Isospin Mixing in the Isobaric Analog State Derived from the $(p, n_{\mathrm{IAS}}\tilde{p})$ Reaction on ^{140}Ce, ^{172,174,176}Yb, and ^{208}Pb

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An exclusive coincidence experiment using the $(p, n_{\mathrm{IAS}}\tilde{p})$ reaction on ^{140}Ce, ^{172,174,176}Yb, and ^{208}Pb was carried out for the first time by measuring decay protons from the isobaric analog states (IAS). Spreading widths of the IAS are deduced from the escape and total widths. The results show a strong isospin dependence which can be explained by the isospin mixing effect due to the coupling to the T_0 component among three multiplets $T = T_0 - 1$, T_0, and $T_0 + 1$ of isovector monopole states in daughter nuclei. Empirical isospin mixing probabilities are found to be consistent with microscopic sum rule predictions. [S0031-9007(98)07482-1]

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The idea of isospin was proposed by Heisenberg more than 60 years ago as a dynamical symmetry in physics [1]. It was applied successfully in the 1950s to explain isospin structures of light nuclei. The most spectacular evidence of the isospin symmetry in heavy nuclei is the discovery of isobaric analog states (IAS) [2]. An IAS has a narrow width manifesting the charge symmetry in heavy nuclei as well as in light nuclei. However, it has still a finite width leading to speculation of coupling to continuum states in heavy nuclei through isospin-violating forces. The main origin of the isospin-symmetry breaking is the Coulomb interaction, and to a lesser extent the short-range charge symmetry breaking and charge-independence breaking interactions [3]. Recently, studies of isospin symmetry have become again a popular subject in nuclear physics, especially due to the development of experimental facilities for charge-exchange reactions and those for radioactive beams [4,5].

The widths of the IAS were deduced from either proton singles spectra or from inclusive neutron-proton coincidence spectra in the early 1970s, while the results were inconsistent with the widths obtained from the (p, d) reaction [6]. Other reactions have also been employed to measure the widths of the IAS. For instance, Taketani *et al.* [7] measured the intrinsic widths of the IAS in tin isotopes by the (p, d) reaction, while Hofmann *et al.* [8] reported the spreading width data measured via the $(^3\mathrm{He}, t_{\mathrm{IAS}}\tilde{p})$ reactions on ^{142,144,146,148,150}Nd. A global analysis of the experimental spreading widths $\Gamma^{\downarrow}$ of 65 IAS in the range $A = \sim 110-238$ has been performed by Jänecke *et al.* [9]. More recently, a compilation of isospin mixing matrix elements has been provided by Reiter and Harney [10] based on analyses of isolated isobaric analog resonances.

The total width of the IAS peak is the sum of the escape and the spreading widths. The total width can be measured in high resolution (p, n) experiments. The escape width can be obtained from an analysis of the direct proton decay following the (p, n_{IAS}) reaction. Then, the spreading width is obtained as the difference of these two observables. The escape width can be related to the coupling of the 1-particle–hole $(1p\text{-}1h)$ states to the continuum, while the spreading width involves the mixing of higher-order configurations than the $1p\text{-}1h$ states. The results, presented in the Letter, are based on two sets of measurements. The total width is measured with (p, n_{IAS}) reactions at 25 MeV. The escape width are measured with the $(p, n_{\mathrm{IAS}}\tilde{p})$ coincidence measurement at 35 MeV. The deduced spreading width, together with their A-dependence, are compared with theoretical predictions.

Several theoretical studies have been carried out to understand widths of IAS in relation with Coulomb matrix elements [11–14]. The importance of the isovector monopole (IVM) resonances in various isospin-mixing effects, especially in the widths of the IAS, has been pointed out [12]. Analyses of the experimental data have been performed based on such ideas, but encountered a difficulty in explaining the dependence of the widths on the mass number A, or equivalently, on the isospin T [9]. In analyses so far performed, only the $T_0 - 1$ component of the IVM has been considered among the three members of the multiplet $T_0 - 1$, T_0, and $T_0 + 1$, where T_0 is the isospin of the parent nucleus. Very recently, the Feshbach projection method [15] was applied to derive explicit formulas to relate the spreading width of IAS with the isospin impurity [16]. It was pointed out that a contribution of the T_0 state among the IVM multiplet is dominant and reproduces properly the empirical isospin dependence of $\Gamma^{\downarrow}$ in Sn and I isotopes, namely of nuclei $A \leq 130$.

