Restoration of Isospin Symmetry in Highly Excited Compound Nuclei

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We have deduced compound nuclear isospin mixing in $^{28}Si^*$ and $^{26}Al^*$ at excitation energies between 33 and 65 MeV. The γ-ray yield from the decay of giant dipole resonances built on excited states is found to be suppressed, implying that isospin mixing is small. By comparison with data from the literature at lower excitation energy, we conclude that isospin is a better symmetry in these compound nuclei at high excitation energy.

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Over 30 years ago, Wilkinson predicted that at high excitation energies, the compound nucleus, whose lifetime is determined primarily by the strong interaction, should not live long enough for isospin symmetry to be broken by the relatively weak Coulomb interaction [1]. More recently, Kuhlmann [2] and Harney, Richter, and Weidenmüller [3] have proposed that compound nuclear isospin mixing should be characterized by an isospin-violating spreading width $\Gamma^{\downarrow}$ which is approximately constant with mass number and excitation energy. This proposal was made on the basis of a large body of data, mostly measurements in different compound nuclei. However, spreading widths deduced from these data scatter over more than 1 order of magnitude [2, 3].

The concept of a constant isospin-violating spreading width leads to a definite expectation concerning the excitation energy E^* dependence of isospin mixing within a given nucleus. At energies where the compound nuclear decay width Γ is much greater than D, the level spacing, compound nuclear reaction theory implies that the mixing should depend on $\Gamma^{\downarrow}/\Gamma$. Hence at high E^*, where $\Gamma \gg \Gamma^{\downarrow}$, the mixing should become small as Wilkinson suggested. At very low E^* where Γ is small, the mixing is weak, on the average, because levels are widely spaced. Thus an additional expectation is that the mixing should be a maximum at energies where $\Gamma \sim D$.

Although some previous experiments have suggested a decrease in isospin mixing over a narrow interval in E^* (see Ref. [3]), the general form of the energy dependence of isospin mixing has not been demonstrated clearly. An additional motivation for a better understanding of compound nuclear isospin symmetry breaking stems from the recent interest in applying similar concepts to the interpretation of measured and proposed compound-nuclear parity [4] and time-reversal violation experiments [5]. These are all examples of a partially broken symmetry in a quantum statistical mechanical system. The underlying symmetry breaking mechanism should be best understood in the case of isospin, making isospin violation a potentially ideal case to study the nature of broken symmetries in complex systems [3].

In this Letter we present evidence that isospin mixing is small in ^{28}Si and ^{26}Al compound nuclei at high E^*, where Γ is very large. Our results, when combined with those from other experiments at lower E^*, support the predicted energy dependence over a wide range of excitation energies.

Our technique involves comparing measured and calculated inclusive γ-ray cross sections for the statistical γ decay of the giant dipole resonance (GDR) built on excited states following heavy-ion fusion. We form $N=Z$ compound nuclei with entrance channel isospin $T=0$. Since $E1$ decays are isovector, $T=0 \rightarrow T=0$ transitions are forbidden, so that the isospin-allowed yield will be due to GDR γ decay populating the less numerous $T=1$ final states, along with γ decay in daughter nuclei following particle emission. Isospin mixing populates $T=1$ initial states, which γ decay with a 3 times larger isospin Clebsch-Gordan coefficient (squared) to the more numerous $T=0$ final states, enhancing the γ-ray yield. We test the aspects of the statistical model which do not involve isospin by comparing calculated and measured γ-ray spectra for reactions populating $N \neq Z$ nuclei, which are much less sensitive to isospin mixing.

