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Singlet Deuteron p-n Correlations in the $^{13}C(p, pn)^{12}C$ Reaction*

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The three-body reaction $^{13}C(p,pn)^{12}C$ has been studied experimentally in a kinematically complete experiment. p-n coincidence events were measured for several bombarding energies between 7.9 and 12.5 MeV using associated time-of-flight techniques, pulse-shape discrimination for the neutron-detection system, and a silicon surface-barrier detector for the charged particles. Only in the region of 12.5-MeV bombarding energy is there an indication of sequential decay via "singlet deuteron" formation. Higher energies were not attainable with the available equipment, and at lower energies sequential decay through levels in ^{13}C and ^{13}N was relatively strong and obstructed the observation of possible contributions from p-n final-state interactions. An upper limit is assigned to the two-body (p,d^*) cross section.

I. INTRODUCTION

Evidence of singlet deuteron production, that is, the formation of a p-n pair in a $^1S_0$ state with low relative energy, has been reported by many authors in the last few years, both from incomplete and from complete three-body experiments.[1] More specifically, Temmer has discussed the possibility of singlet deuteron (d^*) pickup from the ^{13}C nucleus.[2] He cites a $^{13}C(p,n)^{13}N$ time-of-flight (TOF) spectrum showing a peak which is unexplainable by a two-body process and which can be explained by singlet deuteron breakup.

Cohen *et al.*[3] have reported on the detection of singlet deuterons in the reaction $^9Be(p,d^*)^8Be$. In a more recent paper by Cohen *et al.*[4] the ratio of the cross section for the (p,d) and the (p,d^*) reactions are given for a number of target nuclei. Included in this work is the $^{13}C(p,pn)^{12}C$ reaction at 17-MeV bombarding energy for which a relatively strong yield due to singlet deuteron production is asserted.

The intention of this experiment was to study the $^{13}C(p,d^*)^{12}C$ reaction at tandem Van de Graaff energies; i.e., to determine the differential cross section for d^* production, to measure, if possible, angular distributions and excitation functions. Also, it was expected that the $T=1$ character of the singlet deuteron could be shown by choosing bombarding energies such that either a known $T=1$ level or a known $T=0$ level in the compound system ^{14}N is excited. Since the bombarding particle and the target particle are both $T=\frac{1}{2}$ particles and the residual nucleus is a $T=0$ particle, it was expected that the yield of singlet deuterons be greater in the region near a ^{14}N $T=1$ level and smaller near a $T=0$ level, where the reaction is isospin forbidden.

Since the $^1S_0$ p-n system breaks up in a relatively short time and other final-state interactions are expected to contribute, it becomes necessary to use the techniques of the "complete" three-body breakup experiment and detect two particles. The breakup energy is expected to be relatively low compared with the d^* kinetic energy and therefore the position of the nucleons will be confined to a fairly small cone. Placing a neutron detector immediately behind a solid-state charged-particle detector and requiring a coincidence between the two detector signals will result in a system which is sensitive to singlet deuteron breakup. In this experiment such a p-n coincidence system was assembled and measurements were made at several energies and angles.

II. EXPERIMENTAL METHOD

The incident charged-particle beam was obtained from the Rice University tandem Van de Graaff accelerator and was passed through a 90° momentum-analyzing magnet for energy definition before entering the target chamber. The beam current entering the Faraday cage was integrated using a current-to-voltage amplifier, a voltage-to-frequency converter, and a scaler.

Self-supporting carbon targets were prepared from methyl iodide enriched with the ^{13}C isotope. The thickness of the carbon targets was determined by measuring the energy loss of 6.04- and 8.78-MeV α particles from a thorium source as they pass through the target. This method yielded a value of about 350 $\mu g/cm^2$.

The thin-walled 12-in.-diam spherical reaction chamber located approximately in the center of the target room had provisions for mounting a target in its geometrical center and a solid-state detector on an arm which pivots about the center of the chamber.

The beam was stopped on a lead sheet in a shielded cave about 15 m from the target in order to reduce background counts in the neutron detector. This purpose was well accomplished; however, the accuracy of beam integration with this long Faraday cage was only about 5%.

The charged particles were detected with a silicon surface-barrier detector sufficiently thick to stop all particles of interest. Both energy and timing signals were derived from this detector.

