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Study of the isospin response of the ^{4}He continuum using the ^{4}He$(p,p'X)$ reaction

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Cross sections for the ^{4}He$(p,p't)$ and $(p,p'h)$ reactions have been measured at a bombarding energy of 101.2 MeV. Interpreted within a resonance excitation and decay model, the measurements permit a study of charge-symmetric single-nucleon decays of ^{4}He resonances. Measured angular correlations indicate that most of the yield arises from the excitation of the generalized dipole response. The results are consistent with minimal isospin mixing in the region of the dipole resonance.

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The strong interaction is expected to preserve charge symmetry; i.e., after correcting for Coulomb effects, the *p-p* and *n-n* interactions should be equal. Recent experiments [1,2] have established the magnitude of one class of charge symmetry breaking (CSB) interactions in nucleon-nucleon scattering. The comparison of charge-symmetric single-proton and single-neutron decay rates from an excited state of a self-conjugate nucleus is expected to provide an additional test of CSB in nuclei [3]. To the extent that the influence of the Coulomb interaction is small, any CSB of the strong interaction will be reflected by a difference in these decay rates. One widely studied application of this method [4–10] has been to search for isospin mixing of the giant dipole resonance (GDR) of ^{4}He by observing the ratio of cross sections, $R_\gamma=\sigma(\gamma,p)/\sigma(\gamma,n)$. If charge symmetry is exact, then R_γ should be unity.

An extensive evaluation of photoabsorption measurements and the related, inverse radiative capture reactions by Calarco, Berman, and Donnelly (CBD) came to the surprising conclusion that $R_\gamma\approx 1.7$ at the peak of the ^{4}He GDR [4]. Numerous theoretical calculations [11–14] have failed to account for such a large value. The Coulomb interaction can account for at most a 10% increase of R_γ beyond the simplest expectations based on charge symmetry. Since the lowest lying 1^-, $T=0$ state in ^{4}He was expected at quite high excitation [13], the CBD value of R_γ can only be accommodated by inclusion of sizable CSB terms in the nucleon-nucleon interaction.

Not surprisingly, the CBD conclusions have sparked a new round of experiments. Recently, $\sigma(\gamma,p)$ was remeasured by Bernabei *et al.* [5] and $\sigma(p,\gamma)$ was remeasured by Feldman *et al.* [6]. Their results (referred to as FB) are much smaller than those in the CBD evaluation. These data give an average value $R_\gamma\approx 1.1$ in the vicinity of the GDR, consistent with theoretical calculations. However, a measurement [15] of photon elastic scattering from ^{4}He has constrained the total photoabsorption cross section, finding it to be larger than the sum of the FB $\sigma(\gamma,p)$ measurements and the CBD

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value for $\sigma(\gamma,n)$, but consistent with the sum of the values suggested by CBD that provide the anomalous R_γ. If the decay of the GDR is dominated by single-nucleon emission, then the sum of $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ should give the total photoabsorption cross section. The situation has become even more controversial since yet another remeasurement [9] of $\sigma(\gamma,p)$ was found to be consistent with the original CBD values.

The determination of R_γ at the peak of the GDR in ^{4}He using absolute cross sections is complicated since $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ have usually been measured separately using different techniques, thus permitting unknown systematic errors to influence the deduced ratio. Recently, a more direct measurement of R_γ has been made by Florizone *et al.* [10] where single-nucleon decay yields were measured with a single apparatus. That experiment found R_γ consistent with minimal isospin mixing in the region of the GDR, contradicting the CBD conclusions. A similar direct measurement of R_γ for excitation energies (ω) above 31 MeV also exists and gives a ratio near unity [8]. As with many of the previous measurements, the recent experiment covers only a limited portion of the decay-product angular distribution. The determination of the cross sections thus rely on model calculations of the shape of the angular distribution.

Other experiments have provided data complementary to the photoabsorption results. Measurements [16] of $^4\mathrm{He}(e,e'p)$ and $^4\mathrm{He}(e,e'n)$ cross sections showed little isospin mixing in the GDR region, although the $^4\mathrm{He}(e,e'n)$ angular range was quite limited and the conclusions relied on a model calculation to explain significant differences between the angular correlations. Other "complementary" experiments [17] have also yielded results consistent with no isospin mixing but questions have arisen regarding their relationship to R_γ [18].

