wide, separated by 22 cm, followed by a deep Faraday cup. For the purpose of determining the emittance area, the cutoff current in the Faraday cup was taken as 10% of the maximum current that could be transmitted through both slits. The entire assembly could be rotated so that the emittance in two perpendicular directions could be measured. It is expected[11] that the emittance of the beam increases with increasing magnetic field in the collision region. At a field of about 3 mT in the collision region, the measured emittance of the D^- beam is 2π mm mrad $(MeV)^{1/2}$. At a field of 30 mT (large enough for strong-field ionization of D^0) the measured emittance of the D^- beam is as low as 5π mm mrad $(MeV)^{1/2}$, while at a field of 100 mT (strong-field ionization of H^0) the emittance of the H^- beam is as low as 11π mm mrad $(MeV)^{1/2}$. The values of the emittance are low enough for good transmission through tandem accelerators. A recently calculated value[12] for the acceptance of a typical tandem accelerator is 12π mm mrad $(MeV)^{1/2}$.

The ion source described here already yields polarized negative beams of substantially higher current than any other type of polarized negative ion source. The prospects for further increases in beam intensity are encouraging since we have not worked extensively on the development of the Cs^0 source and more intense Cs^0 beams can almost certainly be obtained. The method tested here may also have applications to the production of heavier alkali negative ions for heavy-ion nuclear reaction studies.

We should like to thank Professor R. Middleton for sharing his experience in the construction of Cs^+ ion sources with us. This work was supported in part by the U. S. Department of Energy.

[1]C. W. Potts, IEEE Trans. Nucl. Sci. 24, 1385 (1977).
[2]T. B. Clegg, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions*, edited by W. Grüebler and V. König (Birkhäuser Verlag, Basel and Stutgart, 1976), p. 111.
[3]W. Haeberli, Nucl. Instrum. Methods 62, 355 (1968).
[4]Supplied by ANAC, Inc., Santa Clara, Calif. 95050.
[5]R. Risler, W. Grüebler, V. König, and P. A. Schmelzbach, Nucl. Instrum. Methods 121, 425 (1974).
[6]H. F. Glavish, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions*, edited by W. Grüebler and V. König (Birkhäuser Verlag, Basel and Stutgart, 1976), p. 844.
[7]C. Cisneros, I. Alvarez, C. F. Barnett, and J. A. Ray, Phys. Rev. A 14, 76 (1976); and A. S. Schlachter, P. J. Bjorkholm, D. H. Loyd, L. W. Anderson, and W. Haeberli, Phys. Rev. 177, 184 (1969).
[8]W. Haeberli, Annu. Rev. Nucl. Sci. 17, 373 (1967).
[9]For the analyzing power of the reation $^3H(d,n)^4He$ the value determined by G. G. Ohlsen *et al.* at 51 keV deuteron energy was used [G. G. Ohlsen, J. L. McKibben, and G. P. Lawrence, in *Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wisc., 1971), p. 503].
[10]Atoms in the wrong electron spin state contribute a P_{zz} which is opposite in sign from the atoms in the desired spin state. Thus the valve quoted corresponds to 1.5% atoms in the wrong spin state (see Ref. 3).
[11]G. G. Ohlsen, J. L. McKibben, R. R. Stevens, Jr., and G. P. Lawrence, Nucl. Instrum. Methods 73, 45 (1969).
[12]The stated acceptance applies to an FN tandem accelerator with inclined-field tubes, manufactured by HVEC, Burlington, Mass. [C. Lukner, G. Latzel, and H. Paetz gen. Schiek, Nucl. Instrum. Methods 146, 139 (1977)].

$(sd)^2$ States in $^{14,16}C$

H. T. Fortune,[a] M. E. Cobern,[b] S. Mordechai,[c] G. E. Moore,[d] S. Lafrance, and R. Middleton
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 20 December 1977)

Simple shell-model calculations account for the remarkable similarity in excitation energies and (t,p) strengths of predominantly $(sd)^2$ states in ^{14}C and ^{16}C.

