Isospin asymmetry in the continuum of the A=14 mirror nuclei

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Abstract

We study the isospin asymmetry in the isoscalar (IS) excitations in the mirror nuclei $^{14}\text{O}$ and $^{14}\text{C}$ by using the Hartree-Fock(HF)+random phase approximation (RPA) linear response function theory with a Skyrme interaction to take into account the continuum effect properly. The asymmetry in the IS monopole, dipole responses is pointed out in the continuum near the particle threshold with respect to the excitation energy and the sum rule strength. On the other hand, no clear sign of the asymmetry is found in the giant resonance (GR) region. In the quadrupole case, the calculated strengths of the mirror nuclei show almost the same energy dependence from the threshold to the GR region. It is found that the transition densities of the monopole response show an extended halo structure near the threshold, while those of GR region show a typical radial dependence of the compressional collective mode without any halo effect. Contrary to the transition densities of the monopole response, those of quadrupole response do not show any sign of the extended feature of wave functions neither near the threshold nor the GR energy region. Calculated strength distributions of the IS multipole states are compared with recent experimental data obtained by the multipole decomposition analysis of $\alpha$ inelastic scattering on $^{14}\text{O}$.

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I. INTRODUCTION

A fundamental feature of nuclear structure is associated with a basic symmetry between neutrons and protons in the nuclear interactions. The existence of a general symmetry between \( np, nn \) and \( pp \) interactions was first observed in the low-energy nucleon–nucleon scattering data. The charge independence of the interaction implies the conservation of the isospin symmetry in nuclei [1, 2]. The charge symmetry assumption, based on the equality of the \( nn \) and \( pp \) interactions, might give almost the same excitation spectra in nuclei of the isospin partners. The isospin symmetry, however, is violated by the electromagnetic interaction. Additional symmetry-breaking effects arise from the neutron–proton mass difference, and small charge symmetry and independence breaking forces in the strong interactions.

The isospin impurity was studied by using microscopic models in refs. [3, 4] in relation with Gamow–Teller and Fermi \( \beta \) decays. It was pointed out that the isospin mixing increases rapidly as a function of proton number and becomes few \% in the ground state of \( ^{100}\text{Sn} \). However, it will be less than 0.1\% in light nuclei with the mass less than \( A=16 \) and thus the isospin can be considered to be a good and useful quantum number in the light nuclei. For example, in the \( A=13 \) mirror nuclei \( ^{13}\text{N} \) and \( ^{13}\text{C} \) with the isospin \( T=1/2 \), all states in the spectra show one to one correspondence up to the excitation energy \( E_x=10\text{MeV} \) within few hundreds keV accuracy.

In heavier nuclei, it was expected that the isospin symmetry might be of little significance because of very strong Coulomb field. However, the experimental observation of the isobaric analog states (IAS) in medium heavy nuclei shows that the isospin is well preserved even under the influence of the strong Coulomb field [5]. In light nuclei, the examples of the large isospin asymmetry were found in the first excited \( J^\pi=1/2^+ \) states of \( A=13 \) nuclei, \( ^{13}\text{C} \) and \( ^{13}\text{N} \), and also in the \( J^\pi=1/2^+ \) states of \( A=17 \) nuclei \( ^{17}\text{O} \) and \( ^{17}\text{F} \). This is called Thomas–Ehrman effect [6]. This large asymmetry is considered mainly due to the reduction of the Coulomb energy of loosely–bound low–\( l \) state with small centrifugal barrier. It should be noticed that a large anomaly was also found in the isoscalar (IS) magnetic moments in \( A=9 \) mirror nuclei experimentally [7] and discussed in relation with the Thomas–Ehrman effect [8].