We have used inelastic scattering of 101.2-MeV protons to excite the ^{4}He continuum and an apparatus enabling simultaneous detection of triton (t) and ^{3}He (h) ions resulting from the charge-symmetric proton and neutron decays of the ^{4}He excitations. This allows direct determination of the ratio of coincident yields, $R_X = \sigma(p,p't)/\sigma(p,p'h)$, expected to be related to R_γ. As with the work of Florizone *et al.*, this technique should eliminate potential systematic errors that may be present in previous determinations of R_γ. Using the (p,p') reaction to excite the ^{4}He continuum is somewhat easier from an experimental standpoint than the analogous measurement of R_γ. Small momentum transfers delivered by real photons produce very low energy mass-3 decay particles making their detection difficult.

One drawback in using hadronic probes is that states other than the GDR are likely to be excited, whereas in the long wavelength limit, photoabsorption exclusively excites the GDR. The present experiment will yield complementary results provided the GDR is excited by the $^4\mathrm{He}(p,p')$ reaction and can be distinguished from other multipolarity excitations. To aid this distinction, we have also measured $^4\mathrm{He}(p,p'X)$ ($X=t,h$) angular correlations as a function of ω. A Legendre analysis of that data determines the relative angular momentum of the nucleon/mass-3 final state, constraining the multipolarity of the excitations through angular momentum and parity conservation.

We have also measured the $^4\mathrm{He}(p,p'd)$ and the inclusive $^4\mathrm{He}(p,p')$ cross sections. The angle-integrated coincidence cross sections scaled by the inclusive measurements determine the branching ratios for the decay of continuum states. As discussed below, a combined analysis of the $(p,p'd)$ and $(p,p't)$ data allows an independent determination of the $^4\mathrm{He}\rightarrow n+h$ branching ratio.

The experimental apparatus was mounted in the 162-cm scattering chamber at the Indiana University Cyclotron Facility. A 101.2-MeV proton beam was incident on a 30-cm diameter gas cell containing helium at a pressure of 225 T and room temperature. Scattered protons were detected in the "ejectile" telescopes mounted on the scattering chamber's movable arms. These arms rotated about the center of the gas cell allowing measurements in the angular range $20 < \theta_{p'} < 40°$. The corresponding range of momentum transfers for the $^4\mathrm{He}(p,p')$ reaction is $185 < q < 255$ MeV/c. The details of the ejectile arm telescopes are contained in Ref. [19].

The apparatus used for detecting mass-3 ions ("recoils") was contained within the target chamber thus eliminating the need for low-energy ions to pass through a thick gas target exit window. This enables the broad coverage of rest-frame decay angles critical for accurate determination of the angular correlations. Recoil detectors consisted of position-measuring horizontal drift chambers backed by three detector telescopes, each comprised of a 100-μ-thick silicon surface barrier (SSB) detector and a 5-mm-thick lithium-drifted silicon (SiLi) detector. These detectors are all contained within the same box in an atmosphere of C_4H_{10} at 220 T. In this configuration there is no need for a window between the recoil arm drift-chamber (RADC) and the silicon detectors, thus eliminating an undesirable dead layer. The pressure differential between the target chamber and the RADC was less than 10 T so that a very thin, 1.6 μm Mylar window could be used as a barrier between gases. The SSB/SiLi telescopes provide high resolution total energy and particle identification information.

Together, the ejectile and recoil arm measurements enable complete reconstruction of the reaction kinematics for each event. The ejectile-arm energy and angle measurements determine $\vec{q}$ and ω. The rest-frame decay angle Θ of the recoil particle (with respect to $\vec{q}$) is determined by using the measured location of the reaction vertex and either the position of the recoil event in the RADC or the energy as determined by the SSB/SiLi telescope. The recoil particle's kinetic energy can be corrected for energy loss in the dead layers by reconstructing the trajectory from the position measurements.

Figure 1 shows representative p-t,h angular correlations at $q=225$ MeV/c. The p-t angular correlations span the complete angular range with the inclusion of $^4\mathrm{He}(p,p'p)t$ points, converted to get the angle for the unobserved triton ($\Theta_t = 180° - \Theta_p$). The angular range of the $^4\mathrm{He}(p,p'h)$ data is limited by loss of low-energy helions in the target/detector system dead layers.

