Charge symmetry breaking in ^{4}He

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Calculations for ^{4}He(γ,p)^{3}H and ^{4}He(γ, n)^{3}He have been performed with the recoil-corrected continuum shell model. A charge-symmetry breaking interaction has been introduced in an effort to explain the large value ($\sim$2) observed in recent experiments for the cross section ratio $R=\sigma(\gamma,\mathrm{p})/\sigma(\gamma,\mathrm{n})$. The calculations indicate that it is highly unlikely that such a large value of the cross section ratio can be obtained within standard theoretical assumptions.

NUCLEAR REACTIONS ^{4}He(γ,p), (γ,n), $E_x=20$–36 MeV; calculated $\sigma(E)$, expansion coefficients $a_k(E)$, $B_k(E)$ for $\sigma(E,\theta)$, $P(E,\theta)$. ^{3}H(p,n); calculated $A(E)$, $P(E)$. Studied influence of charge symmetry breaking interaction.

I. INTRODUCTION

The cross section ratio $R=\sigma(\gamma,\mathrm{p})/\sigma(\gamma,\mathrm{n})$ in ^{4}He has been a source of experimental controversy for some time.[1–6] Over a period of approximately ten years, the observed value of this ratio in the energy region $E_x=22$–32 MeV has fluctuated over a range of values between $\sim$1 and $\sim$2. The uncertainty in the observed ratio has been primarily due to the uncertainty in the ^{4}He(γ,n)^{3}He cross section. Recently, two independent measurements have achieved almost identical results for $\sigma(\gamma,\mathrm{n})$. In Ref. 3, a monochromatic photon beam was used to determine ^{4}He(γ,n), and the inverse reaction, ^{3}He(n,γ)^{4}He, was measured in Ref. 4. When detailed balance is applied to the data of Ref. 4, the results are almost indistinguishable from those of Ref. 3, as is shown in Fig. 1. This result provides some confidence in the new $\sigma(\gamma,\mathrm{n})$ data which yield the surprising value of $R\approx 2$ at several points over the energy range of interest.

There have been several theoretical attempts[7–13] to explain the observed values of R by means of model calculations, but none of them appear to provide a satisfactory answer. All of the continuum calculations yield values of R close to 1. The only calculations which predict $R\approx 2$ are those of Gibson.[7] These calculations are based on the results of a bound state diagonalization among translationally invariant shell model basis states. Transitions are calculated from the ground state into each of the discrete $J_\pi=1^-$ eigenstates and then subsequently given widths. As a result, the calculated cross sections do not contain the important interferences which arise by virtue of the overlapping of the resonances and which can greatly reduce the effect of isospin mixing. None of the above studies have considered the effect of an explicit charge symmetry breaking (CSB) term in the nucleon-nucleon interaction.

Measurements[4] of the (n,γ) angular distribution coefficients show that the cross section is dominated by $E1$ transitions. Since the $E1$ translationally invariant charge is $\frac{1}{2}$ ($-\frac{1}{2}$) for p (n), the observed ratio $R\approx 2$ implies some other very large difference between the proton and neutron channels. Differences between the proton and neutron channels do arise by virtue of the Coulomb interaction, which directly affects the proton wave function and also causes the neutron threshold to lie above the proton threshold. But calculations show that these differences alone do not lead to values of R significantly different from 1 except very close to the threshold, where a characteristic rapid rise in R can be expected to occur.

The large observed value of the ratio R has been given[1] as evidence for the existence of a large CSB term in the nucleon-nucleon interaction. The purpose of this article is to test this hypothesis by introducing an explicit CSB interaction into a microscopic calculation of the continuum wave functions. This will determine the magnitude of the CSB interaction required to obtain $R\approx 2$ and will allow comparison of theoretical predictions with other data which are sensitive to charge-symmetry breaking. The motivating idea behind these calcuations has been to use the best available interaction in the best available microscopic model of the ^{4}He continuum states in order to obtain as definitive as possible a prediction of the influence of the assumed CSB interaction.

