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AN ANOMALY IN THE REACTION $n+p \to D+2\gamma$

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ABSTRACT

We analyze the recently observed doubly radiative n - p capture. It is shown that the experimental result is impossible to explain within the present theoretical framework.

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The first observation of the process $n+p \to D+2\gamma$ has recently been reported [1]. The salient features of the experimental results are the following. Below thermal neutron energy, the branching ratio to the well-known process $n+p \to D+\gamma$ is 10^{-3}. The energy distribution for the coincident photons has a minimum for equipartition, contrary to the phase space distribution which peaks for equipartition. It is our purpose in this note to show that the experimental results are grossly anomalous within conventional descriptions of this simplest nuclear system, and this mainly on dimensional grounds. A confirmation of the experimental result could hence have a major impact on the understanding of nuclei and even elementary particles.

It should be noted that the present observation is not in obvious disagreement with other experimental results, since little information exists on 2γ decays: two known cases [2),3)] of nuclear isomeric decays in competition with M4 transitions, one case [4)] of a nuclear $0^+ \to 0^+$ transition as well as the photon decays of the metastable 2s states of electronic hydrogen- and helium-like atoms [5)] and muonic helium [6)]. To our knowledge there exists no observation in nuclear physics of the 2γ transition between states of spin J_i and J_f, for which $J_i + J_f \neq 0$, $|J_i - J_f| < 4$. Even with a fairly high branching ratio, such decays would only give rise to a diffuse gamma background which would interfere little with most experiments.

For the further discussion we note that the initial np states in thermal neutron capture are $^1S_0$ and $^3S_1$ in an incoherent statistical mixture. From the deuteron binding energy, $B = 2.23$ MeV, the photons have reduced wave lengths $\lambdabar \approx 200$ fm, much larger than the effective ranges of the interaction, $r_{os} = 2.7$ fm and $r_{ot} = 1.7$ fm, and even larger than the huge np scattering lengths, $a_s = -23.7$ fm and $a_t = 5.4$ fm. Apart from the region of interaction at short distance, the wave functions are given to a considerable precision by

$$|^1S_0, k\rangle = \chi_s \frac{\sin(kr+\delta_s)}{kr}$$

$$|^3S_1, k\rangle = \chi_t \frac{\sin(kr+\delta_t)}{kr}$$

$$|D\rangle = \chi_t \sqrt{\frac{\varkappa}{2\pi}} \frac{e^{-\varkappa r}}{r} \quad , \quad \varkappa = \sqrt{MB}$$

The D state admixtures are omitted since they affect our conclusions but little. The phase shifts are given with good precision by the effective range formula

$$k \cot \delta = -\frac{1}{a} + \frac{1}{2} r_0 k^2$$

In the limit $r_{ot} = 0$ one has $\kappa a_t = 1$, which guarantees spatial orthogonality of $|^3S,k\rangle$ and $|D\rangle$. We will later discuss corrections to orthogonality.

In the following we note that no accidental cancellations occur in general. On the contrary, all overlap functions are large unless explicit statements are made to the contrary. This is a central point, since the large overlaps make it most difficult to increase any matrix elements substantially above our estimates.

The single photon emission in $n + p \to D + \gamma$ is well understood [7] as a very strong M1 transition $^1S_o \to D$. The cross-section is in the scattering length approximation

$$\sigma = 2\pi\alpha \frac{c}{v_n} (\mu_p - \mu_n)^2 \left(\frac{B}{Mc^2}\right)^{5/2} (\kappa^{-1} - a_s)^2 = 297 \text{ mb}$$

A more accurate evaluation [7] gives $\sigma = 302 \pm 4$ mb. A 10% discrepancy compared to the observed cross-section for this transition has been widely discussed in the literature. It is generally accepted as due to nuclear interaction currents and is quantitatively well reproduced by the calculations [8]. There is no direct measurement which associates this effect with the ^1S_o capture, and occasionally the suggestion has been made that it might be due to an anomalous capture from the $^3S_1$ state [9], which is normally very weak.

The wavelength of the photons in the $n + p \to D + 2\gamma$ reaction is much larger than the deuteron radius. One is therefore naturally led to make a multipole expansion of the electromagnetic potential. The dominant multipole combinations of the emitted photons will be E1 - E1 and M1 - M1. We consider the two cases separately.

a) <u>E1 - E1 case</u>

Since the electric dipole operator is spin-independent, if small retardation effects are neglected, the transition proceeds only from the $^3S_1$ state. The cross-section is

$$\frac{d\sigma}{d\omega_1\, d\Omega_1\, d\Omega_2} = \frac{3}{4} \frac{1}{v_n} 2\pi \left| M(E1,E1) \right|^2 \omega_1^2 \omega_2^2$$

where ω_1, ω_2 are the energies of the photons $(\omega_1 \leq \omega_2,\ \omega_1 + \omega_2 = B)$ emitted into solid angles $d\Omega_1$, $d\Omega_2$ with polarization vectors $\vec{\epsilon}_1$, $\vec{\epsilon}_2$ and v_n is the velocity of the incoming neutron. The actual neutron velocity in the experiment [1] was about 400 m/s. In the numerical estimates below, we will use $v_n = 2200$ m/s, corresponding to thermal neutrons.

