however, enter rather directly in the level-density calculation. In the present calculations as in previous calculations with the two-center model, the volume of the equipotential surface for $V = \frac{1}{2}m\omega^2R^2$ with $\hbar\omega = 41A^{-1/3}$ MeV and $R = r_0A^{1/3}$ fm is maintained. For the large saddle-point distortions the volume contained in other equipotentials is not necessarily conserved. It should be noted, however, that this is a general difficulty that appears in all deformed single-particle calculations that are more general than the simple harmonic-oscillator potential of the Nilsson model. There is also an indication that volume conservation is inadequately treated in the latter potential in that the Strutinsky normalization procedure is necessary to keep the deformation energy well behaved at large deformations. We have tried to qualitatively account for proper volume conservation by requiring the Fermi energy to be invariant with deformation. Some improvement is obtained, but not sufficient to reproduce observations. This problem is being pursued further.

---

*Work supported in part by the U. S. Atomic Energy Commission.

[1] V. M. Strutinsky, Nucl. Phys. A95, 420 (1967), and A122, 1 (1968).

[2] S. G. Nilsson, C. F. Tsang, A. Sobiczewski, Z. Szymanski, S. Wycech, C. Gustafson, I. L. Lamm, P. Möller, and B. Nilsson, Nucl. Phys. A131, 1 (1969).

[3] I. Halpern and W. J. Nicholson, University of Washington Cyclotron Research, Annual Progress Report, 1960 (unpublished).

[4] J. R. Huizenga, R. Chaudhry, and R. Vandenbosch, Phys. Rev. 126, 210 (1962).

[5] G. M. Raisbeck and J. W. Cobble, Phys. Rev. 153, 1270 (1967).

[6] C. J. Bishop, R. Vandenbosch, I. Halpern, R. Shaw, and R. Aley, Bull. Amer. Phys. Soc. 14, 852 (1969).

[7] H. C. Britt, S. C. Burnett, B. H. Erkkila, J. E. Lynn, and W. E. Stein, Phys. Rev. C 4, 1444 (1971).

[8] U. Mosel and H. W. Schmitt, Phys. Lett. 37B, 335 (1971); U. Mosel, to be published.

[9] L. G. Moretto, S. G. Thompson, J. Routi, and R. C. Gatti, Phys. Lett. 38B, 471 (1972).

[10] U. Mosel and H. W. Schmitt, Phys. Rev. C 4, 2185 (1971).

[11] P. Decowski, W. Grochulski, A. Marcinkowski, K. Siwek, and Z. Wilhelmi, Nucl. Phys. A110, 129 (1968).

[12] We are grateful to M. Bolsterli for making this program available to us.

[13] D. S. Burnett, R. C. Gatti, F. Plasil, P. B. Price, W. J. Swiatecki, and S. G. Thompson, Phys. Rev. 134, B952 (1964).

[14] A. Khodai-Joopari, University of California Radiation Laboratory Report No. UCRL-16489, 1966 (unpublished).

[15] V. V. Pashkevich, Nucl. Phys. A169, 275 (1971).

[16] M. Bolsterli, E. O. Fiset, J. R. Nix, and J. L. Norton, Phys. Rev. C 5, 1050 (1972).

[17] M. G. Mustafa, U. Mosel, and H. W. Schmitt, to be published.

Charge-Dependent Effects in the Photodisintegration of ^{4}He†

J. T. Londergan

Department of Physics, Indiana University, Bloomington, Indiana 47401, and Department of Physics, Case Western Reserve University, Clevelend, Ohio 44106*

and

C. M. Shakin

Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106

(Received 12 May 1972)

^{4}He$(\gamma,p)^3$H and ^{4}He$(\gamma,n)^3$He cross sections have been calculated for photon energies from the (γ,n) threshold to 34 MeV. Effects of Coulomb interactions, channel spin mixing, and mass differences have been taken into account using a coupled-channel continuum-shell-model calculation of p-^{3}H and n-^{3}He elastic and charge-exchange scattering. The ratio $\sigma(\gamma,p)/\sigma(\gamma,n)$ is predicted to be close to 1, except at energies very close to the (γ,n) threshold.