The shape of the angular correlations depends on the relative angular momentum of the two-particle state resulting from the decay of the excited ^{4}He nucleus. This sequential excitation/decay assumption is commonly used and has been

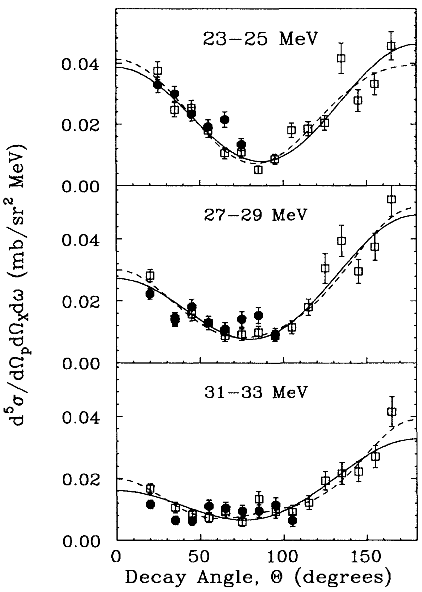

FIG. 1. Typical angular correlations for ^{4}He($p,p't$) (open) and ^{4}He($p,p'h$) (filled). Also shown are Legendre polynomial fits with $L_{\max}=2$ (solid) and $L_{\max}=4$ (dashed).

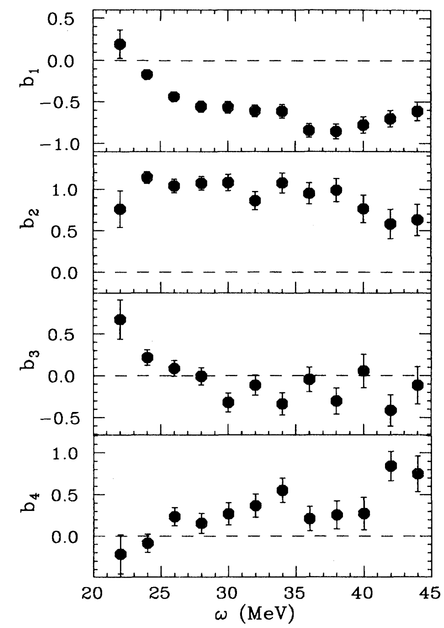

FIG. 2. Coefficients for a Legendre polynomial fit with $L_{\max}=4$ to the ^{4}He($p,p't$) angular correlations.

applied to the analysis of the ^{4}He($e,e'X$) data [16]. In general, the angular correlations can be written in terms of spherical harmonics:

$$W(\Theta,\phi,\omega,q)=\left|\sum_{L,M} C_{L,M}(\omega,q)Y_L^M(\Theta,\phi)\right|^2 \qquad (1)$$

where the $C_{L,M}$ are q and ω dependent amplitudes. The indices L and M represent the relative orbital angular momentum and its projection for the scattering state resulting from decay of the ^{4}He resonance(s). In this representation, the $\hat{z}$ quantization axis has been chosen along $\vec{q}$ and the $\hat{y}$ axis is perpendicular to the scattering plane. If only generalized dipole resonances ($\Delta L=1$, $\Delta S=0$ or 1, and $\Delta J=0$, 1, or 2) are excited, then Eq. (1) can be rewritten as

$$W=c_0+c_1\cos^2\Theta+c_2\sin2\Theta\cos\phi+c_3\sin^2\Theta\cos^2\phi. \quad (2)$$

The vast majority of the data (except for very small Θ and ω) are from a limited range of ϕ centered about $\phi=0$ or 180° meaning the factors of $\cos\phi$ are constants. The primary effect of incomplete ϕ coverage is to shift the symmetry axis of the angular correlation away from $\Theta=90°$.

The angular correlations were fit with a Legendre polynomial series,

$$W=a_0\left(1+\sum_{l=1}^{L_{\max}} b_l(\omega,q)P_l(\Theta)\right). \qquad (3)$$

A pure dipole excitation should require only $L_{\max}=2$. Significant contributions from $l=4$ terms (i.e., b_4 comparable to b_2) will arise when quadrupole excitations are present. The lack of evidence of higher multipolarities in the ω range of interest [20] implies $L_{\max}\leqslant 4$. The meaning of large odd-l terms will depend on the magnitude of b_4. If it is large, then decays from dipole and quadrupole states can interfere to produce large odd-l coefficients. If b_4 is negligible, then a large b_1 may indicate the interference of dipole-resonance decays from different magnetic substates. That is, c_2 of Eq. (2) is nonzero and the angular correlation will be symmetric about some angle other than 90°. A large b_1 can also result from interference between decays from $\Delta L=0$ and 1 excitations. This should be expected for ω near threshold where there can be contributions to the cross section from the 0^+ state at 20.21 MeV [20].

