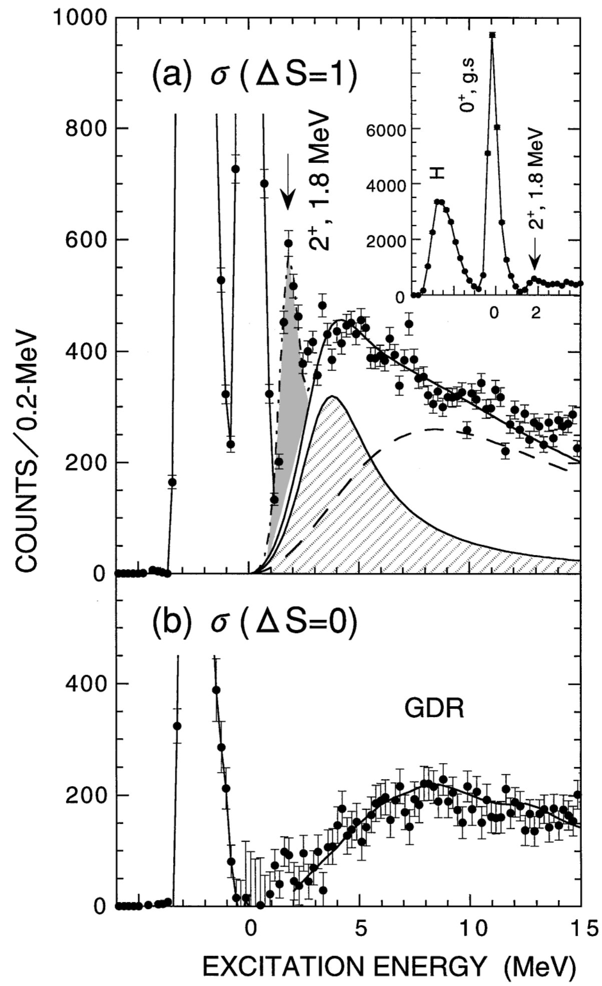

FIG. 2. (a) Spin-flip ($\Delta S = 1$) and (b) spin-nonflip ($\Delta S = 0$) spectra in the ^{6}Li(^{7}Li, ^{7}Be)^{6}He reaction at 65*A* MeV and $\theta_L \leq 1.5°$. The inset in (a) shows transitions to low-lying states of ^{6}He. H denotes a hydrogen contamination in the target. The $\Delta S = 1$ spectrum is fitted with two resonances after accounting for the contribution from a shaded peak of the 1.8-MeV state which is fitted with a Gaussian shape of $E_x = 1.8$ MeV and $\Gamma = 0.5$ MeV (dot-dashed line). A solid line represents fitted Lorentzian curves of $E_x = 4$ MeV, $\Gamma = 4$ MeV (hatched region) and $E_x = 8.5$ MeV, $\Gamma = 15$ MeV (dashed line). The solid line in (b) is a relative strength obtained by the (γ, n) work [14].

an enhancement of the $\Delta S = 1$ excitation is observed at $E_x \sim 4$ MeV. In the $\Delta S = 0$ spectrum [Fig. 2(b)], an analog of the GDR ($\Delta S = 0, \Delta L = 1$) is observed at $E_x \sim 9$ MeV. Here the GDR itself has been established by the ^{6}Li(γ, n) experiment [14]. We found that the shape of the $\Delta S = 0$ spectrum agrees well with a spectrum obtained in the (γ, n) reaction whose relative line shape is shown by a solid line in Fig. 2(b). This fact shows that only the GDR is dominant in the present $\Delta S = 0$ spectrum. The shape of the presently observed GDR is fitted by a Lorentzian line shape. The excitation energy and the width are turned out to be $E_x = 8.5$ MeV and $\Gamma = 15$ MeV, respectively.

The difference between the $\Delta S = 0$ and $\Delta S = 1$ spectra is very remarkable in the low-excitation energy region. A new $\Delta S = 1$ resonance, if it exists, should be identified by subtracting a contribution of the SDR ($\Delta S = 1, \Delta L = 1$) from the $\Delta S = 1$ spectrum. This could be done by the following procedure. By assuming that the SDR is distributed with the same excitation energy and width as those of the GDR, the $\Delta S = 1$ spectrum was decomposed into two resonances after subtracting a contribution of the 1.8-MeV state (a shaded peak). The resonant shape was fitted with a Lorentzian line shape as shown by a solid line in Fig. 2(a). A new resonancelike structure (RS) is clearly identified as shown by a hatched peak in Fig. 2(a). The resulting excitation energy and width are $E_x = 4$ MeV and $\Gamma = 4$ MeV, respectively. The fitted shape of the SDR is shown by a dashed line in Fig. 2(a). Here a cross section ratio of the SDR to the GDR is obtained to be 1.2 and is consistent with that observed in ^{12}C (1.3 ± 0.2) [13]. If we assume that the whole $\Delta S = 1$ spectrum at $E_x \sim 10$ MeV might be due to excitation of the SDR, the cross section ratio increases to about 1.5. Such an increase of the SDR cross section decreases the cross section and width of the RS by about 15%, but the resonance energy is almost unaffected.