Recent experiments[1,2] of the photodisintegration reaction ^{4}He(γ,n) showed a striking behavior for the neutron total cross sections. In particular, the (γ,n) measurements of Berman, Fultz, and Kelly[1] (BFK) for photon energies 21 MeV $\leq E_\gamma \leq 31$ MeV were significantly smaller than the

^{4}He(γ,p) cross sections inferred from the ^{3}H$(p,\gamma)^4$He data of Meyerhof, Suffert, and Feldman,[3] and were also substantially smaller than earlier measurements of ^{4}He(γ,n) cross sections,[4] which were essentially in agreement with the existing (γ,p) measurements in this energy range. Compared with the data of Meyerhof, Suffert, and Feldman,[3] the BFK results gave a ratio $R \equiv \sigma(\gamma,p)/\sigma(\gamma,n)$ of approximately 2, and R appeared to be increasing for $E_\gamma \sim 31$ MeV. The quantity R has recently been extracted by Dodge and Murphy[5] from electron-scattering experiments on ^{4}He corresponding to photon energies 30 MeV $\leq E_\gamma \leq 51.8$ MeV. The extracted (γ,p) cross sections of Dodge and Murphy are in agreement with the cross sections of Meyerhof, Suffert, and Feldman, and they obtain a value for R approximately equal to 1, apparently in disagreement with the BFK results.

The large ratio of R obtained by BFK was rather unexpected, since simple isospin arguments predict a proton-neutron ratio of 1. Differences in proton and neutron cross sections can occur through (i) the Coulomb interaction in p-^{3}H final-state scattering, (ii) the n-^{3}He and p-^{3}H mass difference ($Q = 0.764$ MeV), (iii) effects of higher multipoles ($E2$, $M2$, etc.) in the photodisintegration reaction, (iv) charge-dependent effects in the nuclear interaction, and (v) charge-dependent effects from three- or four-body final states. BFK noted that a naive interpretation of their experimental results implied a violation of charge symmetry significantly greater than zero, while that suggested from an analysis of low-energy $A = 4$ scattering data[6] was consistent with zero.

In view of the present experimental situation, it is clearly of theoretical interest to examine the (γ,p) and (γ,n) cross sections from ^{4}He, and using realistic continuum and bound-state wave functions to investigate sources of charge-dependent effects in the photodisintegration reaction without invoking large violations of charge symmetry in the nuclear interactions. This Letter describes the results of a theoretical calculation of the reactions ^{4}He$(\gamma,p)^3$H and ^{4}He$(\gamma,n)^3$He. The final-state $A = 4$ scattering wave functions were obtained from a coupled-channel continuum-shell-model calculation of p-^{3}H and n-^{3}He elastic and charge-exchange scattering, to be described in detail in a subsequent paper.[7] The photodisintegration reaction was assumed to proceed through $E1$, $E2$, and $M2$ transitions, and contributions from three-body final states were ignored. The Coulomb $p+{}^3$H interaction and the nuclear mass difference Q, which both give rise to isospin-mixing, were taken into account explicitly [effects (i)–(iii) listed above].