The neutron detector consisted of a liquid scintillator in a cylindrical container (5-in. diam and 3-in. thickness), two photomultiplier tubes, and associated electronics. Three signals were derived from the neutron-detection system: the anode signal which contained the timing information, the dynode (DYN) signal whose pulse amplitude is proportional to the scintillation light intensity and which was used in conjunction with the pulse-shape discrimination (PSD) signal in distinguishing neutrons from γ rays, and the PSD signal whose pulse amplitude depends among other things on the scintillation light intensity and on the type of particle causing the scintillation.

Figure 1 shows a block diagram of the electronics used in the experiment. For each event, defined as a slow coincidence between the TOF signal and the solid-state detector (SSD) signal, the four linear signals, TOF, SSD, PSD, and DYN were recorded on magnetic tape. Data analysis and the actual discrimination based on DYN pulse shape were done off line.

The charged-particle energy axis and the TOF axis were calibrated in the usual manner, and the relative and absolute efficiency of the neutron detector was measured as described by Jackson *et al.*[5] The anode threshold and the PSD threshold of the detector corresponded to electron energies of 30 and 115 keV, respectively.

It should be noted that in this experiment the mode of operation was to use the PSD to discriminate against γ rays. This means that DYN pulses below the PSD threshold were assumed to be neutrons. In this mode the bias level is determined by the anode threshold. In a second mode of operation the PSD could be used to accept neutrons. In this case all DYN pulses below the PSD threshold are rejected and the bias level is now determined by the PSD threshold.

III. RESULTS AND DISCUSSION

Figure 2 shows coincidence spectra projected onto the proton axes for bombarding energies T_b between 7.9 and 12.5 MeV and for various detector angles $\theta = \theta_n = \theta_p$ and solid angles Ω. With regard to these spectra it is of interest to look at the kinematics governing this reaction in some detail. Figure 3 gives a graphical representation of the positions of contributions from various final-state interactions on the proton axis as a function of the bombarding energy for two different pairs of angles. The nearly vertical lines labeled ^{13}N corre-

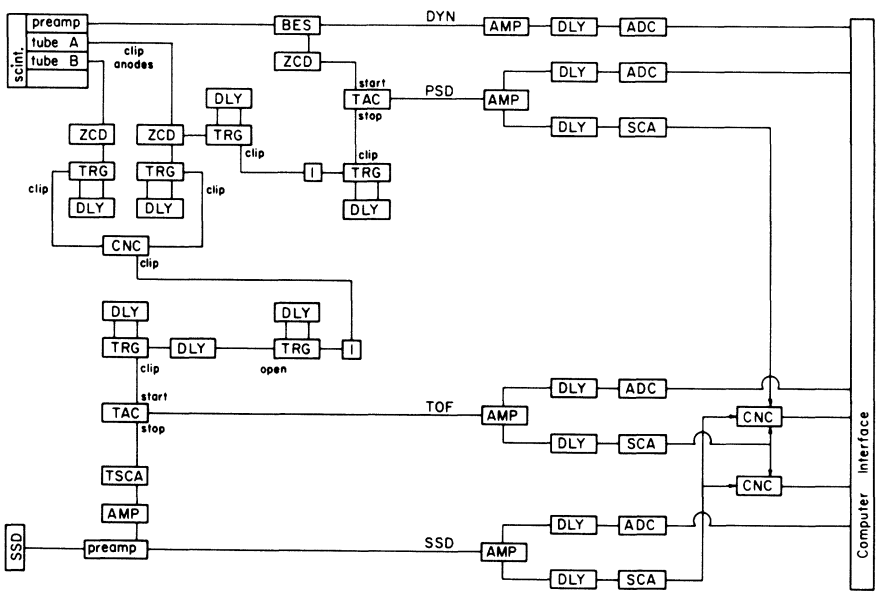

FIG. 1. Block diagram of electronics: TRG, trigger; DLY, delay; ZCD, zero-crossing discriminator; BES, delay-line-shaping amplifier; TAC, time-to-amplitude converter; I, inverter; FAN, fan out; CNC, coincidence unit; TSCA, timing single-channel analyzer; ADC, analog-to-digital converter; AMP, linear amplifier; and SCA, single-channel analyzer.