Proton-decay widths for IAS are crucial to explore isospin mixing in nuclei. Resonant proton elastic

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scattering data give us only partial widths for the proton decay to the ground state. It is highly desirable to measure proton decay widths to excited states, as well, along with total widths to extract information on the isospin mixing and the particle-hole structure of the IAS. Systematic data of the decay of the IAS in nuclei between $A = 130$ and 208 have been eagerly awaited in order to obtain the A dependence of the spreading width, and to make clear the role of different T-components of the IVM, i.e., the dynamics of isospin-symmetry breaking. The low-energy (p, n_{IAS}) reaction is one of the most suitable candidates for this purpose, since its cross sections are more than two orders of magnitude larger [17] than those in the intermediate energy (p, n_{IAS}) or $(^3\mathrm{He}, n_{\mathrm{IAS}})$ reaction, partly because of the strong energy dependence of the effective interaction. However until now, no exclusive coincidence measurements have been reported for the $(p, n_{\mathrm{IAS}}\tilde{p})$ reaction due to experimental difficulties.

The experiment was performed using 25- and 35-MeV protons from the AVF cyclotron and neutron time-of-flight facilities [18] at CYRIC, Tohoku University. The targets used were metallic foil of ^{140}Ce in natural abundance and those of isotopically enriched ^{172,174,176}Yb and ^{208}Pb. Neutrons were detected at 0° with a flight length of 12 m. The contributions from the 2^+ excited analog states in Lu isotopes were measured in separate high resolution experiments with a 44 m flight path. It was concluded that the 0° cross sections for the 2^+ states are almost two orders of magnitude smaller than those for the IAS. Their contributions, therefore, can be safely ignored.

In order to obtain total widths, other high resolution experiments were carried out at 25 MeV with the 44 m flight path. A typical resolution of 27 keV was achieved for the $^{12}\mathrm{C}(p, n_0)^{12}\mathrm{N}$ reaction. The total widths were extracted from the measured peak widths, and were in good agreement with previously reported values except for ^{176}Yb [9]. Decay protons were detected in coincidence with neutrons using a telescope of Si surface-barrier detectors mounted at the distance of 10 cm from the target, and $\theta_p = 135°$ relative to the beam direction. The telescope consisted of a ΔE (250 μm thick), an E (1000 μm), and a veto counter, all with 100 mm^2 active area.

A sample neutron singles-spectrum for the $^{140}\mathrm{Ce}(p, n)$ reaction is shown in Fig. 1 together with a schematic illustration for excitation of the IAS in the (p, n) reaction followed by direct proton decay into residual neutron hole states. Decay proton spectra are displayed in Fig. 2. These proton spectra are very similar to the hole spectra observed in the (d, t) reaction [19]. The branching ratios for the ^{208}Pb IAS obtained in the present work [20] are in good agreement with those from a recent $(^3\mathrm{He}, t_{\mathrm{IAS}}\tilde{p})$ reaction study [21]. In this Letter we discuss only proton strengths summed over all final states.

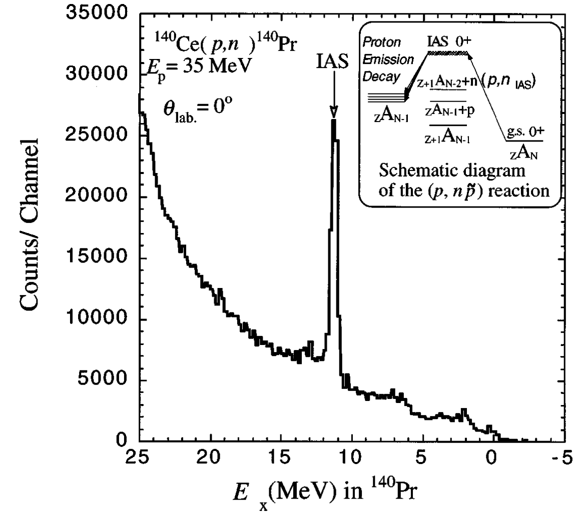

FIG. 1. An inclusive 0° neutron spectrum for the $^{140}\mathrm{Ce}(p, n)^{140}\mathrm{Pr}$ reaction at 35 MeV, together with a schematic diagram (inset) of the $(p, n_{\mathrm{IAS}}\tilde{p})$ reaction.