There is a remarkable similarity between positive-parity states of ^{14}C populated in the $^{12}C(t,p)$ reaction[1] and those of ^{16}C populated[2] in $^{14}C(t,p)$ —in both excitation energies and transfer strengths. We show that this striking similarity arises from quite simple considerations—primarily because the $2s_{1/2}$-$1d_{5/2}$ splitting[3] in ^{13}C and ^{15}C is virtually identical.

The states of interest in $^{14,16}C$ are displayed in the middle two columns of Fig. 1. Except for the

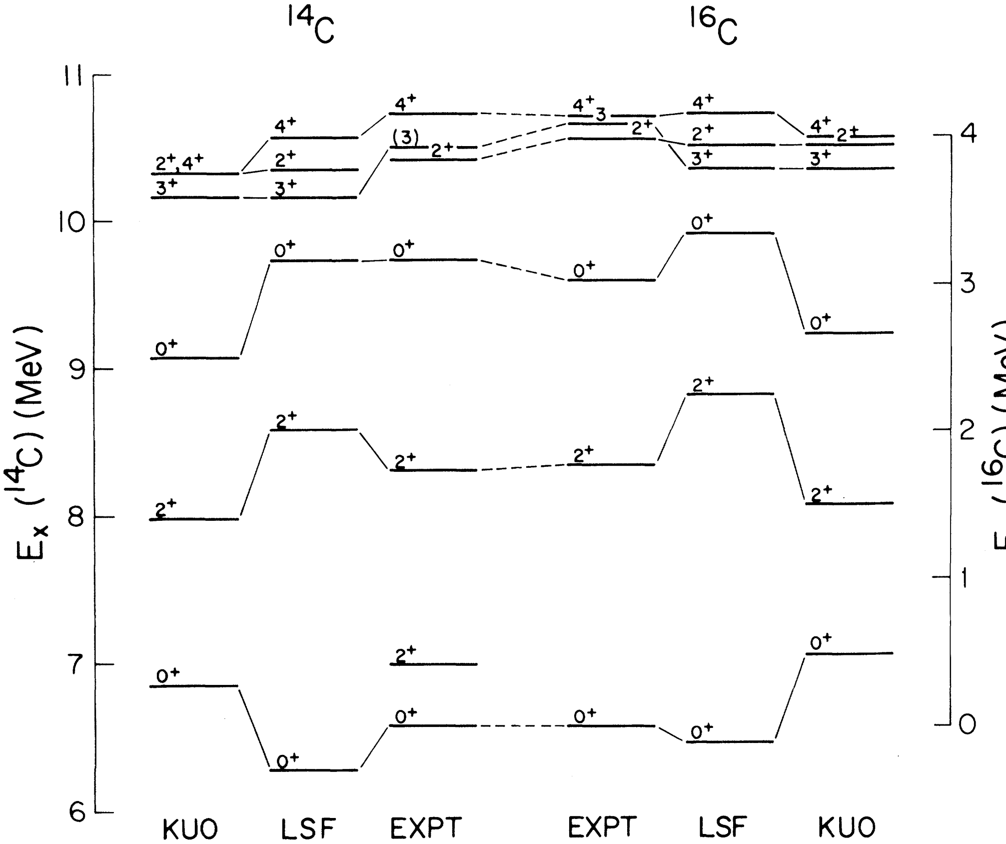

FIG. 1. Experimental excitation energies for positive-parity states in ^{14}C and ^{16}C, compared with those calculated for $(sd)^2$ states using LSF (Ref. 4) and Kuo (Ref. 5) matrix elements. The ground state of ^{14}C (predominantly p^{-2}) is not shown.

0^+ ground state (g.s.) of ^{14}C, these are all the positive-parity states that are known[1-3] in the two nuclei. In ^{14}C, the 0^+ g.s. and 7.01-MeV 2^+ state are dominantly $(1p)^{-2}$ in character, but a majority of the (t,p) strength for the g.s. and virtually all of that for the 7.01-MeV state arise from the $^{12}\mathrm{C}\otimes(sd)^2$ configuration.