The Coulomb energy might be reduced not only for the loosely bound states but also for the unbound resonance and continuum states. In this paper, we will study the continuum states in the \( T=1 \) mirror nuclei \( ^{14}\text{O} \) and \( ^{14}\text{C} \) in order to extract the isospin asymmetry in the spectra. The \( A=14 \) isospin partners are particularly interesting because of a large difference in the threshold energies of the mirror nuclei. Namely, the neutron threshold energy of \( ^{14}\text{C} \) is \( S_n=8.18\text{MeV} \), while the proton threshold energy in \( ^{14}\text{O} \) is \( S_p=4.63\text{MeV} \). This large energy difference between the two nuclei may give rise to a substantial effect on the low multipole strength distributions with \( J^\pi=0^+ \) and \( 1^- \), especially near the threshold. The lowest \( 1^- \) state in \( ^{14}\text{O} \) has been obtained much attention due to its importance on the astrophysical CNO cycle in the stars [9]. The main aim of this paper is to study the isospin asymmetry of the continuum response functions in the \( A=14 \) mirror nuclei both near the threshold and giant resonance region. To this end, we use the Hartree–Fock (HF) + random phase approximation (RPA) continuum response function with a Skyrme interaction to calculate the IS strength distributions of low multipole states in \( ^{14}\text{O} \) and \( ^{14}\text{C} \). The two-body spin-orbit and Coulomb residual interactions are not included in the RPA response. This paper is organized as follows. A brief review of the RPA response function is given in Section II. Calculated results are shown in Section III and compared with available experimental data.
A summary is given in Section IV.

II. CONTINUUM STRENGTH IN $^{14}$O AND $^{14}$C

The RPA linear response theory is based on the time-dependent HF (TDHF) theory \cite{10}. The RPA Green’s function $G^{RPA}$ is obtained as a small amplitude approximation of TDHF and expressed as

\[
G^{RPA} = G^{(0)} + G^{(0)} \frac{\delta V}{\delta \rho} G^{RPA}
\]

\[
= (1 - G^{(0)} \frac{\delta V}{\delta \rho})^{-1} G^{(0)}.
\]

(1)

where $\frac{\delta V}{\delta \rho}$ is the residual particle–hole interaction. The unperturbed Green’s function $G^{(0)}$ is defined as

\[
G^{(0)}(\vec{r}, \vec{r}'; \omega) = \sum_{i \in \text{occupied}} \varphi_i^*(\vec{r}) \left( \frac{1}{\omega + i\eta - h_0 + \epsilon_i} - \frac{1}{\omega - i\eta + h_0 - \epsilon_i} \right) \varphi_i(\vec{r}').
\]

(2)

where $\varphi_i$ and $\epsilon_i$ are the eigenfunction and the eigenenergy of the HF Hamiltonian $h_0$. The operator equation in the r.h.s. of (2) is nothing but the one-body Green’s function in the coordinate space representation. We can use the standard technique to solve the Green’s function taking into account the coupling to the continuum \cite{11}.

The transition strength $S(\omega)$ for the states above the threshold can be obtained from the imaginary part of $G^{RPA}$ as

\[
S(\omega) \equiv \sum_n |< n | f^{\lambda, \tau}(\vec{r}) | 0 >|^2 \delta(\omega - E_n)
\]

\[
= \frac{1}{\pi} \int \int \text{Im} \left\{ f^{\lambda, \tau}(\vec{r}) G^{RPA}(\vec{r}, \vec{r}'; \omega) f^{\lambda, \tau}(\vec{r}') \right\} d\vec{r} d\vec{r}'
\]

(3)

where $f^{\lambda, \tau}(\vec{r})$ is the transition operator with multipolarity $\lambda$ and isospin $\tau$. Below the threshold, the strength is calculated from the residue of the poles in the real part of the response function. The transition operators are given by

\[
f^{\lambda=0, \tau=0} = \sum_{i=1}^{A} r_i^2 \frac{1}{\sqrt{4\pi}} \quad \text{for isoscalar monopole strength}
\]