II. CALCULATION AND DISCUSSION

The calculations reported here employ the recoil-corrected continuum shell model (RCCSM).[14,15] The main feature of the model is that once nonspurious shell model states are constructed for the target and residual nuclei, exact continuum solutions are obtained in the no-polarization approximation to the translationally invariant Hamiltonian. The only inputs to the model are the two-body interaction, V_{ij}, and the oscillator size parameter, $\nu=m\omega/\hbar$. These inputs should, of course, be chosen to be as physically correct as possible. In these calculations, V_{ij} is taken to be the M3Y g-matrix interaction of Bertsch *et al.*,[16,17] which includes central, tensor, and spin-orbit components. The oscillator size parameter was set at $\nu=0.36$ fm^{-2}, since this value best reproduces the ^{3}He

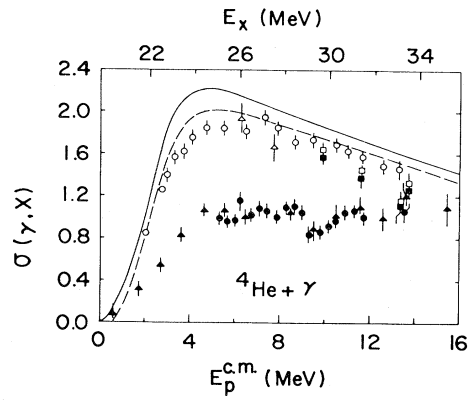

FIG. 1. Photodisintegration cross sections. The ^{4}He(γ,n) calculation is the dashed line; the ^{4}He(γ,p) calculation is the solid line. The solid triangles are the neutron data of Ref. 3; the solid circles are the neutron data of Ref. 4; the solid squares are the neutron data of Ref. 2; the open circles are the proton data of Ref. 31; the open triangles are the proton data of Ref. 32; and the open squares are the proton data of Ref. 3.

form factor.

The approximations in the present calculation should be made clear. As usual, the photon absorption process is treated perturbatively so that the transition amplitude is given as a matrix element of the electromagnetic transition operators between eigenstates of the RCCSM. Both spin dependent and spin independent $E1$, $E2$, and $M2$ operators are included. The $M1$ operator would also have been included except that, with the specific structure which is assumed for the ^{4}He ground state, its contribution is identically zero. The RCCSM eigenstates themselves are calculated in the one-particle—one-hole approximation. This means that the ^{4}He ground state can contain correlations of the type

$$[a^{\dagger}_{ns_{1/2}}a_{0s_{1/2}}]^0_0\,|\,0\rangle$$

TABLE I. Properties of some calculated levels for ^{4}He and ^{16}O. E_μ is the R-matrix eigenvalue which gives the level energy before coupling to the breakup channels. This energy is a c.m. energy measured relative to the proton threshold. Γ_R is the corresponding width extracted via a single level formula. T is the dominant isospin, 0 or 1, and $P(T')$ is the percentage admixture of the other isospin.

Nucleus	J^π	E_μ (MeV)	Γ_R (MeV)	T	$P(T')$ %
^{4}He	1^-	3.52	3.82	1	3.3
	1^-	4.06	4.66	1	0.9
	1^-	4.58	4.88	0	4.1
^{16}O	1^-	3.12	1.76	0	1.4
	1^-	4.77	0.75	1	1.3
	1^-	6.33	2.04	1	2.6
	2^-	3.28	0.94	1	7.0
	2^-	4.08	1.17	0	5.4
	2^-	5.81	1.06	1	45.6
	2^-	6.19	0.64	0	49.7

but not those having $l\neq 0$. The excited states are of 1p-1h character coupled to ^{3}He + n and ^{3}H + p breakup channels. A possible deuteron breakup channel is omitted. However, the deuteron channel opens at $E_x = 23.85$ MeV, at which energy the observed value of R is already large (~ 2). The model yields excellent agreement with particle scattering data over the energy region of interest.[15]

The calculated (γ,n) and (γ,p) cross sections from Ref. 11 are shown in Fig. 1 along with the new (γ,n) data. The only charge symmetry breaking interaction included in this calculation is the Coulomb force. The results demonstrate that the Coulomb interaction alone is insufficient to reproduce the observed ratio of cross sections. This may then be taken as evidence for enhanced isospin mixing in the 1^- resonances caused by a CSB interaction.