In Fig. 2, we display the summed $L=0$ and 2 (t,p) angular distributions observed in the two nuclei, and the angular distributions for the sole 4^+ state in each. The agreement between the two nuclei is remarkable. This extends even to the very weak cross section observed for the 0^+ states at 3.02 and 9.75 MeV in ^{16}C and ^{14}C, respectively, whose angular distributions are displayed in Fig. 3.

We have compared the experimental results with the results of a simple shell-model calculation. We assume the positive-parity states in ^{14}C and ^{16}C to be composed of $(sd)^2$ configurations coupled to the ground states of ^{12}C and ^{14}C, respectively, and take two-body matrix elements from a least-squares fit[4] to data on ^{18}O, and single-particle energies[3] from ^{13}C and ^{15}C. For comparison, calculations were also performed with Kuo's matrix elements.[5] We do a simple two-body calculation for both ^{14}C and ^{16}C, assuming that the main effects of the nonclosed shells manifest themselves in different single-particle energies than one might expect from, say, the ^{17}O spectrum. The principal justification of this approach lies in its success in fitting experimental data.

The $T=1$ two-body space $(sd)^2$ gives rise to three 0^+ states, five 2^+ states, two 4^+ states, and two 3^+ states. The $(1d_{3/2})^2$ component turns out to be unimportant for the properties of the first two 0^+ states. The predominantly $(1d_{3/2})^2$ 0^+ state is calculated to lie near 14-MeV excitation. Thus for the 0^+ states, we consider only $(1d_{5/2})^2$ and $(2s_{1/2})^2$. The $1d_{3/2}$ orbit can likewise to be ignored for the lowest 3^+ state, which in ^{18}O is virtually pure $(1d_{5/2})(2s_{1/2})$. We include the $d_{3/2}$ orbit for the 4^+ and 2^+ states, but for 2^+

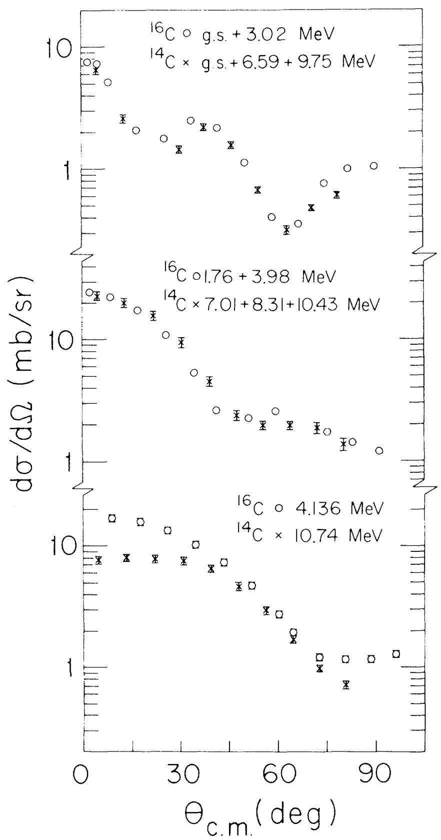

FIG. 2. Summed angular distributions with (from top to bottom) $L = 0$, 2, and 4 for $^{12}C(t,p)^{14}C$ (crosses) and $^{14}C(t,p)^{16}C$ (circles); $E_t = 18$ MeV.