We have measured γ-ray cross sections from the formation of isospin $T=0$ ^{28}Si and ^{26}Al, $T=1/2$ ^{29}Si, and $T=1$ ^{28}Al, ^{30}Si, and ^{26}Mg compound nuclei with initial excitation energies $E^* \simeq 33$, 45, and 65 MeV. Measurements were made using ^{16}O, ^{18}O, ^{13}C, ^{14}N, and ^{15}N beams from the University of Washington tandem linac with energies E_{lab} ranging from 22 to 108 MeV. Targets were self-supporting foils of ^{12}C and ^{13}C. The γ-ray spectrometer was a 25×38 cm cylindrical NaI(Tl) crystal surrounded by a 10.2 cm thick NE110 plastic scintillator to veto cosmic rays and by passive shielding. Neutrons from the target were discriminated from γ rays by time of flight with respect to the pulsed beam. The detector gain was stabilized by an active feedback LED pulser. The detector gain and line shape response were measured using the $^{11}B(p,\gamma)^{12}C$ reaction, and the measured line shape and efficiency of the detector were folded into the statistical model calculations for comparison with the data.

Spectra were compared to CASCADE [6] statistical model calculations, which include effects of isospin mixing according to the equations:

$$\tilde{\sigma}_< = (1 - \alpha^2_<)\sigma_< + \alpha^2_>\sigma_> \ ,$$
$$\tilde{\sigma}_> = (1 - \alpha^2_>)\sigma_> + \alpha^2_<\sigma_< \ , \qquad (1)$$

where $\sigma_<$ and $\sigma_>$ are the entrance channel fusion cross sections for forming $T_< = T_3$ and $T_> = T_3+1$ states in the absence of isospin mixing, and $\tilde{\sigma}_>$ and $\tilde{\sigma}_<$ are the corresponding cross sections for mixed isospin. The isospin mixing admixture $\alpha^2_<$, the fraction of $T_<$ states which mix into $T_>$ states, is given by [3]

$$\alpha^2_< = \frac{\Gamma^\downarrow_</\Gamma_<}{1 + \Gamma^\downarrow_</\Gamma_< + \Gamma^\downarrow_>/\Gamma_>}. \qquad (2)$$

A similar equation for $\alpha^2_>$ follows by interchanging upper and lower symbols. The spreading widths for $T_<$ and $T_>$ states are connected by the statistical model relation $\Gamma^\downarrow_< = \Gamma^\downarrow_>(\rho_>/\rho_<)$ [3], where $\rho_>$ and $\rho_<$ are the level densities of the $T_>$ and $T_<$ states, and hence there is only one free isospin mixing parameter $\Gamma^\downarrow_>$ (or $\Gamma^\downarrow_<$). Mixing of final states does not enter since in the statistical uniform mixing model [3] it does not alter the decay strengths [7].

Additional information on $\rho_>/\rho_<$ is needed to calculate the isospin-allowed γ-ray yield. This was determined, for example, in the A=28 case, by equating the level density of T=1 levels in ^{28}Si with the density of their isobaric analogs in ^{28}Al (see, e.g., Ref. [8]). The total level densities are calculated using a Bethe-type formula for a Fermi gas with uniform single-particle level spacing, with an exponential damping of the shell correction at high E^* [9, 10]. At high E^*, where shell and pairing effects are unimportant and masses should be given by the liquid drop model, the difference in energy between states in ^{28}Al* and their analogs in ^{28}Si* is given by the nuclear symmetry energy and the Coulomb displacement energy. To calculate the level densities we use the liquid drop model of Groote, Hilf, and Takahashi [11], which agrees with experimentally determined Coulomb displacement energies [12] and the phenomenological nuclear symmetry energy determined from energies of isobaric analog states [13].

It is important to know if the observed γ rays are produced from compound-nuclear decay. We have made two tests of the statistical nature of the high-energy γ-ray production. Figure 1 shows γ-ray spectra for the formation of ^{28}Si* at E^*=47 MeV in two different reactions, E_{lab}=70 MeV ^{16}O + ^{12}C and E_{lab}=40 MeV ^{14}N + ^{14}N. If these reactions had the same spin distribution, then the assumption of statistical decay would require the cross sections to be identical. As it is, the ^{14}N+^{14}N cross section is larger because the compound nucleus is formed with a smaller average spin ($8\hbar$ vs $12\hbar$), and the statistical model calculations reproduce both spectra well