Angular distributions of differential cross sections were obtained by gating the data with a width of 10 mrad horizontally for the transitions to the ground state (0^+; g.s.), the first excited state (2^+; $E_x = 1.8$ MeV), the RS at $E_x = 4$ MeV, and the GDR at $E_x = 8.5$ MeV. They are shown in Fig. 3. The angular distributions for the transitions to the ground state and the GDR were compared with the microscopic distorted-wave Born approximation (DWBA) calculations. Details of the calculation were given in Ref. [18]. The absolute magnitudes were arbitrarily normalized. The observed angular distributions for the ground state and the GDR are consistent with the monopole ($\Delta L = 0$) and dipole ($\Delta L = 1$) transitions, respectively, though the measured angular range was limited. The solid and dashed curves in Fig. 3 show the results of the DWBA calculations for the $\Delta L = 1$ and $\Delta L = 0$ transitions, respectively. The ΔL for the RS is consistent with the $\Delta L = 1$ rather than $\Delta L = 0$ calculation. The RS in the $\Delta S = 1$ spectrum is thus due to a dipole excitation.

The parameters (E_x, Γ, and σ) obtained for the RS are summarized together with those for the GDR and SDR in Table I. Here the cross sections σ are obtained from the fitted Lorentzian line shapes. According to the molecular-cluster model [3], the energy-weighted sum rule (EWSR) is proportional to $(N - Z)^2/A(A - 4)$ and NZ/A for the soft DR and the GDR, respectively. In the ^{6}He nucleus, a ratio of the EWSR for the soft DR to the GDR is estimated to be $\frac{1}{4}$. It is of interest to point out that a cross section ratio 0.64 ± 0.20 for the RS to the GDR presently observed by a charge exchange reaction agrees with a value of 0.76 for the EWSR ratio corrected by their excitation energies.

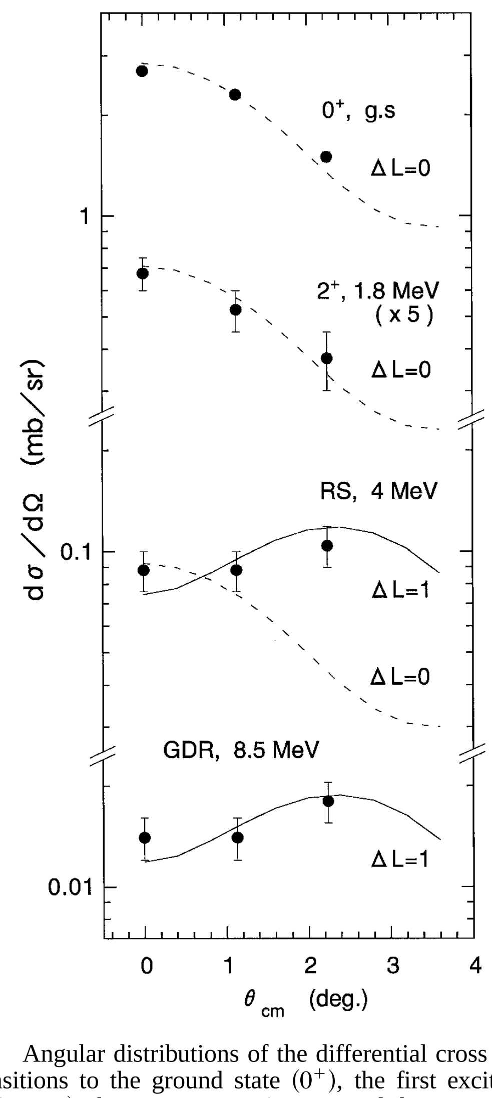

FIG. 3. Angular distributions of the differential cross sections for transitions to the ground state (0^+), the first excited state (2^+; 1.8 MeV), the RS at $E_x = 4$ MeV, and the GDR at $E_x = 8.5$ MeV. The DWBA calculations were performed for the $\Delta L = 1$ transition to a pure particle-hole state with the configuration of $1^-(2s_{1/2} \otimes 1p_{3/2}^{-1})$ and the $\Delta L = 0$ transition to one with $0^+(1p_{3/2} \otimes 1p_{3/2}^{-1})$, and arbitrarily normalized. The experimental angular distributions are compared with the DWBA calculations with $\Delta L = 1$ (solid line) and $\Delta L = 0$ (dashed line).