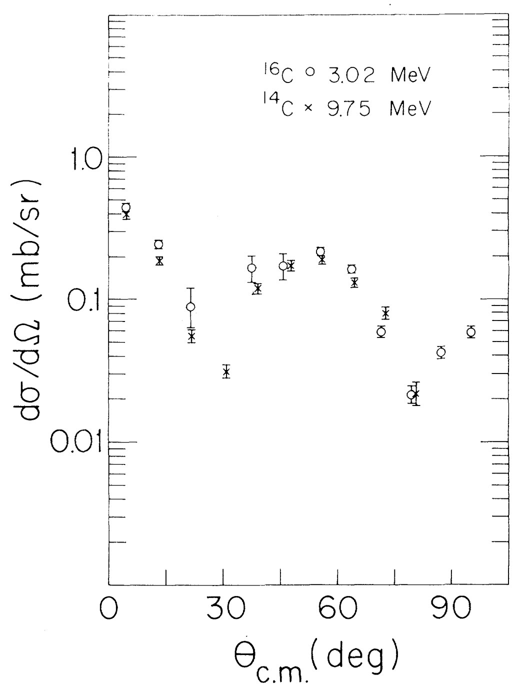

FIG. 3. Angular distributions for $^{12}C(t,p)^{14}C$ (crosses) and $^{14}C(t,p)^{16}C$ (circles), populating the second $(sd)^2$ 0^+ state in $^{14,16}C$; $E_t = 18$ MeV.

the results are virtually identical to those in a $(1d_{5/2}, 2s_{1/2})$ basis.

The two-body matrix elements [Lawson-Serduke-Fortune (LSF) and Kuo] are given in Ref. 4. (in the last two columns of Table VII). The single-particle energies are taken from Ref. 3, except that the $1d_{3/2}$ strength in ^{13}C is taken to lie at $E_x = 8.2$ MeV. The predicted excitation energies are compared with the data in Fig. 1. Wave functions are listed in Table I.

The ^{16}C spectrum[2] contains two 0^+ states, two

TABLE I. Wave functions for predominantly $(sd)^2$ states in $^{14,16}C$.

Wave functions for ^{14}C				E_x (MeV) in ^{14}C				E_x (MeV) in ^{16}C		Wave functions for ^{16}C			
$(1d\frac{5}{2})^2$	$(2s\frac{1}{2})^2$			Calc	Exp	J^π	M.E.	Exp	Calc	$(1d\frac{5}{2})^2$	$(2s\frac{1}{2})^2$		
0.6765	0.7364			6.286	6.577	0^+	LSF	0.0	−0.110	0.6821	0.7313		
0.5132	0.8582			6.876			Kuo		0.490	0.5222	0.8528		
0.7364	−0.6765			9.734	9.746	0^+	LSF	3.020	3.338	0.7313	−0.6821		
0.8582	−0.5132			9.079			Kuo		2.668	0.8528	−0.5222		
$(1d\frac{5}{2})^2$	$(1d\frac{5}{2})(2s\frac{1}{2})$	$(1d\frac{5}{2})(1d\frac{3}{2})$	$(1d\frac{3}{2})(2s\frac{1}{2})$							$(1d\frac{5}{2})^2$	$(1d\frac{5}{2})(2s\frac{1}{2})$	$(1d\frac{5}{2})(1d\frac{3}{2})$	$(1d\frac{3}{2})(2s\frac{1}{2})$
0.5972	0.7526	0.0623	−0.2704	8.600	8.307	2^+	LSF	1.766	2.244	0.6062	0.7550	0.0545	−0.2441
0.4775	0.8346	0.0303	−0.2731	7.897			Kuo		1.507	0.4848	0.8350	0.0722	−0.2502
0.7793	−0.6262	−0.0077	−0.0236	10.356	10.425	2^+	LSF	3.983	3.942	0.7769	−0.6293	−0.0072	−0.0188
0.8615	−0.4985	0.0966	−0.0066	10.329			Kuo		3.945	0.8631	−0.5033	0.0423	−0.0049
$(1d\frac{5}{2})^2$	$(1d\frac{5}{2})(1d\frac{3}{2})$									$(1d\frac{5}{2})^2$	$(1d\frac{5}{2})(1d\frac{3}{2})$		
0.9839	0.1788			10.567	10.736	4^+	LSF	4.136	4.163	0.9890	0.1480		
0.9245	0.3813			10.327			Kuo		3.995	0.9454	0.3259		