(4)

\[
f^{\lambda=2, \tau=0}_\mu = \sum_{i=1}^{A} r_i^2 Y_{2\mu}^\lambda(\hat{r}_i) \quad \text{for isoscalar quadrupole strength}
\]

(5)

The IS dipole operator $\sum_i r_i Y_{1\mu}(\hat{r}_i)$ excites the spurious state corresponding to the center-of-mass motion. Thus, we consider the next order term in the expansion of the spherical Bessel function $j_{\lambda=1}(qr)$ for $qr \ll 1$,

\[
f^{\lambda=1, \tau=0}_\mu = \sum_{i=1}^{A} r_i^3 Y_{1\mu}(\hat{r}_i) \quad \text{for isoscalar compression dipole strength}
\]

(6)
The modified IS dipole operator is also defined as

\[ f^{\lambda=1,\tau=0}_\mu = \sum_{i=1}^{A} (r^3_i - \eta r_i) Y_{1\mu}(\hat{r}_i) \]  

(7)

where \( \eta = 3 < r^2 > /5 \) subtracts the spurious component from the operator (6) [12, 13].

The energy weighted sum rule (EWSR) is defined to be

\[ S_\lambda = \sum_{n,\mu} | < n | f^{\lambda}_\mu | 0 > |^2 = \frac{1}{2} \sum_{\mu} < 0 | [ f^{\lambda*}_\mu, [ H, f^{\lambda}_\mu ] ] | 0 > \]  

(8)

where \( H \) is the hamiltonian for HF and RPA calculations. For the IS excitations, the Skyrme two-body interactions do not give any contributions for the EWSR [10]. Thus the EWSR can be expressed for the operators (4), (5) and (7) to be

\[ S_{\lambda=0} = \frac{\hbar^2}{2m} \frac{1}{\pi} A < r^2 > \]  

(9)

\[ S_{\lambda=2} = \frac{\hbar^2}{2m} \frac{50}{4\pi} A < r^2 > \]  

(10)

\[ S_{\lambda=1} = \frac{\hbar^2}{2m} \frac{3}{4\pi} A (11 < r^4 > - \frac{25}{3} < r^2 >^2). \]  

(11)

The transition density for an excited state, \( | n > \),

\[ \delta \rho(\vec{r}) \equiv < n | \sum_i \delta(\vec{r} - \vec{r}_i) | 0 > \]  

(12)

can be obtained from the RPA response, since the imaginary part of \( G^{RPA}(\vec{r}, \vec{r}'; E_n) \) near the resonance is proportional to \( \delta \rho(\vec{r}) \delta \rho(\vec{r}')^* \). The reduced transition probability is calculated using the transition density (12) as

\[ B(\lambda, \tau: 0 \rightarrow n) = \sum_{\mu} | < n | f^{\lambda,\tau}_\mu | 0 > |^2 = \sum_{\mu} | \int \delta \rho(\vec{r}) f^{\lambda,\tau}_\mu(\vec{r}) d\vec{r} |^2 \]  

(13)

where we use an identity of the one-body transition operator

\[ f^{\lambda,\tau}_\mu = \int \sum_i \delta(\vec{r} - \vec{r}_i) f^{\lambda,\tau}_\mu(\vec{r}) d\vec{r}. \]

The radial transition density, \( \delta \rho_\lambda(r) \), is defined by

\[ \delta \rho(\vec{r}) \equiv \delta \rho_\lambda(r) Y^*_\lambda(\hat{r}) \]  

(14)

III. DISCUSSIONS

The Skyrme interaction SkM* is used to calculate HF potentials and RPA response functions. The HF calculations are performed with the filling approximation putting all nucleons in the HF orbits from the bottom of the mean field potentials. In \(^{14}\text{O}\), the proton number
Z=8 corresponds to the closed shell while the neutron number N=8 in $^{14}\text{C}$ is the closed shell. Moreover, the energy difference between the $1p_{3/2}$ and $1p_{1/2}$ states for neutrons in $^{14}\text{O}$ and protons in $^{14}\text{C}$ are more than 6MeV in the HF calculations. Thus, the pairing correlations might not play any important role in the RPA response in these nuclei [14].