However, there are other phenomena which are also sensitive to isospin mixing in the ^{4}He 1^- states. An important example is found in possible differences between polarization (P) and analyzing powers (A) in ^{3}H(p,n)^{3}He. Such differences can only arise if isospin symmetry is broken.[18]

The polarization-analyzing power difference ($P-A$) may be expanded as a series of associated Legendre polynomials,[19,20]

$$k^2(d\sigma/d\Omega)(P-A)=\sum_L A_L P_L{}^1(\cos\theta)\ , \tag{1}$$

where the coefficients are given by

$$A_L=\sum_{\alpha\beta J\alpha'\beta' J'} C(\alpha\beta J;\alpha'\beta' J';L)(S^J_{\beta\alpha}A^{J'*}_{\beta'\alpha'})\ , \tag{2}$$

where

$$S^J_{\beta\alpha}=\tfrac{1}{2}[T^J_{\beta(\mathrm{n})\alpha(\mathrm{p})}+T^J_{\alpha(\mathrm{n})\beta(\mathrm{p})}] \tag{3a}$$

and

$$A^J_{\beta\alpha}=\tfrac{1}{2}[T^J_{\beta(\mathrm{n})\alpha(\mathrm{p})}-T^J_{\alpha(\mathrm{n})\beta(\mathrm{p})}]\ . \tag{3b}$$

In the above equations, α and β stand for neutron or proton subchannels belonging to a given total spin and parity, and the $T^J_{\alpha(\mathrm{n})\beta(\mathrm{p})}$ are the corresponding T-matrix elements for the (p,n) reaction. From examining the splitting strengths,[19] $A^J_{\beta\alpha}$, one finds that the only significant contributions in the RCCSM to $P-A$ in ^{4}He are associated with the 1^- states. As a contrasting example, for ^{16}O, contributions from both 1^- and 2^- states can be large. Table I gives a summary of the calculated 1^- and 2^- resonances for ^{4}He and ^{16}O in the energy region of interest. The degree of isospin mixing listed in the table was calculated from the R-matrix eigenstates.[21] The widths were determined from the same eigenstates via a one-level formula.[22] One notices the highly mixed 2^- states in ^{16}O. The calculated magnitude of $P-A$ from these 2^- states is approximately the same size as from the much more weakly mixed 1^- states. Therefore, one sees that $P-A$ measurements do not directly exhibit the degree of isospin mixing. Rather, the observation of a difference between P and A indicates only that isospin mixing is present.

As one can see from Fig. 2(b), both the data[23] and the calculations[24] demonstrate isospin mixing for the ^{16}O states. The calculation shown reproduces the observed

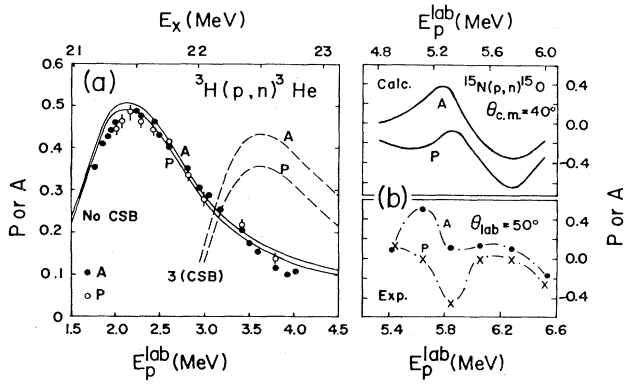

FIG. 2. Polarization and analyzing power. (a) ^{3}H(p,n)^{3}He. The solid curves are the calculations with no CSB. The dashed curves are the calculations with 3 times CSB. The data are from Ref. 25. (b) ^{15}N(p,n)^{15}O. The solid curves are the calculations with no CSB. The data are from Ref. 23. The dashed curve is to guide the eye.

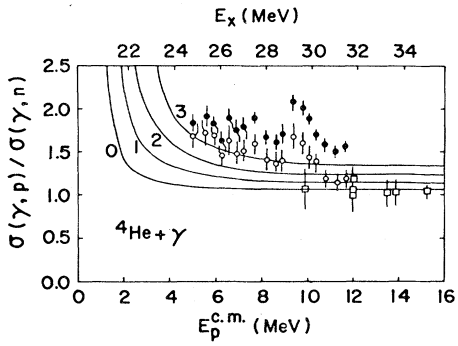

FIG. 3. The ratio $R=\sigma(\gamma,\mathrm{p})/\sigma(\gamma,\mathrm{n})$. The solid lines are the calculations with 0, 1, 2, and 3 times CSB. The solid circles are the data of Ref. 4 divided into the data of Ref. 31; the open circles are the data of Ref. 4 divided into the data of Ref. 5; the open squares are the data of Ref. 2.