TABLE I. Isovector dipole resonances studied by the ^{6}Li(^{7}Li, ^{7}Be)^{6}He reaction at 65*A* MeV.

	GDR	SDR	RS
E_x (MeV)	12.1 ± 1.5^a	^{b}	4 ± 1
Γ (MeV)	15 ± 3	^{b}	4 ± 1
$\sigma(0°)$ (mb/sr)	1.4 ± 0.2	1.7 ± 0.3	0.9 ± 0.2

[a]Excitation energy in ^{6}Li.
[b]E_x and Γ for the SDR are assumed to be the same as those for the GDR.

Recently Danilin *et al.* [10] theoretically predicted that the three-body continuum dipole strength should appear as a resonancelike structure at $E_x \sim 3$ MeV and with a width of $\sim$1 MeV in ^{6}He. This dipole strength does not correspond to a nuclear dipole oscillation. Another specific feature of their prediction is that the 2_1^+ state (1.8 MeV) should be dominantly excited and an additional 2_2^+ state is expected at $E_x \sim 4$ MeV. The width of the RS is about 4 MeV which is much larger than their prediction. Furthermore, we observed only a weak excitation of the 2_1^+ state and no evidence for the 2_2^+ state at $E_x \sim 4$ MeV. The present results are not consistent with their prediction. However, it is noted that we cannot distinguish the RS from the three-body continuum state in the present experiment.

In summary, a dipole excitation concentrated at low-excitation energies ($E_x = 4 \pm 1$ MeV and $\Gamma = 4 \pm 1$ MeV) was observed via the ^{6}Li(^{7}Li, ^{7}Be) reaction at 65*A* MeV. The values of the ΔS, ΔL, E_x, and σ presently deduced for the dipole excitation are consistent with those expected for the soft dipole resonance.

This experiment was performed at the Research Center for Nuclear Physics (RCNP) under Program No. E52. The authors are grateful to the RCNP cyclotron staff for their support and to Professor M. B. Greenfield for critically reading the paper.

*Electronic address: nakayama@ias.tokushima-u.ac.jp

[1] I. Tanihata *et al.*, Phys. Lett. **160B**, 380 (1985).
[2] P. G. Hansen and B. Jonson, Europhys. Lett. **4**, 409 (1987).
[3] Y. Alhassid, M. Gai, and G. F. Bertsch, Phys. Rev. Lett. **49**, 1482 (1982); C. Bertulani and G. Baur, Nucl. Phys. **A480**, 615 (1988); Y. Suzuki, Nucl. Phys. **A528**, 395 (1991).
[4] F. Ajzenberg-Selove, Nucl. Phys. **A490**, 1 (1988); M. F. Werby *et al.*, Phys. Rev. C **8**, 108 (1973).
[5] S. B. Sakuta *et al.*, Europhys. Lett. **22**, 511 (1993).
[6] F. P. Brady *et al.*, J. Phys. G **10**, 363 (1984).
[7] J. Jänecke *et al.*, Phys. Rev. C **54**, 1070 (1996).
[8] T. Kobayashi *et al.*, Phys. Lett. B **232**, 51 (1989); T. Aumann *et al.*, Phys. Rev. C **59**, 1252 (1999).
[9] A. A. Korsheninnikov *et al.*, Nucl. Phys. **A616**, 189c (1997).
[10] B. V. Danilin *et al.*, Phys. Rev. C **55**, R577 (1997).
[11] S. Nakayama *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **404**, 34 (1998).
[12] T. Hoshino, H. Sagawa, and A. Arima, Nucl. Phys. **A523**, 228 (1991).
[13] S. Nakayama *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **402**, 367 (1998); Phys. Rev. C **60**, 047303 (1999).
[14] B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713 (1975).
[15] S. Nakayama *et al.*, Phys. Rev. Lett. **83**, 690 (1999).
[16] M. Fujiwara *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **422**, 484 (1999).
[17] *Table of Isotopes*, edited by C. M. Lederer and V. S. Shirley (John Wiley & Sons, Inc., 1978), 7th ed.
[18] S. Nakayama *et al.*, Nucl. Phys. **A507**, 515 (1990).