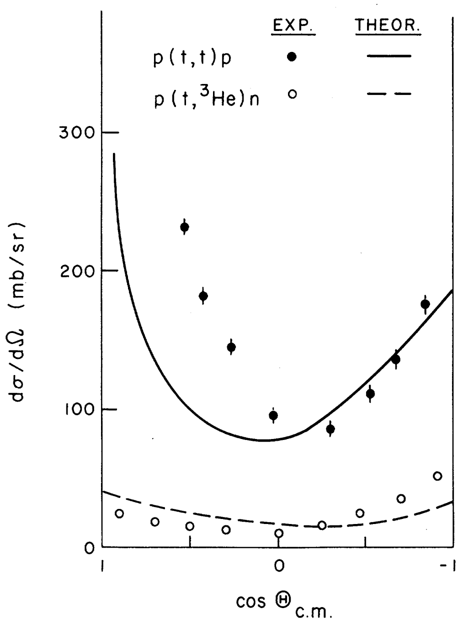

FIG. 1. Comparison of calculated and observed $p+{}^3$H elastic and charge-exchange differential cross sections versus $\cos\theta_{\text{c.m.}}$ for proton laboratory kinetic energy 3 MeV. Experimental data were taken from the compilation in Ref. 9.

In Figs. 1 and 2, we show the elastic and charge-exchange differential cross sections for $p+{}^3$H (solid and dashed lines, respectively) calculated from our $A = 4$ scattering wave functions for proton laboratory kinetic energies of 3 and 8 MeV. The results are very similar to the cross sections obtained from the resonating-group calculation of Szydlik and Werntz[8]; the experimental cross sections[9] are not well reproduced at 3 MeV, but at 8 MeV and higher energies the cross sections are in extremely good agreement with experimental data. The experimentally observed structure at 3 MeV is presumably due to low-lying 0^- and 2^- states in the $A = 4$ system.[10] However, the 2^- contribution to the photodisintegration occurs through $M2$ transitions, which have little effect on the total photo cross sections (although, as pointed out by Crone and Werntz,[11] the ratio $[d\sigma(0°)/d\Omega]/d\sigma(90°)/d\Omega$ depends strongly on $M2$ transitions).

With the wave functions described above, and using the expressions for $E1$, $E2$, and $M2$ transitions from ^{4}He (as given, for example, in Ref. 11), we have calculated the photodisintegration cross sections $\sigma(\gamma,p)$ and $\sigma(\gamma,n)$ as shown in

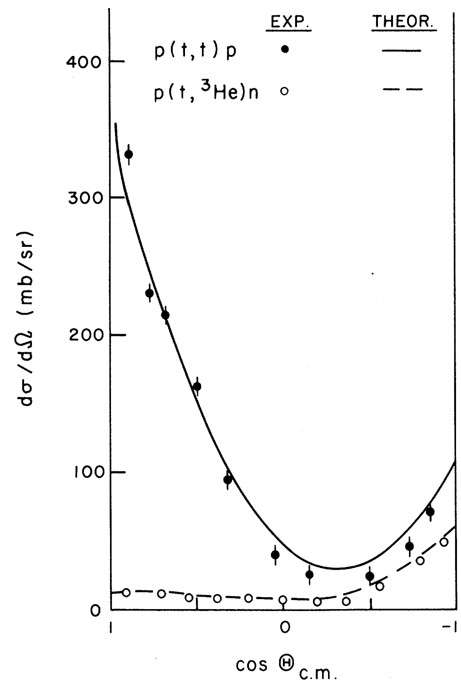

FIG. 2. Comparison of calculated and observed $p+{}^3\text{H}$ elastic and charge-exchange differential cross sections versus $\cos\theta_{\text{c.m.}}$ for proton laboratory kinetic energy 8 MeV. Experimental data were taken from the compilation in Ref. 9.

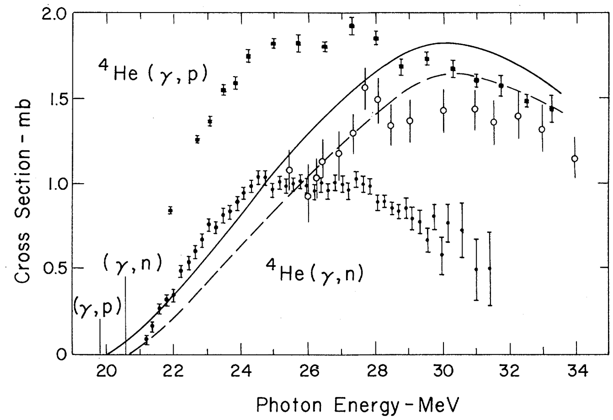

FIG. 3. (γ,p) and (γ,n) calculated and observed total cross sections as a function of photon energy. Solid line, calculated value for (γ,p). Dashed line, (γ,n) cross sections. Solid rectangles, data from Ref. 3. Solid circles, data from Ref. 1. Open circles, data from Ref. 2.