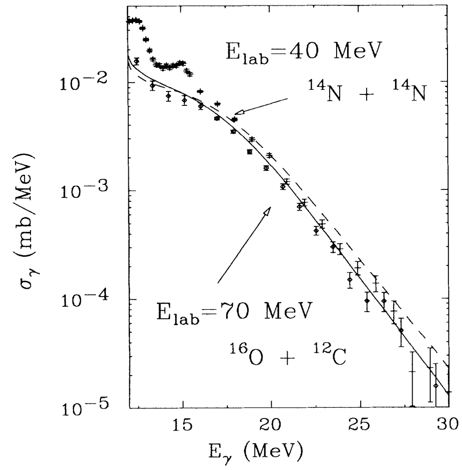

FIG. 1. γ-ray spectra from decay of ^{28}Si* at E^*=47 MeV, formed in different entrance channels: E_{lab}=70 MeV ^{16}O + ^{12}C (solid points and line) and E_{lab}=40 MeV ^{14}N + ^{14}N (horizontal bars and dashed line).

using the same parameters. This result implies that contributions from any nonstatistical production mechanism depending on projectile energy are negligible for $E_\gamma > 16$ MeV. The peaks in the ^{14}N+^{14}N spectrum are believed to be from the excitation of the $J^\pi = 1^+$, 12.7, and 15.1 MeV states in ^{12}C, which have unusually large absolute γ-decay branching ratios, so in the isospin mixing analysis we ignore the γ-ray cross section below E_γ=16 MeV. We have also measured the angular distribution of the γ rays in the E_{lab}=70 MeV ^{16}O + ^{12}C reaction, and the front-back asymmetry in the center-of-mass frame was found to be consistent with zero, as required for statistical decay. In addition, Beck *et al.* have measured predominance of complete fusion up to E_{lab}= 150 MeV in the ^{16}O + ^{12}C and ^{18}O + ^{12}C reactions [14].

Results for the decay of ^{28}Si and ^{30}Si at E^*=45–47 and 63 MeV are shown in Fig. 2. The calculated yield from the N=Z compound nucleus ^{28}Si* depends strongly on the degree of isospin mixing, while the yield from the N≠Z compound nucleus ^{30}Si* does not. To extract isospin mixing, we compare measured and calculated ratios of cross sections for reactions forming N=Z and N≠Z compound nuclei (see Fig. 2). In this manner, dependences on GDR Lorentzian parameters and level density prescription are minimized. In the CASCADE calculation we use the same centroid E_{GDR} as that known for ground-state photoabsorption, one classical dipole sum rule for the total photoabsorption strength, and a larger width (Γ_{GDR} = 12 MeV) than the ground state, adjusted to roughly describe the spectrum shapes. $\Gamma^\downarrow_>$ is assumed to be the same in the N=Z nucleus and the N≠Z nuclei at the same E^*; the weak dependence on isospin mixing of the γ-ray spectra of the N≠Z nuclei makes this an unimportant assumption. We also make the assumption