spond to final-state interactions in the ^{12}C-p system at the indicated excitation energies in ^{13}N, the diagonal lines labeled ^{13}C represent final-state interactions in the ^{12}C-n system, and the dashed lines labeled 0, 50, and 100 correspond to the p-n system at relative energies of 0, 50, and 100 keV, respectively. As can be seen from the figure, the relative positions of various levels do not depend very much on the choice of the angle θ but are a strong function of the bombarding energy. As an example, the spectrum in Fig. 2(b) shows a peak in the region of low relative energy in the p-n system; however, it may also correspond to a decay through the 7.49- and 7.55-MeV levels in ^{13}C. Referring to Fig. 3 it is apparent that this ambiguity may be resolved by repeating

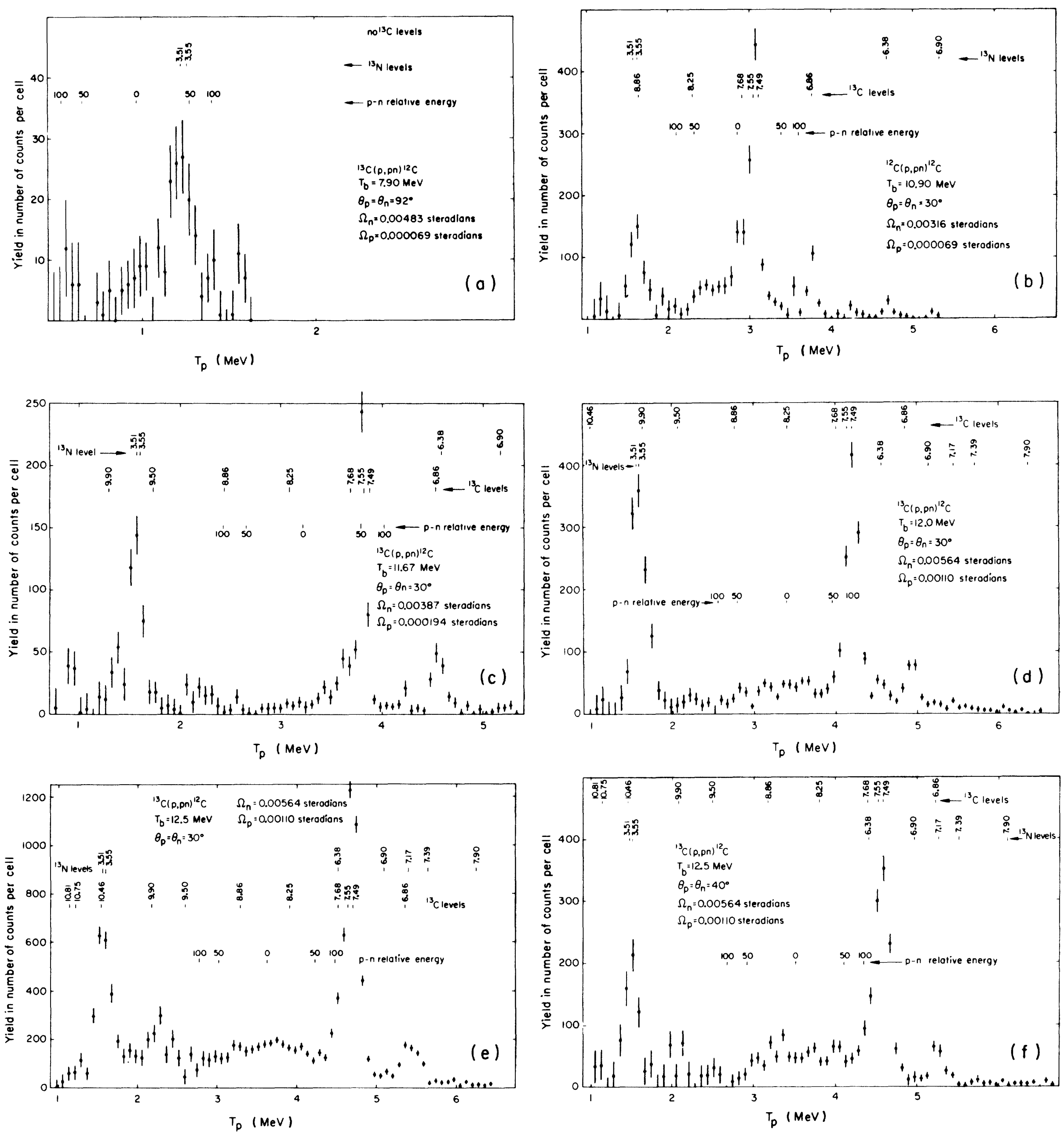

FIG. 2. (a)–(f) Yield in the p-n locus vs proton energy for various values of the bombarding energy T_b and of the neutron and proton detector angles θ_n and θ_p, respectively. The indicated energy positions correspond to emitted proton energies for possible sequential decay through various levels in ^{13}C* and ^{13}N* and through 0-, 50-, and 100-keV excitation in the p-n system.

