Large Isospin-Mixing Matrix Element in ^{12}C†

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Isospin mixing between the 12.71-MeV, 1^+, $T=0$ and 15.11-MeV, 1^+, $T=1$ levels in ^{12}C is measured utilizing two different direct reactions. A consistent value ($\beta^2 \sim 0.01$) is obtained from both the isospin-forbidden reaction ^{12}C$(d,d')^{12}$C* and the comparison of the yields in the analog reactions ^{13}C$(d,t)^{12}$C*(15.11 MeV) and ^{13}C$(d,h)^{12}$B(0.00 MeV). This mixing implies a charge-dependent matrix element between these two levels of approximately 250 keV.

There has been considerable interest[1] in isospin mixing between levels in light nuclei which have similar structure. In the celebrated case[2-4] of ^{8}Be a pair of 2^+ levels, assumed initially degenerate, mix strongly with one another with an isospin-mixing matrix element of 150 keV. Reasonable calculations[5] employing only electromagnetic interactions between nucleons have considerable difficulty obtaining such a large matrix element and perhaps charge-dependent nuclear forces have to be invoked. It would be of real interest to examine other instances where one might find large isospin-mixing matrix elements between specific levels. In general the interacting levels will not be as close in energy as was the case in ^{8}Be, and so the specific levels involved in the isospin mixing may be harder to identify. We wish to report in this Letter on some experiments that obtain the mixing matrix element between the 12.71-MeV, 1^+, $T=0$ and 15.11-MeV, 1^+, $T=1$ states in the ^{12}C nucleus. As these levels differ in energy more than is the case in ^{8}Be and, in fact, are separated by an amount large compared to the size of the mixing matrix element, the resulting isospin impurity is small and considerable care must be exercised in extracting the matrix element.

To facilitate discussion, consider two levels, $\Psi(T=1)$ and $\Psi(T=0)$, which are eigenstates of a charge-independent Hamiltonian. As a result of a charge-dependent perturbation ($H_{\rm CD}$), they mix, producing new eigenstates $\varphi(1)$ and $\varphi(0)$, where

$$\varphi(1) = (1-\beta^2)^{1/2}\Psi(1) + \beta\Psi(0),$$
$$\varphi(0) = -\beta\Psi(1) + (1-\beta^2)^{1/2}\Psi(0), \qquad (1)$$

with

$$\beta = \langle\Psi(1)|H_{\rm CD}|\Psi(0)\rangle/(E_1 - E_0). \qquad (2)$$

The charge-dependent matrix element is $\langle H_{\rm CD}\rangle$ and β is the mixing amplitude between the levels.

The experiments reported in this Letter were performed in two separate stages. The first was a measurement[6] of the inelastic scattering cross sections for deuterons on ^{12}C. The Princeton University azimuthally varying field cyclotron was used to provide deuteron beams at 27.2, 27.6, and 28.0 MeV to bombard a 1.20-mg/cm^2 self-supporting ^{12}C foil. Figure 1(a) shows the

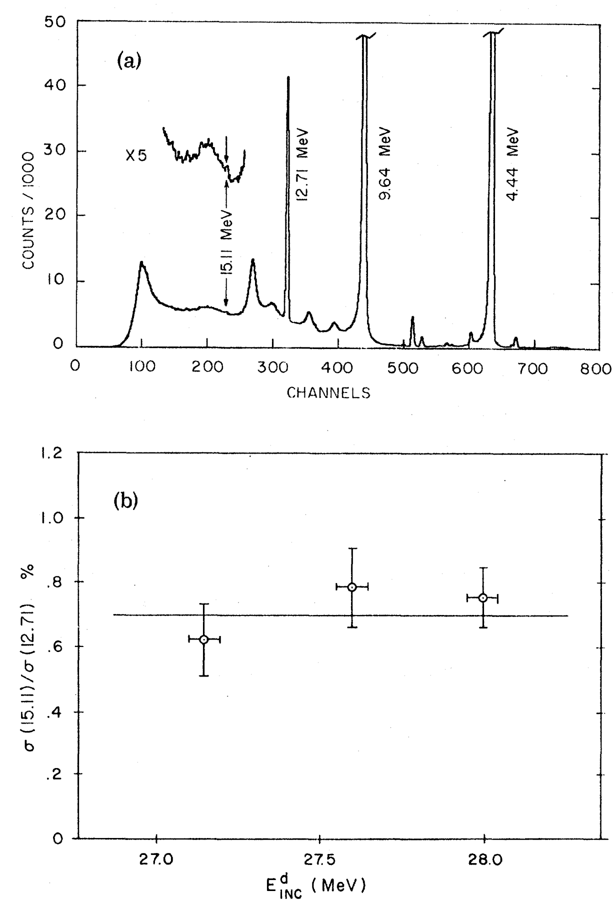

FIG. 1. (a) Spectrum of 28-MeV deuterons inelastically scattered from ^{12}C at 55°. (b) Ratio of 55° inelastic deuteron yields to the 15.11-MeV, 1^+ ($T=1$) and the 12.71-MeV, 1^+ ($T=0$) states in ^{12}C at three energies: 27.2, 27.6, and 28.0 MeV.

