The Neutron Yield from the $C^{13}(p, n)N^{13}$ Reaction*

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The neutron yield from $C^{13}(p, n)N^{13}$ has been studied up to a proton energy of $E_p=3.96$ Mev. A resonance is found at $E_p=3.76$ Mev which corresponds to an excited state in N^{14} at 11.07 Mev and coincides with a previously reported level deduced from the reactions of deuterons on C^{12}. This finding furnishes evidence that the same state of a compound nucleus can be excited by two entirely different processes.

I. INTRODUCTION

THERE is considerable experimental evidence to show that the same energy levels are excited in the residual nucleus from a reaction regardless of its method of formation. Similar evidence regarding the energy levels of compound nuclei, which are formed as an intermediate step in such nuclear reactions, is largely lacking. The energy levels of such compound nuclei are most conveniently studied by observing as a function of the energy of the incident bombarding particle the variations in yield of the decay products. The location and width of any resonances that are observed then provide information regarding the level structure. According to current nuclear theory, it is to be expected that the same levels of a compound nucleus would be excited as a result of different modes of formation; and thus one would expect to observe resonances in the yield of disintegration products corresponding to the same levels in the compound nucleus, regardless of the nature of the target nucleus and the incident particle out of whose interaction it is formed. Usually, however, either the energy relations are such as to make it difficult to reach the same excited state in a compound nucleus by two processes which are not the inverse of each other or only a single appropriate target nucleus is available. The experimental evidence is thus far limited to those excited levels in N^{15} which are excited by the two inverse reactions, $N^{14}(n, p)C^{14}$ and $C^{14}(p, n)N^{14}$. Resonances have been observed in both the proton and neutron yields corresponding to the same levels in N^{15}. There is also evidence that some of these same levels may be involved in the inverse reactions $N^{14}(n, \alpha)B^{11}$ and $B^{11}(\alpha, n)N^{14}$. These processes have been summarized by Hornyak and Lauritsen.[1]

A further test of the theory is possible from a study of the higher levels of N^{14}. An energy-level diagram of N^{14} in this region is shown in Fig. 1. A large number of levels are known from the extensive work of Bonner and his collaborators[2–4] and of Bailey, Freier, and Williams,[5] who have studied the excitation curves for the emission of protons, neutrons, and gamma-rays from C^{12} bombarded with deuterons.

As can be seen from Fig. 1, these same levels in N^{14} can be reached through the bombardment of C^{13} with protons having an energy of the order of 4 Mev. Resonances should then be observed for the neutron production and for the formation of radioactive N^{13} from the reaction $C^{13}(p, n)N^{13}$. This reaction has not been studied in this energy region, although the reaction has been observed and the threshold for neutron production accurately measured by Richards and Smith[6] as 3.236 Mev.

It was the purpose of this experiment to search for resonances in the $C^{13}(p, n)N^{13}$ reaction, and thus to determine whether in this reaction the same energy levels in the compound nucleus N^{14} were excited as are found from the bombardment of C^{12} with deuterons.

II. EXPERIMENTAL PROCEDURE

The Rockefeller electrostatic accelerator at M.I.T. provides a magnetically analyzed proton beam of several microamperes at voltages up to approximately 4

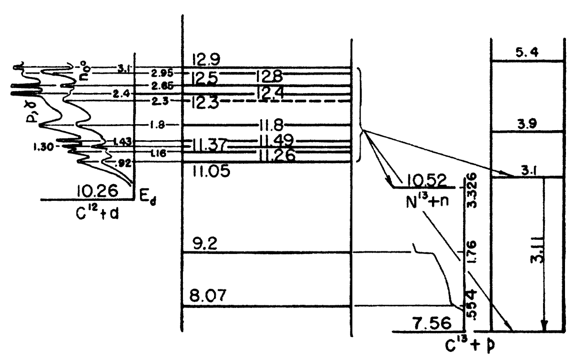

FIG. 1. Virtual energy levels of N^{14}; energies in Mev above the N^{14} ground state.

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[1] W. F. Hornyak and T. Lauritsen (private communication to be published).

[2] Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).