The Skyrme interaction SkM* gives the neutron separation energy $S_n=8.95\text{MeV}$ in $^{14}\text{C}$ and the proton separation energy $S_p=5.70\text{MeV}$ in $^{14}\text{O}$. These values are somewhat larger than the empirical ones $S_n(\text{exp})=8.18\text{MeV}$ in $^{14}\text{C}$ and $S_p(\text{exp})=4.63\text{MeV}$ in $^{14}\text{O}$. In order to perform quantitative study of the threshold effect in the response, we enlarge the spin-orbit coupling has a substantial effect on the single-particle energy, especially around the Fermi surface [15]. For more sophisticated calculations, one should make an effort to readjust the Skyrme parameters including the particle-vibration coupling. Since it is not the aim of the present study to readjust all the Skyrme parameters, we take a conventional approach to obtain the empirical separation energies of A=14 nuclei.

The unperturbed and RPA isoscalar monopole responses of $^{14}\text{C}$ and $^{14}\text{O}$ are given in Fig. 1. There are two bound particle–hole excitations $\nu$, $\pi(1s_{1/2} \rightarrow 2s_{1/2})$ ($\nu$ and $\pi$ stand for neutron and proton, respectively, hereafter) at $Ex\sim31\text{MeV}$ in $^{14}\text{C}$, while the proton particle state of the $\pi(1s_{1/2} \rightarrow s_{1/2})$ configuration is in the continuum in $^{14}\text{O}$ and gives a sharp peak at $Ex\sim27.3\text{MeV}$ in the unperturbed response. The discrete states of the unperturbed response, which are not shown in Fig. 1, couple with the continuum in the RPA response and appears as a sharp peak at $Ex\sim30\text{MeV}$ in $^{14}\text{C}$ and also a peak at $Ex\sim28.5\text{MeV}$ in $^{14}\text{O}$. The unperturbed peak at $Ex\sim27.3\text{MeV}$ in $^{14}\text{O}$ is integrated in the giant resonance peak in the RPA response.

The large threshold strength can be seen just above the proton threshold in $^{14}\text{O}$ and also above the neutron threshold in $^{14}\text{C}$. The energy of the threshold peak in $^{14}\text{O}$ is more than one MeV lower that that in $^{14}\text{C}$ due to the lower proton separation energy $S_p$. One can see that the RPA correlations do not make any appreciable changes on the unperturbed response around the threshold peaks as was pointed out in ref. [16]. The monopole strength below $14\text{MeV}$ in $^{14}\text{O}$ exhausts 10.1% of the energy weighted sum rule value (EWSR), while the monopole strength below $14\text{MeV}$ in $^{14}\text{C}$ has only 8.1% of the EWSR value. The giant resonance peaks appear at $Ex\sim22\text{MeV}$ both in $^{14}\text{O}$ and $^{14}\text{C}$ where RPA correlations enhance the monopole strength. The integrated monopole strength up to GR region ($Ex\leq25\text{MeV}$) is similar in the two nuclei 49.6% in $^{14}\text{O}$ and 48.5% in $^{14}\text{C}$, respectively. The transition densities of the threshold peaks are shown in Figs. 2 (a) for $^{14}\text{C}$ and (c) for $^{14}\text{O}$. The dominant contribution comes from the neutron excitation to the continuum in $^{14}\text{C}$, while the proton continuum excitation has the major contribution in $^{14}\text{O}$. The neutron density shows a halo-type long tail extended more than 10fm in the continuum excitation of $^{14}\text{C}$, while the proton density is rather compact and gives a minor contribution. The same halo effect appears in the proton transition density in $^{14}\text{O}$ near the threshold, while the neutron one is very small and compact. Contrarily, the transition densities of GR region of $^{14}\text{C}$ and $^{14}\text{O}$ in Figs. 2 (b) and (d), respectively, have substantial contributions from both protons and neutrons. The radial dependence of the two contributions is very similar showing the
peak and the node at almost the same radii. The ratio between the proton and the neutron contributions around the peak at $r \sim 4\text{fm}$ is almost the same as that of the proton and the neutron numbers of each nucleus. This is one of the typical feature of the collective IS GR [17]. In general, one can see in Fig. 2 that the proton contribution to the transition densities in $^{14}\text{O}$ is almost identical to the neutron one in $^{14}\text{C}$ both in the radial dependence and in the ratio to another contribution; the ratio of proton to neutron contributions in $^{14}\text{O}$ is very close to that of neutron to proton ones in $^{14}\text{C}$. The IS monopole strength in $^{14}\text{O}$ was observed recently by the multipole decomposition analysis of $\alpha$ inelastic scattering experiments [18]. The IS peak is observed at $E_{x} \sim 7\text{MeV}$ and the integrated strength up to $13.8\text{MeV}$ exhausts about 8% of the EWSR. These experimental data can be compared with the calculated peak at $E_{x} \sim 8\text{MeV}$ which exhausts 10% of the EWSR value. The observed strength in the GR region is about 38% of the EWSR up to $E_{x}=25\text{MeV}$ in the $\alpha$ inelastic scattering. This value is close to the integrated strength of RPA response up to $E_{x}=25\text{MeV}$, i.e., 49.6% of the EWSR.