The proton emission from the IAS is isotropic since the IAS is 0^+. Therefore, the proton decay width is obtained from the (p, n) single cross sections and the double differential cross sections for the $(p, n_{\mathrm{IAS}}\tilde{p})$ coincidence measurements as

$$\Gamma_p^{\uparrow}/\Gamma = \Sigma \Gamma_{p_i}^{\uparrow}/\Gamma, \qquad \text{and}$$

$$\Gamma_{p_i}^{\uparrow}/\Gamma = \int \frac{d^2\sigma_{p_i}}{d\Omega_n\, d\Omega_p}\, d\Omega_p \Bigg/ \left(\frac{d\sigma}{d\Omega_n}\right) = 4\pi\left(\frac{d^2\sigma_{p_i}}{d\Omega_n\, d\Omega_p}\right) \Bigg/ \left(\frac{d\sigma}{d\Omega_n}\right),$$

where the sum is over the final states. The spreading widths $\Gamma^{\downarrow}$ are listed in Table I together with the measure for isospin mixing predicted by the theory described below.

The isospin-mixing amplitude in the parent nucleus can be obtained by coupling to the IVM with the isospin $T_0 + 1$ through the isospin-violating force V_{IV}

$$\alpha_{\pi,M}^{T_0+1} = \frac{1}{\Delta E_{M\pi}} \langle M; T_0 + 1, T_0 | V_{\mathrm{IV}} | T_0, T_0 \rangle,$$

where $\Delta E_{M\pi} = E_M^{T_0+1} - E_\pi$ is the energy difference between the IVM and the ground state of the parent nucleus, $\Gamma^{\downarrow}$ of the IAS is related with the isospin-mixing amplitude $\alpha_{\pi,M}^{T_0+1}$ as

$$\Gamma_A^{\downarrow} = (\alpha_{\pi,M}^{T_0+1})^2 \frac{T_0 + 1}{T_0} (\Delta E_{M\pi})^2 \Bigg\{ \left(\frac{2T_0 - 1}{2T_0 + 1}\right) \frac{\Gamma_M^{T_0-1}}{(\Delta E_M^{T_0-1})^2 + (\Gamma_M^{T_0-1}/2)^2} + \frac{(T_0 - 1)^2}{T_0 + 1} \frac{\Gamma_M^{T_0}}{(\Delta E_M^{T_0})^2 + (\Gamma_M^{T_0-1}/2)^2} + \frac{4T_0^2}{(2T_0 + 1)(T_0 + 1)} \frac{\Gamma_M^{T_0+1}}{(\Delta E_M^{T_0+1})^2 + (\Gamma_M^{T_0+1}/2)^2} \Bigg\}. \qquad (1)$$

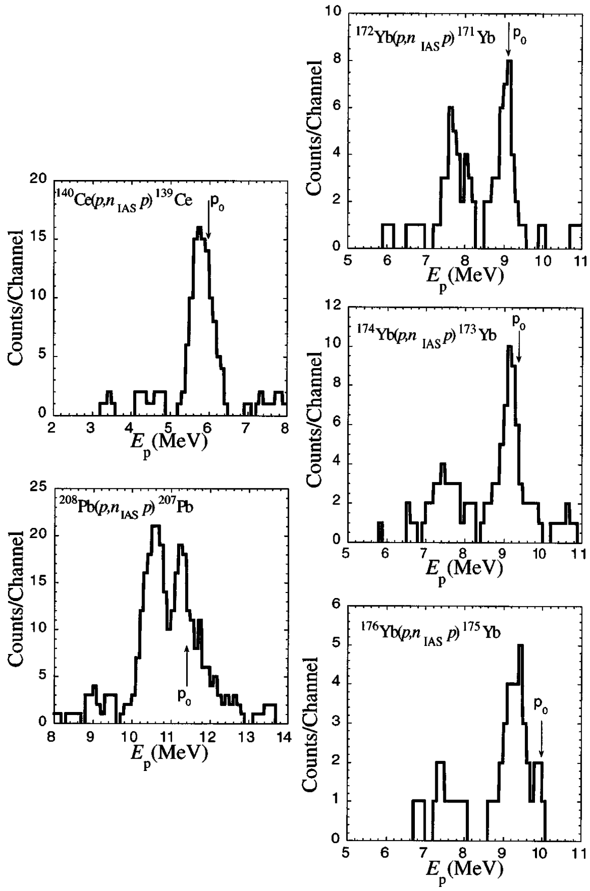

FIG. 2. Energy spectra of coincident protons from the decay of the IAS to low-lying neutron-hole states. An arrow indicates the energy of the highest energy proton. Accidental coincidence events have been subtracted.