[3] Bonner, Evans, Harris, and Phillips, Phys. Rev. **75**, 1401 (1949).

[4] Phillips, Bonner, and Richardson, Phys. Rev. **76**, 169 (1949).

[5] Bailey, Freier, and Williams, Phys. Rev. **73**, 274 (1948).

[6] H. T. Richards and R. V. Smith, Phys. Rev. **77**, 752A (1950).

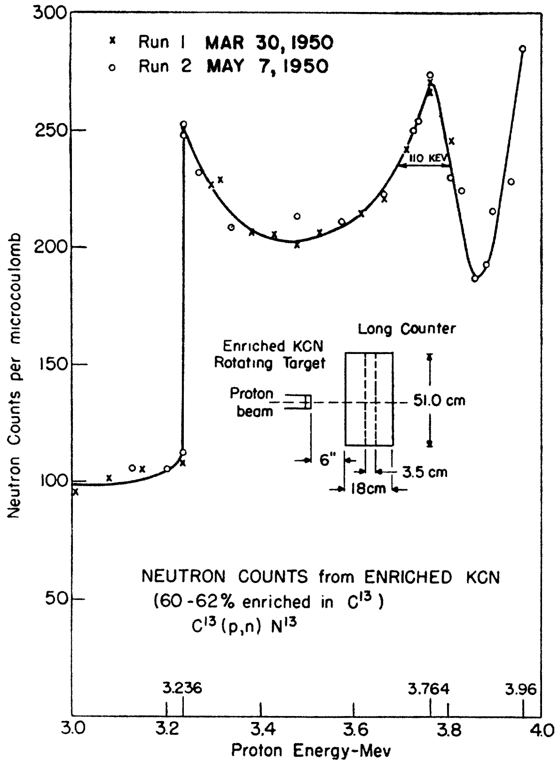

FIG. 2. Neutron counts from enriched KCN.

Mev. The energy resolution is determined by slits placed at the entrance and exit to the analyzing magnet and in these experiments was approximately ±5 kev. The generator voltage in these experiments was measured using a generating voltmeter, the output of which was read on a 0–100 microammeter. Two calibration points were obtained from the $Li^7(p, n)Be^7$ reaction threshold,[7] 1.882 Mev, using successively the proton beam and the mass 2 beam. The scale between was assumed to be linear; this assumption was verified by observation of the threshold for the $C^{13}(p, n)N^{13}$ reaction.

The experiment consisted of the measurement of the variations of neutron yield with proton energy. The neutrons were detected with a conventional BF_3 "long counter"[8] placed with its axis perpendicular to the proton beam, 10 inches from the target. The gamma-ray yield was measured simultaneously with a Geiger-Mueller counter at 90 degrees through the beam direction, 7 inches from the target. A preliminary run was made on a thick target of pure normal carbon. Commencing at 3.26 Mev, the neutron yield rose smoothly from a low background value, and no resonances were observed for proton energies in the range from 3.26 to 3.96 Mev. That the $C^{13}(p, n)N^{13}$ reaction was taking place, however, with the one percent of the C^{13} present in the normal carbon, was determined by plotting the gamma-ray activity in the target as a function of time after shutting off the proton beam. This disclosed an activity of 12±2 min. half-life, which is attributed to N^{13} (λ=10.1 min.).

The low yield from the thick carbon target indicated the need for a target enriched in C^{13}. Satisfactory targets were obtained by the evaporation of KCN onto tantalum sheets. The KCN, obtained from Eastman Kodak Company, had the C^{13} content increased to 60 percent. The target with the tantalum backing was mounted in a rotating-target assembly. At first, difficulty was experienced from the disappearance of the KCN during bombardment. This was prevented by the evaporation of a thin layer of gold over the KCN. The final targets thus consisted of a layer of KCN approximately 10 kev thick covered with a layer of gold less than 5 kev in thickness.