The isoscalar compressional dipole responses of $^{14}\text{C}$ and $^{14}\text{O}$ are given in Fig. 3. In order to subtract accurately the spurious component, I took a small mesh size 0.075fm and the reference radius 15fm. Then more than 95% of the spurious center of mass motion was eliminated from the physical states [19]. In Fig. 3, we adopted the dipole operator (7) where the spurious component is further subtracted from the operator. The dipole response of $^{14}\text{O}$ shows a sharp peak just above the threshold at $E_{x} \sim 6.1\text{MeV}$ and a broad bump peaked at $E_{x} \sim 9\text{MeV}$. In $^{14}\text{C}$, a discrete $1^{-}$ state is found at $E_{x}=7.1\text{MeV}$ together with a broad peak at $E_{x} \sim 11\text{MeV}$. In the two nuclei, substantial strengths are found also above $E_{x}=15\text{MeV}$.

The observed lowest $1^{-}$ state is at $E_{x}=5.17\text{MeV}$ in $^{14}\text{O}$ and at $E_{x}=6.09\text{MeV}$ in $^{14}\text{C}$, respectively [20]. It is remarkable that the calculated energy difference $\Delta E=1\text{MeV}$ between the lowest $1^{-}$ RPA states in the two nuclei is as large as the experimental one $\Delta E(\text{exp})=0.92\text{MeV}$, although the observed $1^{-}$ states are found at somewhat lower excitation energies than the calculated ones. The strength of the threshold $1^{-}$ peak in $^{14}\text{O}$ has 2.5% of the EWSR value, while the discrete lowest $1^{-}$ state in $^{14}\text{C}$ has only 1.1% of the EWSR strength. The low energy peaks above the first excited states show also large differences both in energy and in transition strength. Namely, the peak energy in $^{14}\text{O}$ is 8.9MeV, while that is shifted to about 2MeV higher in $^{14}\text{C}$ with $E_{x}(\text{peak}) \sim 11\text{MeV}$. The integrated strength up to $E_{x}=12\text{MeV}$ is 17.3% of the EWSR in $^{14}\text{O}$ which is much larger than that of the value in $^{14}\text{C}$ with 10.7% of the EWSR value. On the other hand, in the GR region, the two nuclei have almost the same transition strength, i.e., 23% of the EWSR between $12\text{MeV} < E_{x} < 25\text{MeV}$ both in $^{14}\text{O}$ and $^{14}\text{C}$.