energy spectrum obtained with 28.0-MeV deuterons at a scattering angle of 55°. The reaction was studied at three different energies to investigate the energy dependence of the yield in the isospin-forbidden reaction $^{12}C(d,d')^{12}C^*$(15.11 MeV). Figure 1(b) shows the ratio of the yield to the 15.11-MeV, $T=1$ level to that of the strongly excited 12.71-MeV, 1^+, $T=0$ level. It is evident that this ratio is approximately independent of energy and has a value 0.0070 ± 0.0012. If we assume that the observed cross section to the $T=1$, 15.11-MeV level arises as a direct excitation of a small admixture of the $T=0$ configuration at 12.71 MeV, the ratio corrected for Q dependence provides a value for β^2 [see Eq. (1)]. With the use of a distorted-wave Born-approximation (DWBA) calculation for the spin-flip excitation of $p_{3/2}^{\ 8}\to[p_{3/2}^{\ 7}p_{1/2}]^{J=1}$ the energy dependence yields a factor of 1.6 which is uncertain to probably 20%. Thus $\beta^2=(1.6\pm0.3)\times(0.0070\pm0.0012)$. One should of course be somewhat skeptical of this result because of the simple underlying assumptions and because it represents the largest value yet reported[7] on an isospin-mixing matrix element. A recent experiment[8] on the isospin mixing of this pair of levels yielded a value for $\langle H_{\rm CD}\rangle$ of 240–720 keV, but it involved much speculation. Further, a subsequent experiment[9] has cast doubt on this determination of the α width of the 15.11-MeV level; thus such a large value for $\langle H_{\rm CD}\rangle$ must be discounted.

We have obtained an independent determination of the isospin mixing between these two levels via a comparison of the yields of the analog reactions $^{13}C(d,t)^{12}C$(15.11 MeV) and $^{13}C(d,h)^{12}B$(0.00 MeV). If charge independence holds, the ratio of the transfer cross sections is

$$\frac{d\sigma(d,h)/d\Omega}{d\sigma(d,t)/d\Omega}=2.$$

In addition to differences that result from isospin mixing between bound states, there are other charge-dependent effects that are operative. Some of these effects, such as the difference in kinetic energy and Coulomb interaction of the outgoing τ and t, may be treated[10-13] within the framework of the DWBA. In addition, if the pickup proceeds as a one-step direct interaction,

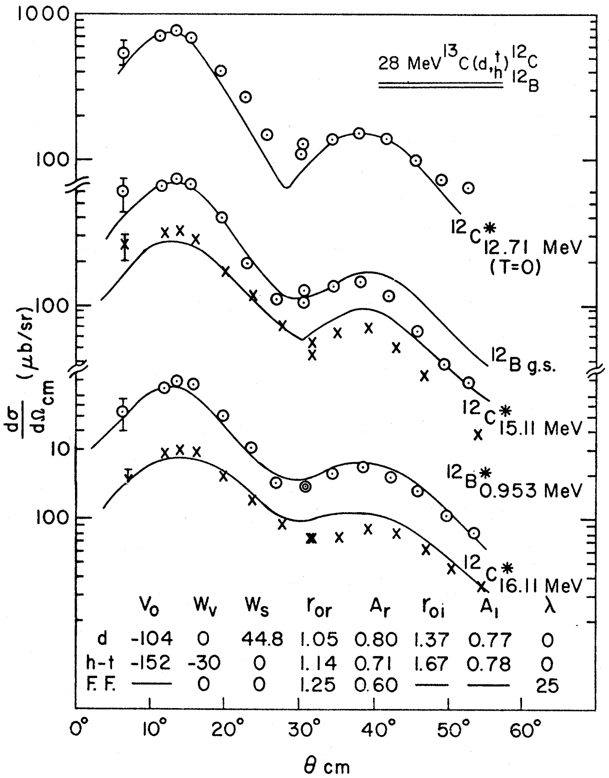

FIG. 2. Angular distributions for single-nucleon transfer from ^{13}C. Data points, circles and crosses. The DWBA angular distributions (solid lines) are obtained with the parameters listed in the figure. F.F. labels the form-factor parameters.