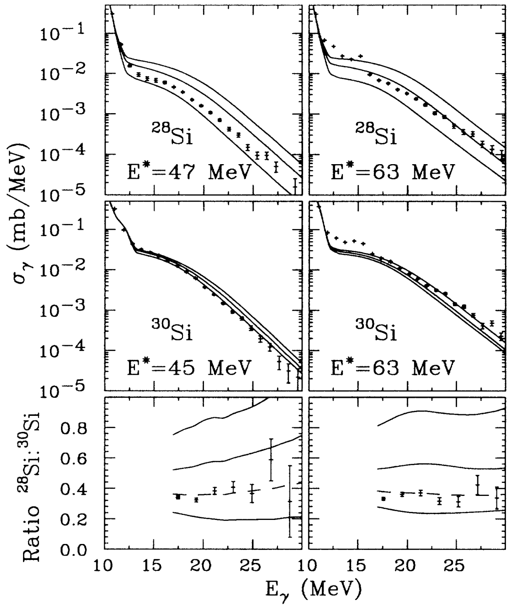

FIG. 2. γ-ray spectra from $E_{\rm lab}$=70 MeV ^{16}O + ^{12}C → ^{28}Si* at E^*=47 MeV, $E_{\rm lab}$=54 MeV ^{18}O + ^{12}C → ^{30}Si* at E^*=45 MeV, $E_{\rm lab}$=108 MeV ^{16}O + ^{12}C → ^{28}Si* at E^*=63 MeV, and $E_{\rm lab}$=100 MeV ^{18}O + ^{12}C → ^{30}Si* at E^*=63 MeV, and the ratios of these spectra. Solid curves are CASCADE calculations for $\Gamma_>^\downarrow$=0 (lowest), 300 keV, and completely mixed isospin. Dashed ratio curve is best value for $\Gamma_>^\downarrow$ (see Table I) deduced from an average over several $N\neq Z$ nuclei.

that $\Gamma_>^\downarrow$ is constant throughout the decay cascade for any given reaction, which is important only for the $E^*\approx 65$ MeV cases. The statistical model calculations include isospin splitting of the GDR energy centroids [15] and corrections to the γ-decay isospin Clebsch-Gordan coefficients from the Pauli blocking of some single-particle transitions [16]; in practice, these two effects approximately cancel.

The spreading width $\Gamma_>^\downarrow$ in ^{28}Si is extracted from the ratio of the cross section for decay of ^{28}Si* to that for four other $N\neq Z$ compound nuclei, ^{28}Al*, ^{26}Mg*, ^{29}Si*, and ^{30}Si*, and the results are averaged to give our best value for $\Gamma_>^\downarrow$. The scatter of the four results is somewhat greater than the statistical error on each, so we take the width of the distribution of the four results as one contribution to the error on $\Gamma_>^\downarrow$. Additional errors on $\Gamma_>^\downarrow$ due to the phenomenological uncertainty in the nuclear symmetry energy, 4.6±0.7 MeV, and level density parameters [10]—single-particle level density parameter $\tilde{a}^{-1}$=7.8±1 MeV and shell damping parameter $\gamma^{-1}=18^{+20}_{-10}$ MeV —are folded in quadrature.

Our isospin mixing results are shown in Table I. The quoted errors on $\alpha_<^2$, typically ±0.03, correspond to typically ±30% in the ratio of the cross sections. A finite isospin mixing admixture, at the 2σ level, is deduced for ^{28}Si at E^*=47 MeV, where $\alpha_<^2$ = 0.047 ± 0.023. The results of Table I may be interpreted as upper limits on

TABLE I. Deduced compound nuclear isospin mixing admixture $\alpha_<^2$ for $T_>$ states, and isospin-violating spreading widths $\Gamma_>^\downarrow$ and $\Gamma_<^\downarrow$, for ^{28}Si and ^{26}Al at excitation energies E^* and (calculated) decay widths $\Gamma_>$ and $\Gamma_<$.

	E^* (MeV)	$\Gamma_>$ (MeV)	$\Gamma_<$ (MeV)	$\alpha_<^2$	$\Gamma_>^\downarrow$ (keV)	$\Gamma_<^\downarrow$ (keV)
^{28}Si	47	0.9	0.5	0.047 ± 0.023	77 ± 60	29 ± 30
^{28}Si	63	1.6	1.1	0.032 ± 0.029	89 ± 64	39 ± 46
^{26}Al	33	0.7	0.3	0.017 ± 0.032	21 ± 25	6 ± 15
^{26}Al	42	1.0	0.6	0.032 ± 0.029	62 ± 60	21 ± 25
^{26}Al	65	2.3	1.6	0.061 ± 0.044	270 ±310	110 ±150

$\alpha_<^2$ of 0.05–0.10. Since complete isospin mixing in N=Z nuclei corresponds to $\alpha_<^2$=0.5, the present results demonstrate that isospin mixing is small. Table I also shows the corresponding values for $\Gamma_>^\downarrow$. The fractional errors are larger for $\Gamma_>^\downarrow$ than for $\alpha_<^2$ because they include a contribution from the uncertainty in the statistical calculation of the compound nuclear decay widths.

