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Evidence for Two-step Processes in Photonuclear Reactions

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Abstract

The measurement of de-excitation γ rays following photodisintegration allows the identification of specific entrance and exit channels in these reactions. From studies of de-excitation γ rays in three separate cases, examples are cited of reactions which, on the basis of nuclear structure arguments, proceed via two-step processes.

Introduction

The study of two-step nuclear reactions is achieving increasing importance, primarily because it permits an understanding of those measured differential cross sections of nuclear reactions which are not amenable to treatment by the direct reaction calculations. Many of the examples given in the literature (Stamp 1974; Iachello and Singh 1974; Asciutto *et al.* 1974; Pougheon *et al.* 1975; Cotanch and Vincent 1976) refer to particle transfer reactions or scattering reactions. Among these, a notable example is the study of the $^{48}Ca(^{16}O, ^{15}C)^{49}Ti$ reaction (Kovar *et al.* 1974) which clearly cannot proceed by a single-step direct process. This example is emphasized because, experimentally, the peak cross section observed at forward angles is not markedly different from those of other transfer reactions which can, in principle, proceed via a single-step direct process.

The purpose of this paper is to present evidence for two-step processes in photodisintegration reactions. This idea has appeared on two earlier occasions. First Sawicki and Czyz (1957) postulated a two-step process to account for the reported large yield of photodeuterons from copper (Byerly and Stephens 1951; Forkman 1956) and sulphur (Katz and Penfold 1951*a*, 1951*b*; Goldemberg and Marguez 1958), but later results (Forkman 1961; Ferrero *et al.* 1960) did not support the earlier experimental findings. In the model of Sawicki and Czyz, the photon energy was absorbed by a single nucleon, which then initiated a pick-up reaction at the nuclear surface, giving rise to the emission of a deuteron.

Secondly, a two-step reaction process was postulated by Quirk and Spicer (1964) in a model which attempted to account for the similarity of photoneutron and photoproton angular distributions. In their model, the absorption of the photon by a proton was followed by a scattering of that proton by a neutron, which was subsequently emitted. Semiquantitative agreement between the model and experiment was found.

In the present paper, three separate examples of photodisintegration reactions in light nuclei are described. Each of them is postulated to proceed mainly via two-step processes for reasons that are based on nuclear structure considerations. For photonuclear reactions in light nuclei, the dipole states are considered to be formed by particle–hole excitations from the nuclear ground state. Furthermore, the decay width is controlled by the overlap of the dipole state wave function with that of the residual state plus the emitted nucleon or cluster of nucleons. For complex clusters we require the nucleons comprising the cluster to be in a relative s state before emission. The argument thus uses a particle–hole picture for the description of the dipole states, and semiquantitative estimates of reduced widths to describe the decay channel. The reduced width γ^2 is given by

$$\gamma \propto \int \psi_e^* \psi_d \, d\tau ,$$

where ψ_e and ψ_d are the wave functions of the exit channel and dipole state respectively. The three examples are now considered in turn.

$^{19}F(\gamma,\alpha)^{15}N^*$ (5·27, 5·30 MeV) Reaction

The de-excitation γ rays from fluorine have been measured by Thomas *et al.* (1972), Shikazono and Kawarasaki (1972) and Thomson (1976). In all three experiments strong indications were seen of γ rays of 5·27 and 5·30 MeV. These have been assigned to the $^{19}F(\gamma,\alpha_1)$ and $^{19}F(\gamma,\alpha_2)$ reactions leading to ^{15}N. Thomson has given for the 150° differential cross section integrated over energy

$$\int_{\text{threshold}}^{30\,\text{MeV}} (d\sigma/d\Omega)_{150^\circ}\, dE = 0\cdot 1 \pm 0\cdot 03 \quad \text{MeV mb sr}^{-1}$$

for the 5·27 MeV γ-ray alone, and

$$\int_{\text{threshold}}^{30\,\text{MeV}} (d\sigma/d\Omega)_{150^\circ}\, dE = 0\cdot 33 \pm 0\cdot 13 \quad \text{MeV mb sr}^{-1}$$

for the 5·27 and 5·30 MeV γ rays together. Assuming isotropy of emission of these γ rays, one finds a little over 4 MeV mb as the integrated cross section for these two specific (γ,α) reactions, or about $1\frac{1}{2}\%$ of the classical dipole sum rule.