The transition densities of several $1^{-}$ states are shown in Fig. 4; (a) and (d) for the lowest $1^{-}$ states, (b) and (e) for the threshold peaks, and (c) and (f) for the GR peaks. In order to subtract the spurious component from the transition density, we define a modified transition density

$$\delta \rho - \alpha \frac{d\rho_0}{dr}$$

where $\rho_0$ is the total density of the ground state. The factor $\alpha$ is determined to satisfy the condition

$$\int (\delta \rho - \alpha \frac{d\rho_0}{dr})r^3 dr = 0$$

which is equivalent to evaluate the strength function with the operator (7)[13]. The transition densities for the lowest $1^{-}$ states show similar radial dependence in Figs. 4 (a) and
with the dominant configuration $\pi(1p_{3/2} \rightarrow s_{1/2})$ does not show any long tail. This difference might be caused by the Coulomb barrier for the dominant proton wave functions in $^{14}_C$ (Fig. 4 (e)) with the dominant configuration $\pi(1p_{3/2} \rightarrow s_{1/2})$ does not show any long tail. This difference might be caused by the Coulomb barrier for the dominant proton wave functions in $^{14}_O$. It is interesting to notice in Fig. 4 (f) that the proton and the neutron contributions have no node in the transition densities, but the IS one shows the node because of the different extensions of the radial wave functions.

In ref.[18], the IS dipole strength in $^{14}_O$ is observed both in the low energy region and the high energy GR region. The experimental data show two peaks in the low energy region below $Ex=10$MeV. The integrated strength exhausts about 24% of the EWSR value below $Ex=13.8$MeV. The two peak structure and the similar sum rule value (18.5% of EWSR up to 13.8MeV) are found in the calculated results of Fig. 3. On the other hand, the observed dipole strength up to GR energy region (up to $Ex=25$MeV) amounts to be 70% of the EWSR value which is much larger than the calculated value of 40.5%.

In the isoscalar quadrupole response of Figs. 5 (a) and (b), the discrete states are found in both nuclei at $Ex=7.1$MeV with $B(IS)=94.6$ fm$^4$ in $^{14}_C$ and at $Ex=7.2$MeV with $B(IS)=52.8$ fm$^4$ in $^{14}_O$, respectively. As far as the excitation energy is concerned, the isospin asymmetry is much smaller in the quadrupole state than the dipole states. This may be traced back to the difference of the particle configurations between the $1_1^+$ and $2_1^+$ states in the two nuclei. The $2_1^+$ states, the main configurations are $\nu(1p_{3/2} \rightarrow 1p_{1/2})$ for $^{14}_O$ and $\pi(1p_{3/2} \rightarrow 1p_{1/2})$ for $^{14}_C$, respectively, and the $1p_{1/2}$ states are bound in both nuclei. The bound particle states for for $2_1^+$ excitations cause only a small energy difference between $^{14}_O$ and $^{14}_C$. On the other hand, the main configurations for the $1_1^-$ states are $\pi(1p_{1/2} \rightarrow s_{1/2})$ for $^{14}_O$ and $\nu(1p_{1/2} \rightarrow 2s_{1/2})$ for $^{14}_C$, respectively. The particle state $\nu(2s_{1/2})$ is bound in $^{14}_C$, while the state $\pi(s_{1/2})$ in $^{14}_O$ is the continuum state. This difference in the particle configurations is the origin of the large difference in the excitation energies of $1_1^-$ states between $^{14}_O$ and $^{14}_C$. The experimentally observed lowest $2^+$ state is at $Ex=6.59$MeV in $^{14}_O$ and at $Ex=7.01$MeV in $^{14}_C$. These data are consistent with the calculated smaller isospin asymmetry in the $2^+$ states than that of the lowest $1^-$ states. Namely, the observed energy differences are $\Delta E=0.92$MeV for the $1^-$ states, while that is $\Delta E=0.42$MeV in the case of $2^+$ states. The calculated results show also the same trend.