2^+ states, one 4^+ state, and a probable 3^+ state. The similarity with the positive-parity states[1] of ^{14}C is striking. Every ^{16}C state has a corresponding state in ^{14}C. Because the $\frac{5}{2}^+$-$\frac{1}{2}^+$ splitting in ^{13}C and ^{15}C is virtually identical, the model predicts very similar results for ^{14}C and ^{16}C. This similarity extends to the transfer strengths, with one slight modification. The 0^+ and 2^+ strength in ^{14}C is split, by mixing between the $(sd)^2$ states and the $1p$-shell 0^+ and 2^+ states. The ^{12}C$(t,p)^{14}$C(g.s.) cross section is stronger[1] than expected for the pure p-shell state[6] by about a factor of 10. The 2^+ state at 7.01 MeV is more than 100 times stronger[1] than predicted for the Cohen and Kurath[6] 2^+ p-shell state. It is for this reason that we compare summed cross sections for 0^+ and 2^+ states. For the second $(sd)^2$ 0^+ state, the model successfully accounts for the fact that its (t,p) strength almost vanishes in both nuclei (Fig. 3) as a result of destructive interference between $(1d_{5/2})^2$ and $(2s_{1/2})^2$ components.

The LSF and Kuo matrix elements produce very similar wave functions, except for the 4^+ state. With LSF, the model predicts an amplitude of about 0.15–0.18 for the $(1d_{5/2})(1d_{3/2})$ component in this state, whereas with Kuo this amplitude is 0.33–0.38. The data[1,2] require an amplitude of about 0.30 to explain the (t,p) strength. The (t,p) cross sections are especially sensitive to this component, since the cross section for a $(1d_{5/2})$ $(1d_{3/2})$ 4^+ state is almost four times that for a $(1d_{5/2})^2$ 4^+ state. Reference 4 discusses further the question of the $(sd)^2$ 4^+ states.

In conclusion, a simple calculation that treats the positive-parity states of ^{14}C and ^{16}C as $(sd)^2$ two-neutron states coupled to inert ^{12}C and ^{14}C cores gives very good agreement with experimental excitation energies and (t,p) strengths.

We acknowledge financial support from the National Science Foundation, and interesting discussions with J. Millener and R. D. Lawson.

[a] Presently at University of Oxford on leave from University of Pennsylvania.
[b] Present address: Westinghouse Electric Corporation, Bettis Atomic Power Laboratory, P. O. Box 79, West Mifflin, Penn. 15122.
[c] On leave from Department of Physics, Ben-Gurion University, Beer-Sheva, Israel.
[d] Present address: Analytic Services Inc., Falls Church, Va. 22041.

[1] S. Mordechai *et al.*, to be published.
[2] H. T. Fortune *et al.*, Phys. Lett. 70B, 408 (1977).
[3] F Ajzenberg-Selove, Nucl. Phys. A268, 1 (1976).
[4] R. D. Lawson, F. J. D. Serduke, and H. T. Fortune, Phys. Rev. C 14, 1245 (1976).
[5] T. T. S. Kuo, Nucl. Phys. A103, 71 (1967).
[6] S. Cohen and D. Kurath, Nucl. Phys. A141, 145 (1970).

Bound-State Calculations of ^{4}He with the Reid Soft-Core Interaction

J. A. Tjon
Institute for Theoretical Physics, University of Utrecht, Utrecht, The Netherlands
(Received 23 February 1978)

The binding energy of ^{4}He is calculated within the framework of the Yakubovsky equations for the Reid soft-core potential. Use is made of separable expansions of the subamplitudes. With neglect of the Coulomb effect and the non-s-wave parts of the two-nucleon t matrix, the binding is found to be 19.5 MeV. With use of the solutions of the integral equations the elastic charge form factor is calculated. In addition to the underbinding of ^{4}He it is found that the secondary maximum in the form factor is much too low as compared to experiment.

In recent years considerable evidence has been presented that the ground-state properties of the trinucleon system cannot be explained by using realistic nucleon-nucleon interactions.[1] In particular, the attempts to describe the region of the secondary maximum in the elastic charge form factor of ^{3}He together with its binding energy have not been successful up to now within a simple picture of the nucleus being made of three nucleons interacting only through pairwise forces. In view of the recent advances made towards the solutions of the four-particle problem in the framework of integral equations, it is natural to ask to what extent this applies also to the ^{4}He sit-

