These results are accurate to within a factor of 2-3.

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DE-EXCITATION NEUTRONS FOLLOWING ^{14}N PHOTODISINTEGRATION

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In a time-of-flight study of ^{14}N photoneutrons in which neutron energy spectra were obtained at different bremsstrahlung end-point energies between 15.5 and 29.5 MeV, de-excitation neutrons from excited states of ^{13}C were observed.

We have found evidence for de-excitation neutrons from excited states of ^{13}C following photoproton emission by ^{14}N, due to the sequential reaction $^{14}N(\gamma,p)^{13}C^*(n)^{12}C$. Such photonucleon cascades have been suggested[1,2] by earlier workers, and sequential two-body breakup has been observed[3] in the reaction $^{12}C(d,n)^{13}N^*(p)^{12}C$, among others.[4]

Photoneutron time-of-flight spectra of ^{14}N and ^{2}H were measured[5] at the National Research Council electron linear accelerator using bremsstrahlung at end-point energy intervals of 2 MeV between 15.5 and 29.5 MeV. The quasimonoenergetic photon spectrum calculated from the photoneutron difference spectrum obtained by subtracting the 21.5-MeV ^{2}H data from the 23.5-MeV data is shown in Fig. 1. The ^{14}N neutron difference spectra for the photon bands 23.5-21.5 MeV and 29.5-27.5 MeV are shown in Fig. 2. If only ground-state transitions to ^{13}N occurred, each

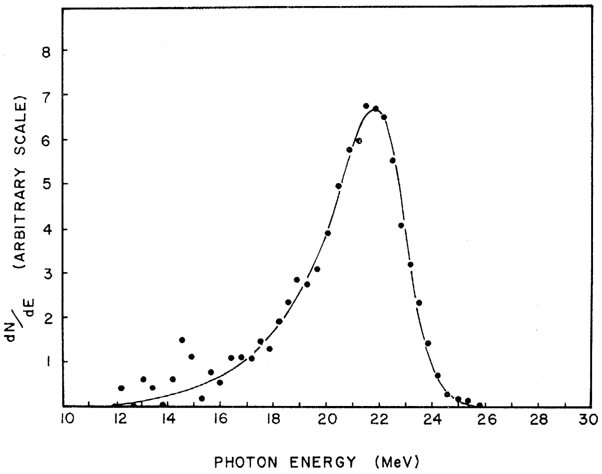

FIG. 1. Photon difference spectrum resulting from the subtraction of a measured 21.5-MeV bremsstrahlung spectrum from a 23.5-MeV spectrum.

difference spectrum would be confined to the energy region under the photon peak, shown dotted. This is clearly not the case.

Neutron emission by $^{14}N^*$ to excited states of ^{13}N will produce peaks in the difference spectrum at energies lower by amounts proportional to the ^{13}N excitation energies, provided that the levels[6] (all of which are proton unstable) have lifetimes long enough for the decay to ^{12}C to occur as a sequence of two-body breakups. Such peaks will rise in energy as the photon energy increases. Our data as a whole indicate that excited-state transitions occur, but the prominent peaks in Fig. 2 at 2.0, 2.9, and 6.3 MeV, and probably the one at 4.1 MeV, are not of this type. They remain nearly fixed in energy as the photon energy bin is changed. They also contain a large fraction of all the observed neutrons.

Several authors[7,8] have noted that the integrated $^{14}N(\gamma, np)$-reaction cross section[9] is larger than the (γ, n_0) and (γ, p_0) cross sections[10-12] integrated over the giant resonance. These are smaller than the total neutron cross section[13,14] by a factor of about 5. The strength of the peaks in Fig. 2 can therefore be explained if they are due to the (γ, np) reaction. Their shape cannot be explained by simultaneous emission of a neutron and proton, however. Direct three-body breakup would produce a broad, smooth distribution of neutron energies. De-excitation neutrons can, however, cause peaks.

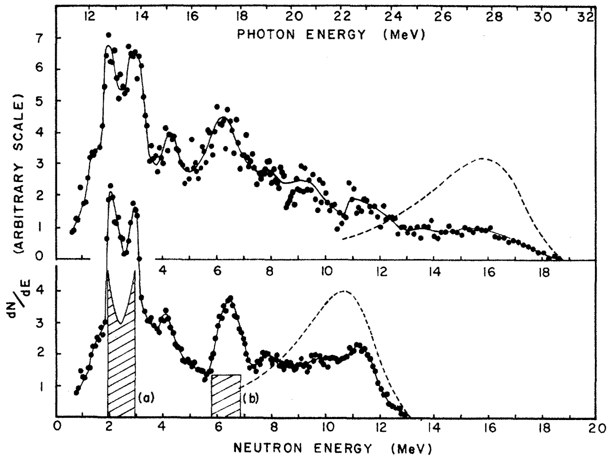

FIG. 2. Measured differences between (i) the 23.5- and 21.5-MeV neutron energy spectra of ^{14}N (lower curve) and (ii) the 29.5- and 27.5-MeV spectra (upper curve). The photon energies k are obtained from ground-state neutron energies T_n by the relation $k \simeq T_n A/(A-1) + B_n{}^A$. The photon differences are shown dotted. The hatched regions are calculated line shapes for de-excitation neutrons, Doppler broadened by photoproton emission. Their vertical scale has no significance. Region (a) is for the 7.55-MeV state of ^{13}C; region (b) is for the 11.8-MeV state.