III. RESULTS

Figure 2 shows the neutron yield in counts per microcoulomb of protons from the enriched KCN targets as a function of proton energy. The yield increases abruptly by a factor of about 2.5 at a proton energy of 3.24 Mev. Within our meter-reading error of ±10 kev, this value agrees with the threshold value of 3.236 Mev found by Richards and Smith.[6] After an initial drop, the yield again rises and passes through a maximum at a proton energy of 3.76 Mev. After this maximum and the subsequent drop, the yield is again rising at 3.96 Mev, the limiting voltage that could be reached in these experiments. The statistical error in the number of counts represented by each point above the threshold energy in Fig. 2 is about one percent. The close agreement between the results taken at different times indicates that during the course of these experiments there was no appreciable accumulation of contamination on the target surface.

That the observed maximum in the excitation curve was caused by C^{13} was shown by observations made on a target of normal KCN. The neutron yield from this target rose smoothly without a detectable break at the C^{13} threshold and up to a proton energy of 3.7 Mev was small compared with that from the enriched target. The gamma-ray yield from both the enriched and unenriched KCN targets rose smoothly up to about 3.8 Mev with comparable intensities. Maxima in the gamma-ray yield from $C^{13}+p$ are apparently masked by a high background.

IV. CONCLUSIONS

It may be seen in Fig. 1 that the first level of N^{14} excited in the bombardment of C^{12} by deuterons is that corresponding to the 0.92-Mev resonance for the emission of protons, gamma-rays, and neutrons. Using the values of $C^{12}+d^2-N^{14}=10.29$ Mev and $C^{13}+p-N^{14}=7.57$ Mev from the compilation of Tollestrup, Fowler, and Lauritsen[9] and the deuteron-resonance energy[4] $E_d=0.91$ Mev, the corresponding level in N^{14} is calculated to be at 11.07 Mev. If this level is excited in the

[7] Herb, Snowden, and Sala, Phys. Rev. 75, 246 (1949).
[8] A. O. Hansen and J. L. McKibben, Phys. Rev. 72, 673 (1947).
[9] Tollestrup, Fowler, and Lauritsen, Phys. Rev. 78, 372 (1950).

$C^{13}(p, n)N^{13}$ reaction, a resonance for neutron production should be observed at a proton energy of 3.78 Mev. The measured maximum for the resonance shown in Fig. 2 is 3.76 Mev, which is in satisfactory agreement with the predicted value. Similar considerations lead to the expectation of another resonance at a proton energy[10] of 4.01 Mev, a possibility that is not excluded by the data shown in Fig. 2. A rather arbitrary value of the half-width of the observed resonance at 3.76 Mev is 110 kev.

Measured in the same rough fashion, the half-widths of the peaks for the neutron, gamma-ray, and proton yields at $E_d=0.92$ Mev in the $C^{12}+d$ reaction are about 100 kev.[2,3,5] We hope in the near future to be able to extend these measurements to slightly higher voltages in order to reach the next few levels.

[10] There is also the possibility of a resonance at $E_p=3.99$ Mev, corresponding to a resonance in the proton yield from $C^{12}(d, p)C^{13}$ at a deuteron energy of 1.14 Mev, as reported in reference 4.

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On the Self-Energies of Quantum Field Theory*

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It is shown that by a means of a canonical transformation in quantum electrodynamics, the photon self-energy and the current associated with a mixture of zero-photon and one-photon states cannot be simultaneously made to vanish to order e^2. This difficulty can be overcome by adding a charged Bose meson field.

THE recent modification of the usual perturbation theory applied to quantum field theory, introduced by one of us,[1] has been applied to the calculation of the photon self-energy. Although the theory has the power to make any single ambiguous divergent integral take on any finite value, including zero, one must be careful that the assignments of ambiguous integrals appearing in the expressions for different physical quantities are consistent one with another. In this note it is shown that to order e^2, both the photon self-energy and the current associated with a mixture of zero-photon and one-photon states cannot be simultaneously set equal to zero.