magnitude of $P-A$ with only the Coulomb force breaking the isospin symmetry. Figure 2(a) demonstrates that no significant $P-A$ splitting is observed in ^{4}He even though the calculated 1^- levels are substantially mixed. The reasons for the absence of a significant $P-A$ splitting in ^{4}He are rather subtle,[19] but one main reason is the large widths of the 1^- states. When the continuum is included in the calculation, the states become so broad that they completely overlap one another. The $P-A$ splitting is therefore not observed, because the isospin mixed states remain essentially degenerate. In the ^{16}O case, the levels are well separated compared to their widths and one can observe regions of proton-neutron asymmetry in the wave functions.

It is clear from the size of the ^{4}He 1^- widths that one cannot expect to deduce the degree of isospin mixing from arguments based on an analysis of the three individual 1^- resonances in ^{4}He. The resonances overlap so much that there is just a region of 1^- strength. This circumstance has also been pointed out by Barker and Mann.[26] Therefore, if one wishes to extract information about charge symmetry breaking from the observed value $R\sim 2$, one must perform continuum calculations in which a CSB interaction is introduced directly into the Hamiltonian.

Many attempts have been made to calculate CSB potentials.[27] Many different results were obtained for the possible contributing diagrams because of uncertainties in the coupling constants. It was clear, however, that no physically reasonable choices for the coupling constants could produce a CSB potential large enough to account for the Okamoto-Nolan-Schiffer[28,29] anomaly. The calculations do, however, provide one with an idea of the possible ranges associated with CSB potentials. Using this information, Sato[30] and Schlomo[27] have constructed phenomenological CSB potentials which do a reasonable job of eliminating discrepancies in the Coulomb energy shifts in mirror nuclei. The potential of Ref. 27 is

$$V_{\mathrm{CSB}}=(V_\sigma m_\sigma^3/4\pi)Y(m_\sigma r) + \vec{\sigma}_1\cdot\vec{\sigma}_2(V_\pi m_\pi^3/4\pi)Y(m_\pi r)\ , \tag{4}$$

where

$$V_\sigma=65\ \mathrm{MeV\,fm^3},\quad V_\pi=20\ \mathrm{MeV\,fm^3}\ , \tag{5}$$

and where

$$Y(x)=e^{-x}/x\ . \tag{6}$$

The range parameters are fixed at $m_\sigma=2.79\ \mathrm{fm}^{-1}$ and $m_\pi=0.704\ \mathrm{fm}^{-1}$. This CSB potential is used in the calculations that follow and will be included as an additional repulsion between protons. There is also evidence for a charge independence breaking (CIB) interaction.[27] This will be included as a 3% increase in the $T=1$, p-n interaction. However, the CIB interaction does not have a substantial effect on any of our calculated results.

In Fig. 3 are plotted the data of Ref. 4, expressed as the ratio $R=\sigma(\gamma,\mathrm{p})/\sigma(\gamma,\mathrm{n})$ as in Ref. 4 The ratio R was constructed by taking the (γ,n) data of Ref. 4 divided into the (γ,p) data of Ref. 5 (shown as open circles) and divided into the (γ,p) data of Ref. 31 (shown as solid circles). This gives one an idea of the possible spread in R due to different (γ,p) results. Also shown in Fig. 3 are calculated values of R including 0, 1, 2, and 3 times the potential in Eq. (4). The effect of the CSB interaction is twofold: It raises the calculated (p,n) threshold from 0.69 MeV (no CSB) to 2.05 MeV (3×CSB), compared with the measured threshold energy of 0.76 MeV, and it also causes an increase in the ratio R at energies above the threshold. As one can see, to obtain a value of R within the observed range, it requires a CSB interaction approximately three times larger than that required to eliminate the Okamoto-Nolan-Schiffer anomaly.