Fig. 3. For energies E_γ above 26 MeV, agreement with experimental (γ,p) data is rather good, but below this energy both the (γ,p) and (γ,n) cross sections are significantly smaller than experiment.[1-3] Up to 26 MeV the (γ,p) calculated cross section closely resembles the R-matrix (γ,p) calculation of Crone and Werntz[11] using the Werntz-Meyerhof[12] phase-shift solution WM I; this is not surprising since the ordering of levels in the $A=4$ system is the same in our calculation as with the WM I parameters. The (γ,n) cross sections are somewhat smaller than experiment[1,2] up to about 25 MeV; above this energy the cross sections become significantly larger than the BFK values, but are in agreement with the results of Busso *et al.*[2] *We should emphasize that we have the most confidence in our theoretical results at the higher energies where our fits to the p(t, t)p and p(t, ^{3}He)n data are excellent (see Figs. 1 and 2).*

In Fig. 4 the solid line is the calculated value of $R\equiv\sigma(\gamma,p)/\sigma(\gamma,n)$ as a function of energy E_γ. R decreases with energy from a value of $R=1.7$ at 22 MeV to $R=1.1$ at 34 MeV. For energies $E_\gamma > 25$ MeV, R is clearly in disagreement with the values obtained by BFK relative to the inferred (γ,p) cross sections.[3] In our calculation, for energies just above the (γ,n) threshold, the mass difference Q between n-^{3}He and p-^{3}H channels is responsible for the large proton-neutron ratio. Such mass-difference effects contribute roughly as Q/E_n, where E_n is the n-^{3}He c.m. energy; with increasing photon energy these effects become negligible. For energies $E_\gamma\sim 30$ MeV, the total cross section from $E2$ absorption becomes noticeable; $E2$ transitions contribute unequally to proton and neutron cross sections because of different effective charges for proton and neutron $E2$ transitions.[13] For energies below about 25 MeV, a ratio $R\sim 1.5$ is consistent with the Q-dependent

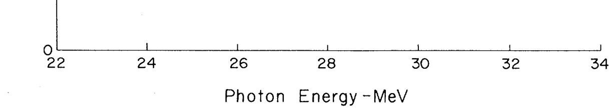

FIG. 4. Comparison of calculated and observed ratio of $(\gamma,p)/(\gamma,n)$ cross sections for ^{4}He, as a function of photon energy. Solid circles, data from Ref. 1. Open circles, data from Ref. 5. Solid line, calculated value of R. Dashed line, value of R obtained when $S=0$, $T=0$ $J^\pi=1^-$ resonant state is added.

effects, but for $E_\gamma \sim 30$ MeV it is difficult to produce $R > 1.2$ with this model. For $E_\gamma \geq 30$ MeV we have graphed the results for R extracted recently by Dodge and Murphy[5] from electron scattering on ^{4}He. Our results are in good agreement with Dodge and Murphy's values for R in this region.

In order to enhance the charge dependence in the final states, we have investigated the effects resulting from a low-lying $A = 4$ resonance with quantum numbers $S = 0$, $T = 0$, $J^\pi = 1^-$. Such a state is not predicted either by analyses of experimental data[10] or from shell-model calculations in $A = 4$[14] (indeed, it is a spurious state for one-particle, one-hole harmonic-oscillator shell-model states, and would presumably appear as a low-lying three-particle, three-hole state). If present, this state might interfere strongly, through Coulomb mixing, with the $S = 0$, $T = 1$, 1^- states reached by electric-dipole transitions. The scattering potential in the $A = 4$ system was modified to produce a p-wave resonance with $S = T = 0$ at proton lab kinetic energy 3 MeV (the potential was left unchanged in all other channels). The resulting values of R are plotted in Fig. 4. It is apparent that the presence of such a state produces a change in R, but it results in values of R less than 1.