then the difference in the neutron and proton form factors involved in the pickup can be treated explicitly. Figure 2 shows the angular distributions obtained for the yield to the 1^+, $T=1$, 15.11-MeV level in ^{12}C and its analog, the ^{12}B ground state. The angular distributions for the 2^+, $T=1$, 16.11-MeV level, its analog in ^{12}B, as well as the 12.71-MeV level are also shown. Note the direct nature and similarity of the angular distributions in every case. As the (d,t) reaction on ^{13}C can form both $T=1$ and $T=0$ states in ^{12}C, isospin mixing leads to interference effects in the pickup amplitudes, and thus 1% mixing may give rise to much larger effects in the pickup reaction. Neglecting for the moment the charge-dependent effects in the scattering wave functions, the ratio of the analog cross sections can be written as follows:

$$\frac{\sigma((d,\tau)^{12}B)}{\sigma((d,t)^{12}C)}=\frac{\langle 1\tfrac{1}{2},\,1-\tfrac{1}{2}|\tfrac{1}{2}\tfrac{1}{2}\rangle^2\sum_{j=1/2,3/2}|\langle\tfrac{1}{2}\tfrac{1}{2}0\{|J_0 1 0;\,j\rangle|^2}{\sum_{j=1/2,3/2}|\sum_{\alpha_0,T_0}\langle T_0\tfrac{1}{2},\,0\tfrac{1}{2}|\tfrac{1}{2}\tfrac{1}{2}\rangle\beta_{T_0}\langle\tfrac{1}{2}\tfrac{1}{2}0\{|J_0T_0\alpha_0;\,j\rangle|^2},\qquad(3)$$

where the first term in the numerator is a vector addition coefficient coupling the isospins, and the second term is the fractional-parentage coefficient (FPC) linking the ground state of ^{13}C to the appropriate level in the $A=12$ system. The notation employed for the FPC's is as presented by Cohen and Kurath.[14] The results of Ref. 14 would predict the product of the square of the vector addition coefficient times the spectroscopic factor to be equal for the 12.71- and 15.11-MeV levels. This is borne out by our analysis of this data and so we use the FPC's of Ref. 14 to formulate our results. Most of the yield to these levels is due to the pickup of a $1p_{3/2}$ particle; hence, using the results of Cohen and Kurath,[14] Eq. (3) becomes

$$\sigma((d,\tau)^{12}\mathrm{B}(\mathrm{g.s.}))/\sigma((d,t)^{12}\mathrm{C}(15.11\ \mathrm{MeV})) = |0.707(1-\beta^2)^{1/2}+0.736\beta|^{-2}. \tag{4}$$

With the value[15] of $\beta=0.11$ obtained in the (d,d') experiment, the ratio is predicted to be reduced by 19% over what it would be for no isospin mixing ($\beta=0$).

DWBA fits to the relevant levels are shown in Fig. 2 along with the parameters employed. Spectroscopic factors were obtained via comparison of the DWBA calculation with the experimental data at the first maxima. For ^{12}C the values 0.49, 1.44, and 2.07 are obtained as spectroscopic factors for the 12.71-, 15.11-, and 16.11-MeV levels, respectively, while for ^{12}B, the 0.00- and 0.95-MeV levels yield 1.10 and 2.05. Thus it is clear that the relative yield to the ^{12}C 15.11-MeV level is larger than that to its analog in ^{12}B, while the 2^+ states agree very well. The value of β [see Eq. (4)] required to give the observed ratio for the analogous 1^+ levels is $\beta=0.13$, which must be taken as being in excellent agreement with the value $\beta=0.11\pm0.01$ obtained in the (d,d') measurement. Thus the value of $\langle H_{\mathrm{CD}}\rangle$ should be taken to be 250 keV with an error, say, of ±50 keV.

It seems worthwhile to mention that if the 1^+, $T=0$ and $T=1$ states are assumed to arise from $[p_{3/2}{}^7p_{1/2}]^{J=1,T}$, and a $[p_{3/2}{}^7]$ configuration is assumed for the $A=11$ system, then $\langle H_{\mathrm{CD}}\rangle$ can be obtained as the following mass difference:

$$\langle\Psi(p_{3/2}{}^7p_{1/2}),T=1|H_{\mathrm{CD}}|\Psi(p_{3/2}{}^7/p_{1/2}),T=0\rangle$$
$$=M(^{11}\mathrm{C},0.00)-M(^{11}\mathrm{B},0.00)-M(^{12}\mathrm{C},15.11)+M(^{12}\mathrm{B},0.00)=240\ \mathrm{keV}.$$

This phenomenological calculation of course includes *all* charge-dependent effects that may be present in the nucleus.