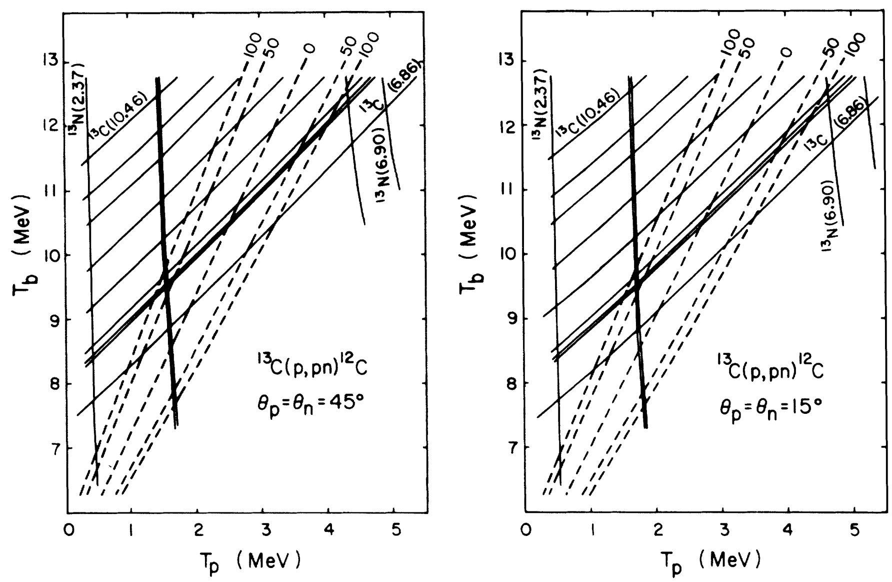

FIG. 3. Relative position of various possible final-state interactions as projected onto the proton axis, and displayed as a function of the bombarding energy and for two different angle combinations. The dashed lines labeled 0, 50, and 100 correspond to relative energies (in keV) of the singlet deuteron; the other lines correspond to final-state interactions in the $^{12}C+n$ and $^{12}C+p$ systems, respectively, at the excitation energies 6.86, 7.49, 7.55, 7.68, 8.25, 8.86, 9.50, 9.90, and 10.46 MeV in ^{13}C, and at energies 2.37, 3.51, 3.55, 6.38, and 6.90 MeV in ^{13}N.

the measurement at a different energy. Figure 2(c) shows the peak again corresponding to the 7.49- and 7.55-MeV levels in ^{13}C, and there is essentially no contribution from the singlet deuteron which would be maximum at zero relative energy in the p-n system.

Of the data taken, only that at 12.5-MeV bombarding energy shows any indication of contributions from singlet deuteron formation and yet the effect is completely dominated by the other peaks due to sequential decay through levels in ^{13}C and ^{13}N [see Fig. 2(e)]. Also, because of these strong contributions from ^{13}C and ^{13}N levels it was not possible to observe any isospin dependency of the d^* yield as mentioned in the Introduction. Figure 4 shows a portion of the data for 12.5 MeV and 30° shown in Fig. 2(e). The line represents a calculation of the theoretical enhancement factor for the $^1S_0$ p-n final-state interaction using the Phillips, Griffy, and Biedenharn (PGB) formulation.[6] The curve was normalized to fit the experimental data at the top of the peak. As is seen in the figure the data are well represented by the theoretical curve in the region about the p-n peak, which is rela-

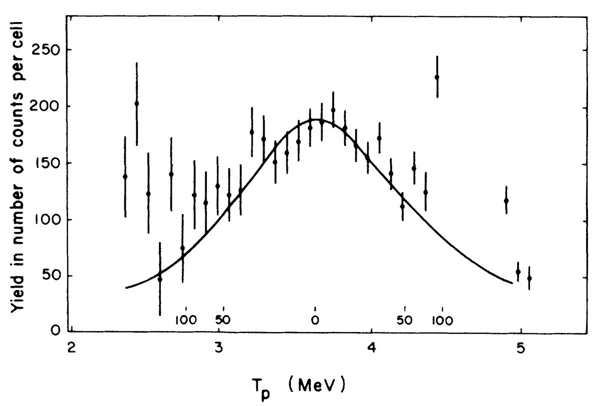

FIG. 4. Theoretical curve (PGB) of the singlet deutron enhancement superimposed on a portion of the data of Fig. 2(e). Scattering length, −23.7 F; effective radius, 2.76 F.