The other feature of note in these experimental results is the complete absence of any γ rays of 6·32 MeV energy, which is the excitation of the $1p_{3/2}$ hole state in ^{15}N. This is commented upon because a first thought concerning the mechanism of E1 photon absorption is that it should involve the excitation of a 1p particle to the 2s–1d shell. E1 absorption is required on the grounds that Thomson's (1976) measurement of the cross section for the emission of the 5 MeV γ rays indicates a resonance peaking at 15 MeV and with full width at half-maximum of about 5 MeV. These properties would lead one to consider it as isoscalar E2 if it is not to be classified E1. However, the integrated cross section for these two (γ,α) reactions exceeds the Gell-Mann–Telegdi sum rule for this giant resonance by a factor of three. It is concluded therefore that the cross section peak is due to E1 radiation.

To discuss this (γ,α) reaction, let us assume the wave function of the ^{19}F ground state be as given by Zuker (1969; see also Zuker *et al.* 1968). That is, we have

$$^{19}F,\, \tfrac{1}{2}^+,\, \tfrac{1}{2}: \quad -0\cdot 53\, s^3 + 0\cdot 56\, d^2(01)s - 0\cdot 47\, d^2(10)s - 0\cdot 42\, d^3 ,$$

in an obvious notation. The dipole states of ^{19}F must then have wave functions which are admixtures of the ^{19}F ground state wave function modified by: (i) the excitation of one s–d nucleon to the 2p–1f shell, or (ii) the excitation of one 1p nucleon to the 2s–1d shell. The wave functions of the dipole states so formed, and of an α particle plus the ^{15}N (5·27 MeV) state, with its wave function as given by Zuker *et al.* (1968) and Zuker (1969), are orthogonal. Since the ^{15}N (5·27 MeV) state wave function consists of components with two and four holes in the 1p shell, and we demand that the nucleons constituting the emitted α particle be in a relative s state before emission, the overlap integral described must be zero.

For this reason, the one-step reaction mechanism is unlikely to occur, unless it involves direct excitation of the α particle itself, with its subsequent emission. Thomson (1976) has estimated the integrated cross section for this latter process, and concludes that the integrated cross section for the total (γ, α) process is less than 1·2 MeV mb. That is, it is smaller than the (γ, α) reaction cross section to the 5·27 and 5·30 MeV states of ^{15}N. Thus it is concluded that, if the direct α-particle excitation process plays any part, it is not the major contributor.

However, using Zuker's wave functions (Zuker *et al.* 1968; Zuker 1969) we note the interesting fact that the overlap of the ^{19}F ground state wave function with that of $^{15}N^*$ (5·27 MeV) plus an α particle is large; the Zuker wave functions give a lower limit of 0·2. This nonzero overlap suggests a two-step model of the reaction mechanism in which the incident photon is absorbed by a nucleon which then is reabsorbed and scatters from an α-particle cluster, the latter being emitted. Such a mechanism would leave ^{15}N in a 3-particle–4-hole state (relative to ^{16}O), and this concurs nicely with the theoretical expectations for the structure of the lowest $1/2^+$ and $5/2^+$ states of ^{15}N.

Such a mechanism also accounts for the complete lack of population of the 6·30 MeV $(3/2^-)$ state of ^{15}N. This state is predominantly a 1-hole state relative to ^{16}O, and a similar overlap argument to that given with respect to the 5·27 MeV state leads to the result that the overlap of the ^{19}F ground state with that of the $^{15}N^*$ (6·30 MeV) state plus an α particle is zero, thus accounting for the nonobservance of the (γ, α) reaction in that particular channel.

$^{15}N(\gamma, t)^{12}C^*$ (4·43 MeV) Reaction

The de-excitation γ rays following the photodisintegration of ^{15}N have been measured by Patrick *et al.* (1976). Among a number of γ rays which are identified with electromagnetic decays in ^{14}N and ^{14}C, they observe a strong broad γ ray of 4·44 MeV energy. It is attributed by these authors to the $^{15}N(\gamma, t)^{12}C$ reaction leaving the ^{12}C nucleus in its first excited state. The possibility that this γ ray arises from $^{16}O(\gamma, \alpha)^{12}C$ is easily ruled out, since this γ ray has never been observed during irradiation of a water target. The other possibility is that it arises from the $^{15}N(\gamma, \alpha)^{11}C$ reaction. The estimate of the Doppler broadening of this line due to the recoiling nucleus favours a (γ, t) assignment over the (γ, α) one (Patrick *et al.*).

Two mechanisms are possible to account for the triton emission proposed by Patrick *et al.* (1976). The first requires the presence in the ^{15}N ground state wave function of configurations of the type $(1p_{3/2})^8 (1p_{1/2})^1 (1d)^2$ or $(1p_{3/2})^8 (1p_{1/2})^1 (2s_{1/2})^2$. According to Zuker *et al.* (1968) and Zuker (1969), the intensity of the former configuration in the ^{15}N ground state wave function is approximately 20%.