Figure 2 shows the fit coefficients as a function of ω for the p-t angular correlations. The relatively large b_2 and small b_4, especially below 30 MeV, indicates a response dominated by generalized dipole transitions. Above 30 MeV, b_4 becomes more significant indicating the increasing importance of quadrupole excitations. Below 30 MeV, the large b_1 coefficient most likely arises from a combination of interference of the dipole state(s) with the 0^+ state and interference between different magnetic substates. b_3 is relatively insignificant.

One also must consider the possibility that the ($p,p'X$) cross sections are due to quasifree nucleon-nucleon scattering (QFS) rather than a two-step resonance excitation/decay process. Ignoring strong final-state interactions, QFS should lead to large yields when the mass-3 particles are emitted backwards in the rest frame of the excited ^{4}He nucleus or equivalently, for nucleons emitted forward. Thus, an enhancement of the back-angle ($p,p't/h$) angular correlation would be indicative of a significant QFS contribution. Figure 1 indicates that this is certainly not the case at least for the 23–25 MeV data. Furthermore, previous inclusive ^{4}He(p,p') studies [21] suggest that the response of the nuclear continuum in the region of interest is enhanced over that expected from QFS.

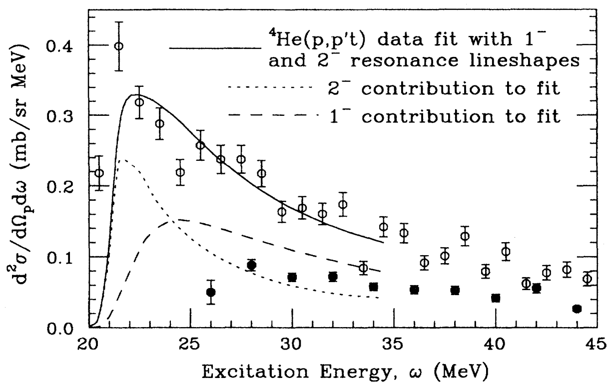

FIG. 3. Angle-integrated ^{4}He$(p,p't)$ (open) and ^{4}He$(p,p'd)d$ (filled) cross sections for $q=225$ MeV/c.

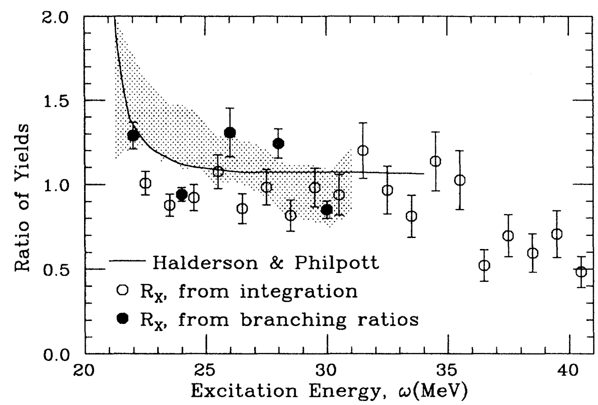

FIG. 4. Ratio of triton-to-helion yields, R_X, at $q=225$ MeV/c. Also shown is R_γ (shaded region) deduced from the data of Feldman [6] and the calculation from Ref. [14].

While the Legendre analysis suggests that the ^{4}He continuum below 30 MeV is dominated by generalized dipole transitions, it does not allow us to determine the J^π of the state(s) excited. In order to provide an estimate of the relative amounts of 1^- and 2^- strength, we have fit the angle-integrated $(p,p't)$ cross section $(4\pi a_0)$ with resonance lineshapes determined from an R-matrix analysis of the $A=4$ system [22]. This fit (Fig. 3) indicates that the region between 25 and 35 MeV is largely dominated by 1^- strength (approximately 63% of the total cross section) and a strong 2^- excitation near 22 MeV. If the 2^- response is allowed to saturate the cross section at 22 MeV then the lower limit on the 1^- strength is 0.43 ± 0.03. The failure of the fit near threshold is likely due to the omission of the 0^+ state from the fit, which, if included, would result in less deduced 2^- strength and subsequently more 1^- strength at higher excitation.