where $\Delta E_M^T = E_A - E_M^T$ is the energy difference between the IAS and the IVM with the isospin $T = T_0 + 1$, T_0, and $T_0 - 1$ in the daughter nucleus. The width of the IVM with the isospin T at the energy of the IAS is denoted by Γ_M^T. The energy of the IVM E_M^T with the isospin T in the daughter nucleus is given by

$$E_M^T = \hbar\omega + \frac{V_1}{A}\vec{t}\cdot\vec{T}_0 .$$

where $\hbar\omega$ is the excitation energy of the IVM, and is taken to be $\hbar\omega = 170/A^{1/3}$ MeV from RPA systematics [12]. V_1 is the strength of the Lane potential, and $\vec{t}(|\vec{t}| = 1)$ is the isospin of the IVM. The isospin mixing probability can be parametrized as

$$(\alpha_{\pi,M}^{T_0+1})^2 = \frac{1}{T_0 + 1} P_{\mathrm{IM}}, \qquad \text{where } P_{\mathrm{IM}} = CZ^2A^{2/3} . \tag{2}$$

The parameter C gives a measure for isospin mixing, and has been estimated to be 3.5×10^{-7} from the liquid-drop model by Bohr and Mottelson [22], while that from the sum-rule model by Auerbach [12] is 6.8×10^{-7}. A microscopic HF + TDA model [4,5] gives almost the same results as the sum rule prediction. It is of crucial importance to determine this parameter from experimental information to compare with different models.

Assuming $|E_A - E_M^T| \gg \Gamma_M^T$ and $|E_A - E_M^{T_0+1}| \approx |E_A - E_M^{T_0}| \approx |E_A - E_M^{T_0+1}| \approx$ constant, one can rewrite Eq. (1) to show the isospin dependence more explicitly as [12]

$$\Gamma_A^{\downarrow} \approx P_{\mathrm{IM}} \frac{1}{T_0}\Bigg\{\Gamma_M^{T_0-1}(E_A)\left(\frac{2T_0 - 1}{2T_0 + 1}\right) + \Gamma_M^{T_0}(E_A)\,\frac{(T_0 - 1)^2}{T_0 + 1} + \Gamma_M^{T_0+1}(E_A)\,\frac{4T_0^2}{(2T_0 + 1)(T_0 + 1)}\Bigg\}. \tag{3}$$

Notice that the second term with $T = T_0$ in Eq. (3) gives a dominant contribution in nuclei since $T_0 \gg 1$. The experimental spreading widths are compared with the theoretical prediction in Fig. 3. The width $\Gamma_M^T(E_A)$ in Eq. (3) originates from the Feshbach projection method and there is no way to access this experimentally. However, it was shown theoretically that a reasonable value of $\Gamma_M^T(E_A)$ for $T = T_0$ should be in the range 500–700 keV [12], while $\Gamma_M^T(E_A)$ of the $T = T_0 - 1$ component has been reported by MacDonald and Birse [23] to be ~1.8 MeV. In the present analysis we take the values 600 keV and 1.8 MeV, respectively, for $\Gamma_M^T(E_A)$ with $T = T_0$ and

TABLE I. Experimental and theoretical spreading widths of IAS.