From the above calculations, it is found that the matrix element between the two predominately $S=1$, $J^\pi=1^-$ levels, including both internal and external mixing, of the 3×CSB + Coulomb interaction is about 750 keV. Despite the enormous size of this CSB interaction, the calculated angular distributions still do an excellent job of reproducing the data, as shown in Fig. 4. The asymmetry coefficients for $(\vec{p},\gamma)$ do become slightly worse, as is shown in Fig. 5, but not significantly so. However, when comparison is made with P and A from ^{3}H(p,n)^{3}He, one

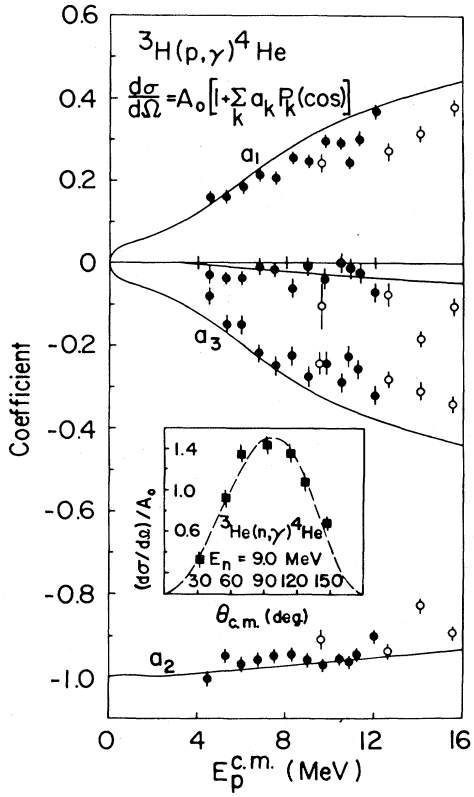

FIG. 4. The angular distribution coefficients for ^{3}H(p,γ)^{4}He. The solid curves are the calculation with 3(CSB). These curves are virtually indistinguishable from the corresponding results (Ref. 11) obtained with no CSB. The solid circles are the data of Ref. 33; the open circles are the data of Ref. 34. The insert is a cross section for ^{3}He(n,γ)^{4}He. The dashed curve is the calculation with 3(CSB). The solid squares are the data of Ref. 35.

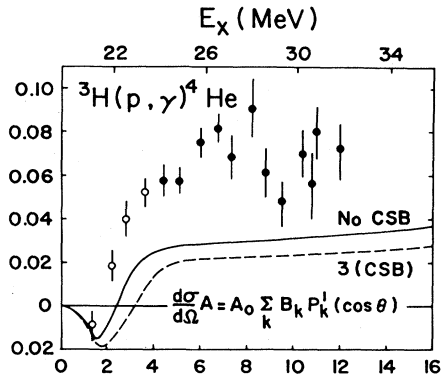

FIG. 5. The B_2 asymmetry coefficient for ^{3}H(p,γ)^{4}He. The solid curve is the calculation with no CSB. The dashed curve is with 3(CSB). The solid circles are the data of Ref. 33; the open circles are the data of Ref. 36.

sees from Fig. 2(a) that the agreement with experiment is destroyed. Not only are the peaks in P and A significantly shifted in energy by the CSB interaction, but the calculated $P-A$ differences become significantly larger than the observed values. The maximum measured $P-A$ difference occurs at the maximum of P and A and is zero to within an error of approximately 0.02 to 0.03.[37] The calculated $P-A$ values with $3\times$CSB are some four times larger than this uncertainty.

III. CONCLUSION

In summary, these calculations suggest that the large observed value $R \approx 2$ cannot be explained within the standard assumptions of nuclear theory even when an explicit CSB interaction is included in the Hamiltonian. A CSB interaction of sufficient strength to reproduce the observed value of R is three times stronger than that needed to account for the Okamoto-Nolan-Schiffer anomaly. It also yields a (p,n) threshold energy which is almost three times larger than the observed one and this, in turn, leads to results for P and A and $P-A$ which are significantly different from the data. A CSB interaction of this magnitude would obviously have been observed in many other reactions.

The above arguments are based on RCCSM calculations which are themselves limited by the truncations which were necessary to simplify the calculations (no multiparticle multihole excitations and no breakup channels other than single nucleon channels). However, the present model has been quite successful in describing other low energy data and it is difficult to see how any more complicated structures could create the very large proton-neutron asymmetry which is implied by the observed values of R. In addition, the calculations reported here have employed a specific form for the CSB potential. While the form which we have assumed appears to be very reasonable, we cannot rule out the possibility that some different form for the CSB potential might exist which does not lead to the discrepancies described above.

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