As is seen in Fig. 5, the threshold strength does not show any substantial enhancement in the quadrupole response, but the strong GR peaks are clearly seen around $Ex=20$MeV in the two nuclei. The EWSR of IS quadrupole response below $Ex=25$MeV exhausts 85.3% in $^{14}_C$ and 85.5% in $^{14}_O$. As far as the GR is concerned, the two nuclei show almost the same excitation spectra both in energy and in strength distribution. The transition densities of the lowest $2^+$ and GR states are shown in Fig. 6. It is interesting to notice that the proton amplitude is larger in the lowest $2^+$ state of $^{14}_C$, while the neutrons have the dominant contribution in $^{14}_O$. This is because the proton excitation $(1p_{3/2} \rightarrow 1p_{1/2})$ is allowed in $^{14}_C$, while the neutron excitation $(1p_{3/2} \rightarrow 1p_{1/2})$ is allowed in $^{14}_O$. In Figs. 6 (b) and (d), the transition densities of quadrupole GR show a typical collective IS nature, i.e., the radial dependence is surface peaked, so called, Tassie-type and the neutron (proton) contribution is larger than the proton (neutron) one in the neutrino-rich (proton-rich) nucleus $^{14}_C$ ($^{14}_O$). One can not see any substantial long-tail in the transition densities of the quadrupole response even in the low energy states. This is due to a larger centrifugal barrier for the quadrupole
response than the monopole and the dipole responses [21].

IV. SUMMARY

We studied the isospin asymmetry in the IS multipole responses of $A=14$ mirror nuclei $^{14}$C and $^{14}$O using the HF+RPA theory with Skyrme interaction to take into account the continuum coupling properly. We found that the IS strength distributions near the threshold show a large asymmetry between the two nuclei for the monopole and the dipole responses. On the other hand, the strength distributions in the GR region are very similar in both the peak energy and the sum rule value. It is seen a clear sign of the halo-type extension of the transition densities in the threshold monopole response. Contrarily, those of GR peaks do not show any sign of the halo effect, but give a typical IS collective features. For the quadrupole response, the two nuclei show very similar features not only in the GR region, but also in the lower energy region near the threshold. The calculated results of $^{14}$O are compared with recent experimental data obtained by the multipole decomposition analysis of $\alpha$ inelastic scattering. The calculated monopole and the dipole strength distributions show good agreement with the empirical ones near the threshold. The empirical sum rule strength of the monopole states is also close to the calculated one in the GR region below $Ex=25\text{MeV}$, while the empirical dipole strength is reported to be larger than the calculated one in the high energy region between $12\text{MeV}<Ex<25\text{MeV}$. In order to confirm further the isospin asymmetry of $A=14$ nuclei, we need the experimental data of $^{14}$C in the continuum region.