	Experiment						Theory[a]	
Nucleus	E_x of IAS (MeV)	Γ (keV)	$\Gamma^{\uparrow}$ (keV)	$\Gamma^{\downarrow}$ (keV)	P_{IM}	C $\times 10^{-7}$	P_{IM}	$\Gamma^{\downarrow}$ (keV)
^{140}Ce-^{140}Pr	11.04	50 ± 2	12 ± 2	38 ± 6	0.061 ± 0.005	6.7 ± 1.0	0.071	44
^{172}Yb-^{172}Lu	13.73	106 ± 10	31 ± 4	75 ± 11	0.122 ± 0.008	8.0 ± 1.1	0.119	73
^{174}Yb-^{174}Lu	14.80	106 ± 11	29 ± 4	77 ± 12	0.125 ± 0.009	8.2 ± 1.2	0.119	73
^{176}Yb-^{176}Lu	16.03	113 ± 14	31 ± 5	82 ± 16	0.133 ± 0.009	8.6 ± 1.7	0.121	74
^{208}Pb-^{208}Bi	15.17	236 ± 20	130 ± 10	106 ± 22	0.173 ± 0.014	7.3 ± 1.5	0.185	113
Average						7.8 ± 0.7		

[a]Calculated with $\Gamma_M^{T_0-1}(E_A) = 1.8$ MeV, $\Gamma_m^{T_0}(E_A) = 600$ keV, $\Gamma_M^{T_0+1}(E_A) = 150$ keV, and $C = 7.8 \times 10^{-7}$.

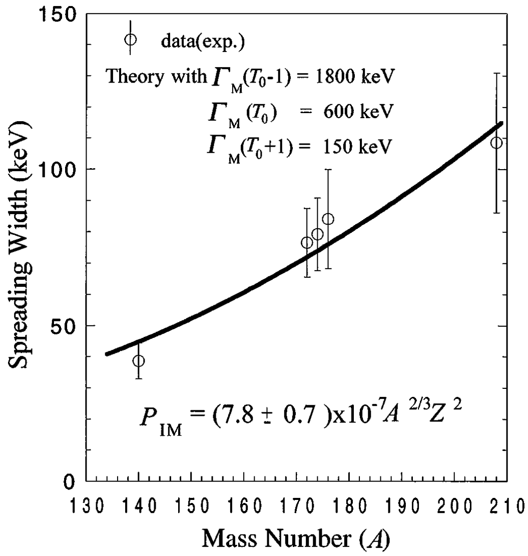

FIG. 3. Experimental and theoretical mass-number dependence of the spreading width $\Gamma_A^{\downarrow}$. The line is an eye guide of theoretical predictions for nuclei ranging $A = 134$ through 208 calculated with isospin mixing probability $P_{\rm IM} = (7.8 \pm 0.7) \times 10^{-7} A^{2/3} Z^2$ obtained by fitting.

$T = T_0 - 1$. As for the less important $T = T_0 + 1$ component in Eq. (3), we assume $\Gamma_M^T(E_A) = 150$ keV.

Figure 3 shows experimental and predicted spreading widths over a mass range 134 through 208 ($T = 11$ through 22). The curve shows the values predicted by Eq. (3) with $\Gamma_M(E_A)$ mentioned above. By fitting the curve to the experimental values, we obtain for the isospin mixing parameter C in Eq. (2) to be $(7.8 \pm 0.7) \times 10^{-7}$ on the average over nuclei presently investigated. The $P_{\rm IM}$ and C values thus obtained are also listed in Table I. The error indicated comes only from the fitting procedure. It should be noted that the present result is very close to that obtained by the microscopic model calculations [4,12].

As seen in Fig. 3, the mass number dependence of $\Gamma_A^{\downarrow}$ is reproduced very well by the calculated curve. More than 70% of the values $\Gamma_A^{\downarrow}$ come from the $T = T_0$ term with increasing importance as the mass number increases. These features are different from other theoretical models in the literature [7,9,13], where the $T = T_0 - 1$ term is the dominant one. It is obvious that the first and the third terms in Eq. (3) have different isospin dependence and cannot reproduce the experimentally observed increase of the width as a function of isospin or mass number. The new model with the Feshbach projection method, on the other hand, gives us a natural explanation of the observed T dependence of the width of the IAS.

In summary, the experimental data on the spreading width $\Gamma_A^{\downarrow}$ of the IAS obtained by the $(p, n_{\rm IAS}\tilde{p})$ reaction have been reported for the first time in the mass region $A = 140-208$. The extracted experimental widths were compared with the calculated values based on the Feshbach projection method. The increasing width with the mass number can be explained only by the isospin mixing contribution of the $T = T_0$ component of the isovector monopole resonance. The isospin-mixing probabilities from the microscopic models, which are a factor 2 larger than the hydrodynamical prediction, give a good account of the data with a reasonable set of the other parameters.

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