The model of direct formation of a triton, followed by its emission, demands that dipole excitations of the type $1p_{3/2} \rightarrow 1d_{5/2}$ (the strongest particle–hole transition in ^{15}N; Fraser *et al.* 1970) or $1p_{1/2} \rightarrow 1d_{3/2}$ occur and are followed by a two-nucleon pick-up process in which the nucleon excited in the dipole transition picks up the two 1d nucleons to form a triton, which is then emitted. Now, the work of Patrick *et al.* detected the γ ray emitted in the decay of the 4·44 MeV state of ^{12}C. So, a direct triton emission would require a nonzero overlap between a dipole state of ^{15}N and a triton plus ^{12}C* (4·44 MeV). Now the dipole states, as noted in the previous section, are formed by the excitation of 1p nucleons to the 2s–1d shell. The 4·44 MeV state of ^{12}C, according to McKay and Spicer (1975) has a complex wave function and, in accordance with arguments given above, we seek first a dipole state configuration that has nonzero overlap with the wave function of the 4·44 MeV state of ^{12}C, plus three nucleons in a relative s state. The overlap integral in this case is approximately 0·07, using the ^{12}C (4·44 MeV) state wave function given by McKay and Spicer and the calculations on the dipole states of ^{15}N of Fraser *et al.*

The alternative picture is one of a two-step process, again involving a $1p_{3/2} \rightarrow 1d_{5/2}$ single-nucleon excitation in the formation of the dipole state. This time it is proposed that the component of the ^{15}N ground state wave function involved is the major $(1p_{1/2})^{-1}$ component, and that the excited nucleon scatters from the three $1p_{1/2}$ nucleons which are then emitted in the form of a triton. The excited nucleon is reabsorbed in the nucleus. In this case, using the same sources as before (Fraser *et al.* 1970; McKay and Spicer 1975), the overlap integral is estimated to be about 0·28 in magnitude. Thus it may be expected that a two-step process would occur with rather greater probability than a single-step process.

It is worthy of note that the excited $1d_{5/2}$ nucleon just referred to must also have a significant probability of escaping from the nucleus. Therefore, some fraction of the *photoproton* angular distribution should reflect the contribution of a two-step process in the photoproton emission; i.e. the $1p_{3/2} \rightarrow 1d_{5/2}$ excitation followed by a proton–triton scattering with the proton being emitted from the nucleus.

It would seem that a mechanism for triton emission which involves appeal to an impurity component of the wave function followed by amalgamation of an excited nucleon, with two nucleons already in a relative s state with respect to the state of the excited nucleon, is relatively unlikely. Thus, the most reasonable mechanism for the reaction is a two-step one: photon absorption by a nucleon followed by nucleon–triton scattering. This has the very strong advantage that its description involves the major component of the ^{15}N ground state wave function.

^{28}Si(γ, p)^{27}Al* (4·05 MeV) Reaction

Thomson *et al.* (1972*a*) observed the population of the 4·05 MeV ($3/2^-$) level of ^{27}Al following the photodisintegration of ^{28}Si. It was found to be populated in about 4% of the photodisintegrations. Wildenthal and Newman (1968) found, from a study of the ^{28}Si(d, ^{3}He)^{27}Al reaction, two states populated by $l = 1$ pick-up reactions. These are the 4·05 and 5·16 MeV states, both of which have large spectroscopic factors for the pick-up reaction, and small spectroscopic factors in the ^{26}Mg(^{3}He, d)^{27}Al reaction (Endt and Van der Leun 1973). They are thus labelled as states formed by coupling a proton hole to the ground state of ^{28}Si.

The question of whether the proton hole is 1p or 2p in nature is evidently settled by the work of Arditi *et al.* (1971), who concluded that the 1p proton hole states are spread over about 15 MeV, with centroid well above 10 MeV in excitation. The proton hole state must thus be 2p in nature.

A state such as a $2p_{3/2}$-hole state could be formed as a final state in the photodisintegration of ^{28}Si if there were a significant component of $(2p_{3/2})^{2n}$ impurity in the ground state of ^{28}Si. The reaction mechansim would then be a single-step process involving excitation of one of the $2p_{3/2}$ protons, with the excited particle being emitted.