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[1] W. Heisenberg, Z. Physik 77, 1 (1932).
[2] A. Bohr and B. R. Mottelson, Nuclear Structure, Vol. I (Benjamin, New York, 1969).
[3] I. Hamamoto and H. Sagawa, Phys. Rev. C48, R960 (1998).
[4] H. Sagawa, Nguyen van Giai and T. Suzuki, Phys. Lett. B353, 7 (1995).
[5] J. D. Fox, C. F. Moore and D. Robson, Phys. Rev. Lett. 12, 1981 (1964).
[6] J. B. Ehman, Phys. Rev. 81, 412 (1951).
R. G. Thomas, Phys. Rev. 88, 1109 (1952).
[7] K. Matsuta et al., Nucl. Phys. A588, 153c (1995); K. Matsuta et al., Hyperfine Interact. 97/98, 519 (1996).
[8] Y. Utsuno, Phys. Rev. C70, 0110303R(2004).
[9] P. Decrock et al., Phys. Rev. Lett. 67, 808(1991).
T. Motobayashi et al., Phys. Lett. B264, 259(1991).
[10] G. F. Bertsch and S. F. Tsai, Phys. Report 18, 125 (1975).
[11] S. Shlomo and G. F. Bertsch, Nucl. Phys. \textbf{A243}, 507 (1975);  
S. F. Liu and Nguyen van Giai, Phys. Lett. \textbf{65B}, 23 (1976).  
[12] M. N. Harakeh and A. E. L. Dieperink, Phys. Rev. C\textbf{23}, 2329(1981).  
Nguyen Van Giai and H. Sagawa, Nucl. Phys. \textbf{A371}, 1 (1981).  
[13] I. Hamamoto, H. Sagawa and X. Z. Zhang, Phys. Rev. C\textbf{57}, R1064 (1998).  
[14] E. Khan, N. Sandulescu, M. Grasso and Nguyen Van Giai, Phys. Rev. C\textbf{66}, 024309 (2002).  
[15] C. Mahaux, P.F. Bortignon, R.A. Broglia and C. H. Dasso, Physics Reports 120,1 (1985).  
G. Colò, Toshio Suzuki and H. Sagawa, Nucl. Phys. \textbf{A695}, 167 (2001).  
[16] I. Hamamoto, H. Sagawa and X. Z. Zhang, Phys. Rev. C\textbf{55}, 2361 (1997).  
[17] H. Sagawa, Phys. Rev. C\textbf{65}, 064314(2002).  
[18] H. Baba, Doctoral Thesis (2005); H. Baba et al., RIKEN Accel. Prog. Rep. \textbf{38}, 48(2005) and private communications.  
[19] I. Hamamoto and H. Sagawa, Phys. Rev. C\textbf{66}, 044315(2002).  
[20] Table of Isotopes I (edited by R. B. Firestone, 1996, John Wiley and Sons, Inc)  
[21] H. Sagawa, Phys. Lett. \textbf{B286}, 7(1992).  
D. V. Fedorov, A. S. Jensen and K. Riisager, Phys. Lett. \textbf{B312}, 1(1993).
Figures

FIG. 1: (Color online) Unperturbed and RPA IS monopole response $S$ in $^{14}$C and $^{14}$O calculated by the self-consistent response function theory with the Skyrme interaction SkM*. Unperturbed and RPA responses (3) are calculated by using the Green’s functions (2) and (1), respectively, with the operator (4). See the text for details.
FIG. 2: (Color online) Transition densities (12) of the IS monopole states in $^{14}$C and $^{14}$O; (a) and (c) at the threshold peaks, and (b) and (d) at the GR peaks. The transition density is shown in an arbitrary unit.
FIG. 3: (Color online) IS compressional dipole response $S$ in $^{14}$C and $^{14}$O calculated by the self-consistent RPA response function theory with the Skyrme interaction SkM$^*$. The dipole operator (7) is adopted in the calculations. The dashed–dotted line at $Ex = 7.75\text{MeV}$ shows a discrete $1^-$ state in $^{14}$C. See the text for details.
FIG. 4: (Color online) Transition densities of the IS dipole states in $^{14}$C and $^{14}$O; (a) and (d) of the lowest $1^-$ states, (b) and (e) at the threshold peaks, and (c) and (f) at the GR peaks. The transition density is shown in an arbitrary unit.
FIG. 5: (Color online) IS quadrupole response $S$ in $^{14}$C and $^{14}$O calculated by the self-consistent RPA response function theory with the Skyrme interaction SkM*. The operator (5) is used in the calculations. The solid lines show a discrete $2^+$ state in $^{14}$C and a narrow resonance $2^+$ state in $^{14}$O. See the text for details.
FIG. 6: (Color online) Transition densities of the IS quadrupole states in $^{14}$C and $^{14}$O; (a) and (c) of the lowest $2^+$ states, and (b) and (d) at the GR peaks. The transition density is shown in an arbitrary unit.