The Hamiltonian of the coupled Dirac-Maxwell fields may be written:

$$H=H_0+H_1+H_2 \tag{1}$$

with

$$H_0=\int e_{ps}(\alpha_{ps}{}^+\alpha_{p's})\delta(\mathbf{p}-\mathbf{p}')d\mathbf{p}d\mathbf{p}' +\int \kappa a_{\lambda\boldsymbol{\kappa}}{}^+a_{\lambda\boldsymbol{\kappa}'}\delta(\boldsymbol{\kappa}-\boldsymbol{\kappa}')d\boldsymbol{\kappa}d\boldsymbol{\kappa}', \tag{2}$$

$$H_1=-\frac{e}{2\pi}\int\frac{d\mathbf{p}d\mathbf{p}'d\boldsymbol{\kappa}}{\kappa^{\frac{1}{2}}}\delta(\mathbf{p}-\mathbf{p}'-\boldsymbol{\kappa}) \times\{(\alpha_{ps}{}^+\alpha_{p's'})a_{\lambda\boldsymbol{\kappa}}\langle\mathbf{p}s|\alpha_\lambda|\mathbf{p}'s'\rangle +(\alpha_{p's'}{}^+\alpha_{ps})a_{\lambda\boldsymbol{\kappa}}{}^+\langle\mathbf{p}'s'|\alpha_\lambda|\mathbf{p}s\rangle\}, \tag{3}$$

$$H_2=\frac{e^2}{2\pi^2}\int\frac{d\mathbf{p}d\mathbf{p}'d\mathbf{p}''d\mathbf{p}'''}{|\mathbf{p}-\mathbf{p}'|^2}\delta(\mathbf{p}-\mathbf{p}'+\mathbf{p}''-\mathbf{p}''') \times(\alpha_{ps}{}^+\alpha_{p's'}\alpha_{p''s''}{}^+\alpha_{p'''s'''}) \times\langle\mathbf{p}s|1|\mathbf{p}'s'\rangle\langle\mathbf{p}''s''|1|\mathbf{p}'''s'''\rangle. \tag{4}$$

The notation employed above is the same as in H.S. I. and will not be described here again.

As described in H.S. II, one now transforms the Hamiltonian H by means of a sequence of finite unitary transformations $e^{iS(\epsilon)}$ such that in the limit as the parameter $\epsilon\rightarrow\infty$, all the "virtual" terms in H are made to vanish. $S(\epsilon)$ is expanded in a powers series in the electronic charge.

$$S(\epsilon)=S_1(\epsilon)+S_2(\epsilon)+\cdots, \tag{5}$$

where $S_n(\epsilon)$ is of order e^n. One can now write the transformed Hamiltonian H' as a power series in e:

$$H'=e^{-iS(\epsilon)}He^{+iS(\epsilon)},$$
$$H'=H_0+\{H_1-i[S_1(\epsilon), H_0]\}+\{H_2-i[S_1(\epsilon), H_1] -\tfrac{1}{2}[S_1(\epsilon),[S_1(\epsilon), H_0]]-i[S_2(\epsilon), H_0]\}+\cdots. \tag{6}$$

Eliminating the "virtual" terms in H' step by step in powers of e, we first choose $S_1(\epsilon)$ such that

$$\lim_{\epsilon\rightarrow\infty}\{H_1-i[S_1(\epsilon), H_0]\}=0. \tag{7}$$

The function $S_1(\epsilon)$ is

$$S_1(\epsilon)=-\frac{ie}{2\pi}\int\frac{d\mathbf{p}d\mathbf{p}'d\boldsymbol{\kappa}\delta(\mathbf{p}-\mathbf{p}'-\boldsymbol{\kappa})}{\kappa^{\frac{1}{2}}(e_{ps}-e_{p's'}-\kappa)}g(\mathbf{p}s|\mathbf{p}'s'|\epsilon) \times\{(\alpha_{ps}{}^+\alpha_{p's'})a_{\lambda\boldsymbol{\kappa}}\langle\mathbf{p}s|\alpha_\lambda|\mathbf{p}'s'\rangle -(\alpha_{p's'}{}^+\alpha_{ps})a_{\lambda\boldsymbol{\kappa}}{}^+\langle\mathbf{p}'s'|\alpha_\lambda|\mathbf{p}s\rangle\}, \tag{8}$$

* Research carried out under contract with the AEC.

[1] H. Snyder, Phys. Rev. **78**, 95 (1950). This article will henceforth be denoted as H.S. I., and the article H. Snyder, Phys. Rev. **79**, 520 (1950) will be denoted as H.S. II.