While we feel confident in the results obtained for the isospin mixing of these 1^+ levels in ^{12}C, the experimental techniques used here may not be universally employable. The interpretation of this set of measurements is especially simple because just one common 1^+, $T=0$ level appears to have any yield in both the (d,d') and (d,t) reactions and thus one need not be concerned about the effects of other levels. In general, this will not be true and the more typical situation may well be far more complicated.

Thus it appears that another matrix element between states of different T has been found which is considerably larger than is calculated using electromagnetic interactions.[8] Perhaps we are acquiring solid evidence for requiring a charge-dependent part of the short-range interaction in nuclei.

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[15]Of course the (d,d') experiment does not fix the sign of β. The sign is, however, determined from the value of $\langle H_{CD}\rangle$ calculated using the mass differences cited in the next to last paragraph of this Letter. This result is to be expected on physical grounds and, as is the case for ^{8}Be (Refs. 1–3), the neutron pickup strength tends to increase in the upper level as this configuration has the higher Coulomb energy.

Doorway States and Background Cross Sections in ^{29}Si (γ, n)†

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A study of the reaction ^{29}Si(γ,n) near threshold suggests that a doorway state with $J^\pi = \frac{3}{2}^-$ common to the channels ^{28}Si$+n$ and ^{29}Si$+\gamma$ lies near 750 keV. We observe experimentally Lane's prediction of a significant nonresonant background cross section associated with strong partial-width correlations.

Evidence for doorway states[1] which influence radiative excitation and decay of highly excited nuclear states has been based in large part on the observation of nonstatistical effects in the resonance structure of the radiative cross sections. Recent experimental efforts[2,3] have focused on observation of resonance structure in two reaction channels leading to formation of the same compound states. The objective in these studies has been to observe in each reaction local concentrations of strength that correspond to excitation of the same intermediate states, and further to establish a correlation between the partial widths of these states. Such correlation effects can be interpreted in terms of a doorway state "common" to both channels.

As evidence for a common doorway state in ^{29}Si, this note reports the localization of resonance strength in the reaction ^{29}Si$+\gamma \rightarrow {}^{29}$Si* at the same excitation as proposed by Newson[4] for a neutron doorway in the reaction ^{28}Si$+n$, and an almost complete correlation between the partial widths for the corresponding resonances in the two reaction channels. At the same time we wish to present evidence for a third anomaly which can be attributed to the presence of a common doorway state, namely, the presence of a strong background cross section which produces a pronounced interference asymmetry in the shape of a resonance in the (γ,n) reaction at 761 keV. Lane[5] recently predicted such a nonresonant cross section as a direct consequence of the existence of strong correlations in partial widths.

The data were obtained from high-resolution studies of the photoneutron cross section near threshold for ^{29}Si. The measurements were performed at the threshold photoneutron facility[6] at the Argonne high-current electron linac. A 63-g sample of SiO_2 enriched to 95% ^{29}Si was irradiated by a pulsed bremsstrahlung beam with the end-point energy adjusted so that the nuclear states excited by photon absorption could decay by neutron emission only via a transition to the ground state of ^{28}Si. Neutron resonance groups corresponding to each of the states excited were observed by time-of-flight measurements, with the array of neutron detectors set to observe neutrons emitted at 90° and 135° relative to the photon beam. Data taken at 90° with a proton-recoil detector are shown in Fig. 1. A measurement of the photoneutron spectrum with ^{6}Li-glass neutron detectors covering the energy range 5–400 keV revealed only one additional weakly excited resonance level at 60 keV. Extensive data on the total neutron cross section of ^{28}Si are available from the measurements of Schwartz, Schrack, and Heaton.[7] A comparison of the corresponding resonance energies, corrected for recoil effects in the photon and neutron channels, gave agreement for all neutron groups observed in the (γ,n) reaction. One striking feature of the photoneutron spectrum is the sharp interference asymmetries observed in the shapes of resonances at 761 and 530 keV.

We attempted to assign spins of the strong neutron groups by studying the angular distribution of the photoneutrons. Dipole absorption by the $\frac{1}{2}^+$ ground state of ^{29}Si excites $\frac{1}{2}$ and $\frac{3}{2}$ states which then decay by neutron emission to the 0^+ ground state of ^{28}Si. For the spin sequence $\frac{1}{2}-\frac{1}{2}-0$, the