The question of whether there is $(2p_{3/2})^{2n}$ impurity in the ground state of ^{28}Si may be qualitatively tested by inspection of the low-excitation energy levels of ^{27}Al, if it is assumed that the ground state of ^{27}Al is adequately described by coupling a proton hole to the ^{28}Si ground state. Since the $1f_{7/2}$ single-particle state is always expected at a lower energy than the $2p_{3/2}$ single-particle state, it follows that the presence of $(2p_{3/2})^{2n}$ impurities in the ^{28}Si ground state should be accompanied by the presence of $(1f_{7/2})^{2n}$ impurities also. Carrying this argument into the ^{27}Al situation, it means that if there is a low-lying $3/2^-$ level in that nucleus there should be observed also, at lower excitation, a $7/2^-$ state. Such a state is not observed in ^{27}Al, but one is in fact seen as described above in ^{31}P. From this we argue qualitatively that there is $(2p_{3/2})^{2n}$ impurity in ^{32}S, but not in ^{28}Si. If this is so, we are led again to postulate a two-step mechanism for the photodisintegration of ^{28}Si leading to the 4·05 MeV state of ^{27}Al as a final state. Here we postulate that a nucleon absorbs the energy of the incident photon and is then involved in a nucleon–nucleon scattering which is followed by emission of a proton. The other nucleon involved in the scattering process must finish in the $2p_{3/2}$ single-particle state, for population of that state to be observed.

It is of interest that the 5·02 MeV ($3/2^-$) state of ^{31}P is populated in the photodisintegration of ^{32}S (Thomson *et al.* 1972*b*). However, as noted above, there is a $7/2^-$ state in ^{31}P lower in excitation than the first $3/2^-$ state, so that reaction mechanisms utilizing the $(2p_{3/2})^{2n}$ impurity in the ^{32}S ground state or the two-step process are tenable.

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References

Arditi, M., *et al.* (1971). *Nucl. Phys.* A **165**, 129–44.
Ascuitto, R. J., King, C. H., McVay, L. J., and Sorenson, B. (1974). *Nucl. Phys.* A **226**, 454–92.
Byerly, P. R., and Stephens, W. E. (1951). *Phys. Rev.* **83**, 54–62.
Cotanch, S. R., and Vincent, C. M. (1976). *Phys. Rev. Lett.* **36**, 21–5.
Endt, P. M., and Van der Leun, C. (1973). *Nucl. Phys.* A **214**, 1–625; Errata (1975) in *Nucl. Phys.* A **248**, 153–5.
Ferrero, F., Ferroni, S., Malvano, R., Menardi, S., and Silva, E. (1960). *Nucl. Phys.* **15**, 436–51.
Forkman, B. (1956). *Ark. Fys.* **11**, 265–75.
Forkman, B. (1961). *Nucl. Phys.* **23**, 269–84.
Fraser, R. F., Garnsworthy, R. K., and Spicer, B. M. (1970). *Nucl. Phys.* A **156**, 489–500.
Goldemberg, J., and Marguez, L. (1958). *Nucl. Phys.* **7**, 202–8.
Iachello, F., and Singh, P. P. (1974). *Phys. Lett.* B **48**, 81–3.

Katz, L., and Penfold, A. S. (1951*a*). *Phys. Rev.* **81**, 815–19.
Katz, L., and Penfold, A. S. (1951*b*). *Phys. Rev.* **83**, 169.
Kovar, D. G., Henning, W., Zeidman, B., Eisen, Y., and Fortune, H. T. (1974). *Phys. Rev. Lett.* **33**, 1611–14.
McKay, C. M., and Spicer, B. M. (1975). *Aust. J. Phys.* **28**, 241–6.
Patrick, B. H., Bowey, E. M., and Muirhead, E. G. (1976). *J. Phys.* G **2**, 751–67.
Pougheon, F., Rotbard, G., Roussel, P., and Vernotte, J. (1975). *Phys. Rev. Lett.* **34**, 158–60.
Quirk, T. W., and Spicer, B. M. (1964). *Nucl. Phys.* **51**, 345–52.
Sawicki, J., and Czyz, W. (1957). *Nucl. Phys.* **4**, 248–56.
Shikazono, N., and Kawarasaki, Y. (1972). *Nucl. Phys.* A **188**, 461–87.
Stamp, A. P. (1974). *Nucl. Phys.* A **220**, 137–65.
Thomas, B. J., Buchnea, A., Irish, J. D., and McNeill, K. G. (1972). *Can. J. Phys.* **50**, 3085–9.
Thomson, J. E. M. (1976). Ph.D. Thesis, University of Melbourne.
Thomson, J. E. M., Champion, N. D., Stewart, R. J. J., and Thompson, M. N. (1972*a*). *Aust. J. Phys.* **25**, 669–79.
Thomson, J. E. M., Stewart, R. J. J., and Thompson, M. N. (1972*b*). Proc. Int. Conf. on Nuclear Structure Studies using Electron Scattering and Photoreaction, Sendai, pp. 297–305 (Tohoku University).
Wildenthal, B. H., and Newman, E. (1968). *Phys. Rev.* **175**, 1431–41.
Zuker, A. P. (1969). *Phys. Rev. Lett.* **23**, 983–7.
Zuker, A. P., Buck, B., and McGrory, J. B. (1968). *Phys. Rev. Lett.* **21**, 39–43.

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