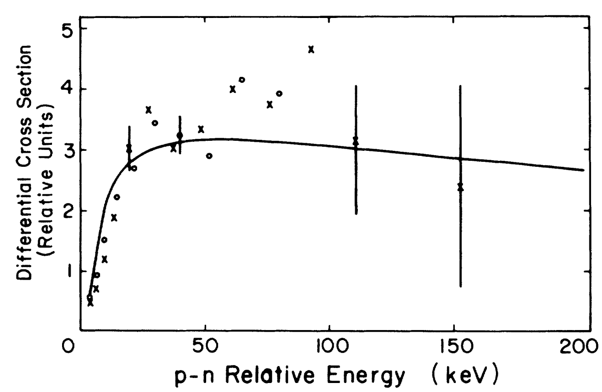

FIG. 5. Differential cross section for $^{13}C(p,d^*)^{12}C$ as a function of the p-n relative energy. The ×'s are data points such that the proton has less energy than the neutron and the O's are data points such that the proton has more energy than the neutron.

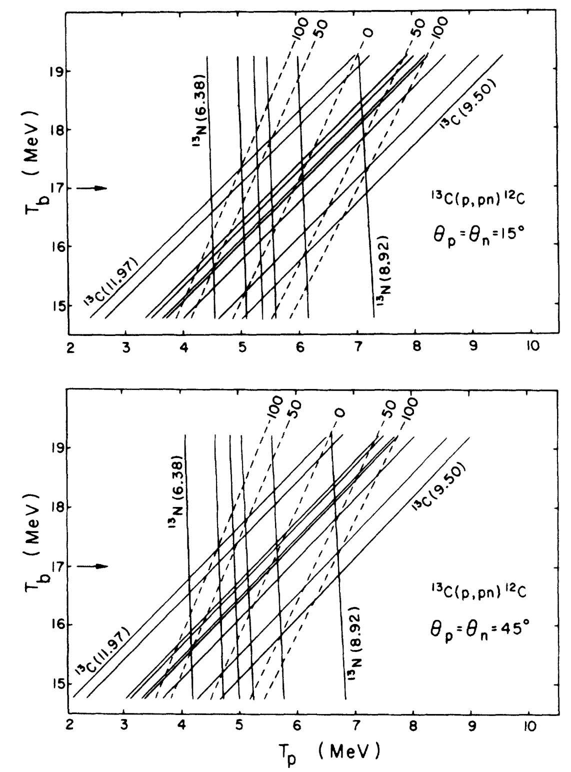

FIG. 6. Kinematics similar to Fig. 3 for a higher range of bombarding energies. The excitation energies in ^{13}C are 9.50, 9.90, 10.46, 10.75, 10.81, 11.00, 11.08. 11.72, and 11.97 MeV, and in ^{13}N are 6.38, 6.90, 7.17, 7.39, 7.90, and 8.92 MeV.

tively free from contributions of other final-state interactions.

Figure 5 shows the two-body differential cross section for the (p, d^*) process as a function of the breakup energy. Again, the curved line is calculated using the PGB theory. In the determination of this cross section the probability of experimentally detecting the breakup products of the "singlet deuterons" as a function of the relative energy was taken into account. Integrating the cross section of Fig. 5 with respect to the relative energy β between zero and some maximum energy[7] yields for the (p, d^*) reaction

$$\frac{d\sigma}{d\Omega}=\int_0^{\beta_m}\frac{d\sigma}{d\Omega d\beta}\,d\beta\,,$$