The clearest features in Fig. 2, which we believe are due to sequential (γ, pn) reactions, are a cleft peak extending (in the lower curve) from 1.9- to 3.1-MeV laboratory energy, and a single peak at 6.3 MeV extending from about 5.7 to 7.2 MeV. The latter was also observed by Fuchs.[2] We ascribe these peaks to neutrons from the 7.55-MeV ($\frac{5}{2}^-$) and the 11.8-MeV ($\frac{3}{2}^-$) levels of ^{13}C nuclei which were recoiling due to photoproton emission by ^{14}N. Photoprotons frequently exhibit an angular distribution of the form $1 + \beta \sin^2\theta$, with a maximum at 90°, where θ is the angle of the detector relative to the photon beam and β is a positive number. In such a case, more recoiling ^{13}C nuclei per unit solid angle approach and recede from a detector at 90° than is the case for an isotropic first reaction. Hence maximum Doppler shift is more probable in the anisotropic case, and a cusped neutron energy distribution can occur. The shaded areas in Fig. 2 represent the Doppler-broadened line shapes expected if (a) 22-MeV photons are absorbed by ^{14}N which then emits d-wave protons[15] to the 7.55-MeV level of ^{13}C which in turn decays to the ground state of ^{12}C; and (b) if 22-MeV photons eject s-wave protons to the 11.8-MeV level which then emits neutrons to ^{12}C. At 90° to the photon beam direction the limits on the neutron kinetic energy T_n, shown in Table I, are

$$T_n{}^{\pm} = T_{n0} \pm 2(T_{n0}T_{p0})^{1/2}/(A-1) + T_{p0}/(A-1)^2 - T_0/A, \qquad (1)$$

where T_{i0} is the energy of nucleon i corresponding to breakup at rest, A is the nuclear mass, and T_0 is the recoil energy of the parent nucleus due to the photon. Table I also contains values of $T_n{}^{\pm}$ calculated for 27.5-MeV photons. The increased broadening expected (due to greater T_{p0}) is observed in the upper data set of Fig. 2.

Table I. Limits on the energy of de-excitation neutrons from the 7.55- and 11.8-MeV excited states of ^{13}C, Doppler broadened by photoprotons from ^{14}N calculated for 22- and 27.5-MeV photons.

	7.55-MeV state		11.8-MeV state	
k (MeV)	$T_n{}^-$ (MeV)	$T_n{}^+$ (MeV)	$T_n{}^-$ (MeV)	$T_n{}^+$ (MeV)
22.0	1.84	3.05	5.73	6.94
27.5	1.66	3.28	5.31	7.44

The observed particle distribution as a function of energy in a two-step reaction is, according to Morinigo,[16]

$$d\sigma/dT_n \propto T_n^{1/2} W_1 W_2 W_3, \tag{2}$$

where $W_1 \propto (g^2-u^2)^{-1/2}$. The velocity u corresponds to T_0, and velocity g to T_n. In our case, $u^2 \ll g^2$; so $(d\sigma/dT_n) \sim W_2 W_3$, where W_2 is sensitive to the angular distribution in the first breakup, and W_3 arises from the final angular distribution. In our special case of neutron detection at 90° to the photon beam,

$$W_2 = 1+\beta(\beta+1)(1+\lambda/\tau)^2(g^2-2u^2)/8v^2, \tag{3}$$

where $\tau = g^2+u^2$, $\lambda = v^2-w^2$, v is the ^{13}C recoil velocity arising from a proton of energy T_{p0}, and velocity w, added vectorially to u and v, gives g. We have assumed (a) for the 7.55-MeV level, an angular distribution of the precursor photoproton corresponding to $\beta = 1.5$, combined with an isotropic distribution of neutrons about the ^{13}C recoil direction; and (b), for the 11.8-MeV level, isotropic photoproton emission, followed by isotropic neutron emission ($\beta = 0$, $W_3 = 1$). The agreement of these shapes with the data is good. They contrast sharply with the distribution for three-body breakup.[17] We make no claim that these are the best angular distributions for the cases studied. Rather they serve as examples of how the line is sensitive to W_2.

We conclude that the reaction ^{14}N(γ, pn) takes place with high probability by a sequence of two-body decays.

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