Our conclusions regarding the applicability of a two-step excitation/decay model for the $(p,p'X)$ reaction and the fraction of the yield due to 1^- strength are supported by an analysis of cross sections from the ^{4}He(p,n) reaction at 100 and 200 MeV [23]. In that work, distorted-wave impulse approximation (DWIA) calculations account for nearly all of the observed yield at low excitation as being due to isovector 2^- and 1^- resonances. DWIA calculations performed for the ^{4}He(p,p') reaction suggest that the isovector 1^- resonance excitation still dominates even though excitation of the isoscaler 1^- resonances at 24 and 28 MeV [20] is possible. This is further supported by the similarity of the shapes of the ^{4}He(p,n) spectrum to what we observe for the angle-integrated $(p,p't)$ cross section (Fig. 3).

The lack of back angle data in the present experiment prevents the direct integration of the ^{4}He$(p,p'h)$ yield over all Θ. However, there are two methods for producing a very good approximation to R_X. One way is to integrate the exclusive yields over the angular range, $0\leqslant\Theta\leqslant90°$. If only a single resonance were excited then the angle-integrated yield would be equivalent to $2\pi a_0$. The second way is to use the angle-integrated $(p,p't)$ and $(p,p'd)$ cross sections scaled by the inclusive (p,p') cross section to establish the branching ratios for the $p+t$ and $d+d$ decays of the ^{4}He excitations. The $n+h$ decay branch can be inferred from these measurements, since for $\omega<30$ MeV the single-nucleon decays and the deuteron decay branches account for nearly 100% of the width of the ^{4}He resonances. The resulting values of R_X are shown in Fig. 4. We see that the two methods of extracting the ratio are in good agreement. The average value of R_X for $24\leqslant\omega\leqslant31$ MeV is 0.95 ± 0.05 which compares favorably with the ratio of $R_\gamma=1.09\pm0.17$ based on the FB $\sigma(\gamma,p)$ measurements. These ratios are significantly less than the CBD ratio of ~1.7 near the peak of the GDR.

We observe a ^{4}He$\rightarrow d+d$ branching ratio of $\sim15\%$ in the interval $26\leqslant\omega\leqslant30$ MeV. This relatively large branching ratio must be the result of exciting states other than the GDR since previous experiments (for example, [24]) show that the ^{4}He$(\gamma,d)d$ cross section is almost three orders of magnitude smaller than the (γ,p) and (γ,n) cross sections. At present, our analysis cannot determine the multipolarity of the ^{4}He states that decay by deuteron emission. The relatively large size of the deuteron branch does not imply that the single-nucleon decay branches are significantly contaminated by quadrupole or spin-flip dipole strength. According to the most recent $A=4$ compilation [20], states in this region of excitation which decay by deuteron emission have very small proton/neutron decay branches. One exception to this is the 1^+ state at 28.3 MeV which should be primarily a $^3S_1$ state and thus give rise to an isotropic $(p,p'd)$ angular correlation. Since this is not consistent with our data, this state should not be a significant contributor to the $(p,p'd)$ yield.

In summary, an experimental method for measuring charge-symmetric single nucleon decays of the ^{4}He continuum excited by the (p,p') reaction has been presented. The method relied on detecting low-energy mass-3 ions resulting from the decay of ^{4}He resonances. A Legendre analysis of the ^{4}He$(p,p't)$ angular correlations indicates that a generalized dipole response is excited by the ^{4}He(p,p') reaction. Furthermore, the angle-integrated ^{4}He$(p,p't)$ cross section can be well represented by a response dominated by a $J^\pi=1^-$ resonance. This suggests that although this reaction does not excite ^{4}He identically to photoabsorption there are a number of similarities. The charge-symmetric ratio R_X observed in the present work is found to be unity, similar to the value of R_γ deduced from recent determinations of

$\sigma(\gamma,p)$ [5,6] and from direct $\sigma(\gamma,p)/\sigma(\gamma,n)$ ratio measurements [10]. Even if one were to argue that our results arise because of the differences between inelastic proton scattering and photoabsorption, it seems reasonable that the isospin mixing suggested by the CBD results would have a noticeable effect on our ratio; i.e., we would have observed a ratio much closer to 1.7 than our observed value of unity.

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