which can be compared with the cross section for the (p, d) reaction. The ratio of these cross sections for various targets has been calculated and lies between 5 and 20; in particular for ^{13}C at 17-MeV bombarding energy the calculated cross section for (p, d) is nine times the cross section for (p, d^*) whereas the measured ratio was 17.[8] For this experiment the data for 12.5 MeV, 30° can only be used up to about 50- or 100-keV relative energy because of other sequential-decay peaks. Extrapolating the theoretical curve to an upper limit of integration of 700 keV, the area under the theoretical curve is roughly estimated to be 0.7 mb/sr. Because of possible contributions from the 8.25- and 8.86-MeV levels in ^{13}C, and p-n triplet final-state interactions this is only an upper limit on the cross section for the (p, d^*) process. Using the absolute cross sections for the ^{12}C(d, p)-^{13}C reaction from Hamburger[9] to calculate – via the principle of detailed balance – the corresponding cross sections for the ^{13}C$(p, d)^{12}$C reaction at $E_p \simeq 12.5$ MeV one finds for $\theta_d \simeq 30°$ approximately 8 mb/sr. With this value and $\sigma(p, d^*) \simeq 0.7$ mb/sr the ratio of triplet to singlet deuteron production becomes $\sigma(p, d)/\sigma(p, d^*) \simeq 11$, in agreement with the calculations of Ref. 8.

Cohen *et al.*[4] have investigated the same reaction at 20 and 35° and at $E_p = 17$ MeV. Their spectra show the same strong sequential decay through levels in ^{13}C as we have observed plus a relatively strong peak attributed to the singlet deuteron final-state interaction. Although no absolute cross sections are given in Ref. 4 and therefore no direct comparison with our results can be made it appears from a comparison of the relative strengths of the other final-state interaction peaks which are present both at 17- and 12.5-MeV bombarding energy that the "singlet deuteron" contribution reported in Ref. 4 is stronger than the one observed in this experiment. In interpreting this peak one must, however, consider the three-body kinematics in the region of $E_p = 17$ MeV (see Fig. 6). Here it can be seen that several levels in ^{13}C cluster around the region of low relative energy for the p-n system. At least one of them, namely the level at 10.75-MeV excitation energy in ^{13}C has a fairly large neutron width as can be seen from the large cross section of the ^{12}C$(d, p)^{13}$C$^*_{10.75}$ reaction.[10] The cross section for the transition to this excited state in the above reaction is of the same order of magnitude as the one for the 7.55-MeV level which is seen to contribute very strongly in the experiment described in this paper. Furthermore, the ^{12}C(n, n) reaction shows a very pronounced resonance corresponding to the 10.75-MeV state in ^{13}C. This suggests that a substantial part of the yield attributed to the p-n final-state interaction in Ref. 4 might indeed be due to contributions from the ^{12}C-n final-state interaction through the 10.75-MeV resonance in ^{13}C. Since these ^{13}C levels diverge from the region of low relative energies in the p-n system when the bombarding energy is changed, it should be fairly easy by additional experiments to verify the importance of the ^{13}C levels.

It follows from the above that it is in general very difficult to observe and clearly identify contributions from the $^1S_0$ proton-neutron final-state interaction in reactions involving more than three or four nucleons. In heavier systems the measurement of excitation functions and angular distributions for the d^* production becomes an increasingly hopeless task because the increasing level densities make it impossible to find conditions under which the relatively broad d^* contribution can be observed without possible obstruction from other final-state interactions.

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Effective Interaction and Effective Operators with Hard-Core Potentials

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The effective interaction with hard-core potentials is studied when both a correlated and an uncorrelated basis is used. While the use of a correlated basis leads to a series expansion which is uniquely defined to any order, the use of an uncorrelated basis leads to a series expansion which is not uniquely defined to any order, although the series can converge to a unique result. A method is given for evaluating this series perturbatively, which is numerically simple and improves the accuracy of calculation of matrix elements of operators sensitive to the core region. It does not require the rearrangement of the graphs in ladder-type terms; the rearrangement can be done whenever it is convenient. The separation method and the reference-spectrum method are discussed in the light of the present method.

1. INTRODUCTION

The problem of handling potentials having a hard core has been treated extensively in the literature, and the methods proposed will not be reviewed in detail here. Basically there are three: (i) the method of left-unitary operators,[1] (ii) the method of pseudopotentials,[2,3] and (iii) the G-matrix formalism.[4]

Method (i) consists of introducing a correlated many-particle orthonormal basis λ_n which is continuous and vanishes for any interparticle distance less than or equal to the core radius, starting from an uncorrelated basis Φ_n, by means of a left-unitary operator N

$$\lambda_n = N\Phi_n, \quad \langle\lambda_n|\lambda_m\rangle = \langle\Phi_n|\Phi_m\rangle = \delta_{nm}.$$

The basis λ_n frees us of mathematical problems and makes it possible to make recourse to perturbative procedures, but involves many-particle integrals whose numerical convergence in a cluster expansion has not yet been investigated.