At higher projectile bombarding energies, $E_{\rm lab}\simeq 150$ and 215 MeV ($E^*\simeq 85$ and 110 MeV), nonstatistical contributions become apparent in the spectrum shape, which is flatter than the statistical model calculation. Hence we cannot deduce isospin mixing for $E^*\geq 85$ MeV. It is difficult to know how much, if any, contribution from nonstatistical emission may be present at E^*=63 MeV. As shown in Fig. 2, the statistical model calculation underestimates the E^*=63 MeV spectrum in ^{30}Si at $E_\gamma\sim 20$ MeV by (10–15)%. If we make the extreme assumption that all of this discrepancy is due to nonstatistical emission, then based on our E^*=85 MeV data we would lower our deduced mixing at E^*=63 MeV by at most 1σ.

In Fig. 3, we show our results for the isospin mixing admixture for T=0 states in ^{28}Si together with results from other experiments. Larger isospin mixing has been deduced at lower energies from cross-section ratios for ^{24}Mg(α,γ_0)/^{26}Mg(α,γ_0) [3,17] and for (γ,α_0)/(γ,p_3) [18], as well as from mirror (^{16}O,p)/(^{16}O,n) channel correlations [3,19]. We have converted these results, expressed in terms of $\alpha_>^2$ in Refs. [3,18], to $\alpha_<^2 = \alpha_>^2\ (N_>/N_<)$, where N is the effective number of decay channels [3]. We also show previous Seattle results [20] at E^*=34 MeV obtained using the present method. It is clear that $\alpha_<^2$ is smaller at excitation energies $E^*\sim$34–63 MeV than at $E^*\sim$20 MeV, consistent with the idea that isospin is a better symmetry at higher excitation energy because the short-lived compound nucleus decays before the Coulomb interaction can equilibrate the isospin degree of freedom.

The solid curves in Fig. 3 show Eq. (2) calculated for constant spreading widths $\Gamma_>^\downarrow$= 30, 80, and 150 keV and decay widths calculated from CASCADE. A comparison of the calculated curves and the data points demonstrates consistency, to within a factor of 5 or so, with a constant $\Gamma_>^\downarrow$. This compares favorably with the degree to which $\Gamma_>^\downarrow$ is known to be independent of mass, namely,

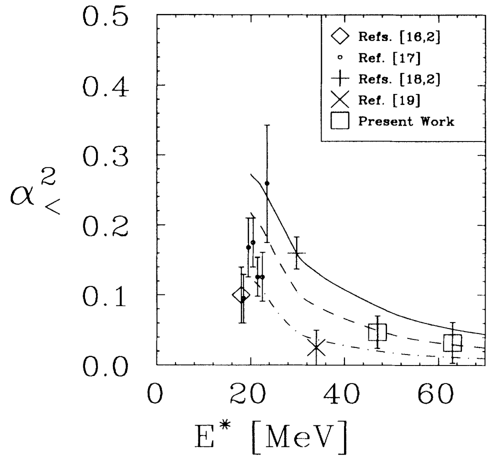

FIG. 3. Isospin mixing $\alpha^2_<$ as a function of excitation energy E^* in ^{28}Si. Curves show $\alpha^2_<$ for $\Gamma^{\downarrow}_>$=30 (dash-dotted), 80 (dashed), and 150 keV (solid).

to somewhat worse than a factor of 10 (see Fig. 15 of Ref. [3]). Low-lying discrete states are known to be relatively pure, on the average [21], with isospin mixing admixtures of <0.01. Thus Fig. 3 implies in addition that isospin mixing exhibits a maximum at moderate excitation energies $E^* \lesssim 20$ MeV. We conclude that compound nuclear isospin mixing in ^{28}Si does indeed exhibit an energy dependence in qualitative accord with the assumption of a constant isospin-violating spreading width. We close with the comment that to our knowledge there exist no theoretical calculations of compound-nuclear isospin-violating spreading widths.

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