In conclusion, our model calculation gives reasonable values for $A = 4$ scattering cross sections and ^{4}He(γ, p) cross sections to $E_\gamma = 34$ MeV. Charge-dependent effects can be moderately large, notably Q-dependent effects at low energies; however, the proton/neutron ratio R differs markedly from the BFK values even after inclusion of several charge-dependent effects. Our results are presently in good agreement with the values of R inferred by Dodge and Murphy. If the BFK results are correct, our calculations suggest that the large values of R are an indication of significant violation of charge symmetry in the nuclear interactions.[15]

---

†Work supported in part by the U. S. Atomic Commission.

*Present address.

[1]B. L. Berman, S. C. Fultz, and M. A. Kelly, Phys. Rev. C 4, 723 (1971), and Phys. Rev. Lett. 25, 938 (1970). See also B. L. Berman, F. W. K. Firk, and C.-P. Wu, Nucl. Phys. A179, 791 (1972).

[2]L. Busso, S. Costa, L. Ferrero, R. Garfagnini, L. Pasqualini, G. Piragino, S. Ronchi della Rocca, and A. Zanini, Lett. Nuovo Cimento 3, 423 (1970); F. Ferrero, C. Manfredotti, L. Pasqualini, G. Piragino, and P. G. Rama, Nuovo Cimento 45B, 273 (1966).

[3]W. E. Meyerhof, M. Suffert, and W. Feldman, Nucl. Phys. A148, 211 (1970). These authors normalize their data to that of J. E. Perry and S. J. Bame, Jr., Phys. Rev. 99, 1368 (1955).

[4]A. N. Gorbunov and V. M. Spiridonov, Zh. Eksp. Teor. Fiz. 34, 862, 866 (1958), and 33, 21 (1957) [Sov. Phys. JETP 7, 596, 600 (1958), and 6, 16 (1958)]; A. N. Gorbunov. Phys. Lett. 27B, 436 (1962).

[5]W. R. Dodge and J. J. Murphy, II, Phys. Rev. Lett. 28, 839 (1972).

[6]E. M. Henley, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1966), p. 43.

[7]J. T. Londergan and C. M. Shakin, to be published. The continuum shell treatment was similar to an earlier calculation of $A = 4$ continuum states by J. Hüfner and C. M. Shakin, Phys. Rev. 175, 1350 (1968).

[8]P. Szydlik and C. Werntz, Phys. Rev. 138, B466 (1965).

[9]Experimental $A = 4$ scattering data have been taken from the compilation by J. D. Seagrave, in *Symposium on Few Body Problems, Light Nuclei and Nuclear Interactions*, edited by G. Paic and I. Slaus (Gordon and Breach, New York, 1968), p. 787.

[10]W. E. Meyerhof and T. A. Tombrello, Nucl. Phys. A109, 1 (1968).

[11]L. Crone and C. Werntz, Nucl. Phys. A134, 161 (1969).

[12]C. Werntz and W. E. Meyerhof, Nucl. Phys. A121, 38 (1968).

[13]On removing c.m. effects from photodisintegration amplitudes, we obtain effective charges for $E2$ transitions of $\frac{5}{8}e$ and $\frac{1}{8}e$ for proton and neutron decays, respectively.

[14]A. de-Shalit and J. D. Walecka, Phys. Rev. 147, 763 (1966); P. P. Szydlik, Phys. Rev. C 1, 146 (1970); B. R. Barrett, Phys. Rev. 154, 955 (1967).

[15]Effects of three-body final states, which we have not considered in this calculation, are probably not the cause of large values for R, since the cross sections for three-body final states in ^{4}He $+\gamma$ are small even up to 34 MeV (see Ref. 10).