Normally, the process goes in two steps via an intermediate ^3P state of the np system. The matrix element for this process is

$$M^P(E1,E1) =$$

$$= -\frac{1}{(2\pi)^6\sqrt{4\omega_1\omega_2}}\int d^3k\,\langle D|e\vec{v}_p\cdot\vec{\epsilon}_2|\vec{k}\rangle\frac{1}{\omega_1+E_k}\langle\vec{k}|e\vec{v}_p\cdot\vec{\epsilon}_1|{}^3S\rangle + (1\leftrightarrow 2)$$

$$= \frac{\alpha}{\sqrt{18\pi^3}}\,\frac{a_t}{\varkappa^{5/2}}\,\frac{B}{\sqrt{\omega_1\omega_2}}\left(\frac{1}{1+\sqrt{\frac{\omega_1}{B}}}+\frac{1}{1+\sqrt{\frac{\omega_2}{B}}}\right)(\vec{\epsilon}_1\cdot\vec{\epsilon}_2)$$

where plane waves have been used for the intermediate states. After summation over photon polarizations and integration over one direction, the cross-section becomes

$$\frac{d\sigma}{d\omega_1\,d\Omega_{12}} = \frac{\alpha^2}{3\pi v_n}\,\frac{B^2a_t^2}{\varkappa^5}\,\omega_1\omega_2\left(\frac{1}{1+\sqrt{\frac{\omega_1}{B}}}+\frac{1}{1+\sqrt{\frac{\omega_2}{B}}}\right)^2(1+\cos^2\theta)$$

and the total cross-section

$$\sigma = \frac{2}{9}(20+\pi-32\ln 2)\,\alpha^2\frac{c}{v_n}\left(\frac{B}{Mc^2}\right)^{5/2}a_t^2 = 1.2\cdot 10^{-4}\ \mathrm{mb}$$

Similar results have been obtained by Grechukhin [10] by the same reasoning, but we differ by a factor $16\times\frac{1}{2}=8$ in the total cross-section.

The branching ratio $\sigma_{\gamma\gamma}/\sigma_\gamma$ is $4\cdot 10^{-7}$, a factor of 3000 smaller than the measured value [1]. The calculated energy spectrum is a slightly modified phase space distribution of type I, whereas the observed spectrum is of type II with a minimum at $\omega_1=\omega_2=B/2$ (see Fig. 1).

The dimensional structure of the cross-section can be derived from the expression

$$\sigma \propto \text{area} \times (\text{time}\times\text{rate}) \times (\text{time}\times\text{rate})\ .$$

A neutron that hits within an <u>area</u> $\propto a_t^2$ accelerates the proton; the <u>time</u> which the neutron spends within a distance a_t from the proton is $\propto a_t/v_n$; the <u>rate</u> of E1 photon emission is $\propto \alpha\omega^3a_t^2/c^2$; the <u>time</u> available for the second photon emission is $\propto 1/\omega$. Putting this together gives

$$\sigma \propto \alpha^2 \frac{c}{v_n} \left(\frac{\omega a_t}{c}\right)^5 a_t^2 \propto \alpha^2 \frac{c}{v_n} \left(\frac{B}{Mc^2}\right)^{5/2} a_t^2$$

in agreement with the detailed calculations.

In addition to the two-step emission, there may be a contribution from the contact gauge term $(e^2/2M)\vec{A}(\vec{r}_p) \cdot \vec{A}(\vec{r}_p)$ in the interaction Hamiltonian, which creates the two photons in one point. The matrix element for this process is

$$M^{gauge}(E1,E1) = \frac{\alpha}{4\pi^2 M\sqrt{\omega_1\omega_2}} (\vec{\epsilon}_1 \cdot \vec{\epsilon}_2) \langle D | {}^3S_1 \rangle$$

Normally, this is zero because of the orthogonality between the deuteron and the ${}^3S_1$ scattering wave functions. However, one may conceive of a departure from orthogonality because of the presence of mesons and isobars in a more complete description of the wave function. The depletion of the two-nucleon part of the wave function occurs only inside the range of the force. Therefore, a very conservative upper limit to the overlap of the two-nucleon parts of the wave functions is obtained by integrating from r_{ot} to infinity

$$|\langle D | {}^3S_1 \rangle| \ll \sqrt{2\pi\varkappa^{-1}}\, r_{ot}$$

$$\left| \frac{M^{gauge}}{M^P} \right| \ll \frac{3r_{ot}}{2a_t} = 0.5$$

Hence, the gauge term cannot increase the matrix element by a large factor. It should also be noted that the energy spectrum is of phase space type I, proportional to $\omega_1\omega_2$, in disagreement with experiment.

Adler [11] has considered effects of a much larger departure from orthogonality. If it is assumed that most of the 10% discrepancy in the singly radiative np capture cross-section is due to an anomalous capture from the ${}^3S_1$ state [9], this determines the non-orthogonality to be of about the same size as the radial overlap between the deuteron and the ${}^1S_o$ scattering wave functions,

$$\langle D | {}^3S_1 \rangle \approx \int_0^\infty u_D u_{1s}\, dr = \sqrt{8\pi\varkappa^{-1}} (\varkappa^{-1} - a_s)$$

This is 30 times larger than our estimated upper limit and gives a total cross-section of 20 μb, still short of the experiment by a factor of 20, and with a wrong energy spectrum.

The currents associated with meson exchanges and isobar excitations can contribute to the two-photon amplitude. The one-pion-exchange contribution to the E1 - E1 matrix element is

$$M^{OPE}(E1,E1) = \frac{1}{(2\pi)^3\sqrt{4\omega_1\omega_2}} \langle D|[[V^{OPE}, ie\vec{r}_p\cdot\vec{\epsilon}_1], ie\vec{r}_p\cdot\vec{\epsilon}_2]|^3S_1\rangle$$

$$= \frac{\alpha}{18\pi^2\sqrt{\omega_1\omega_2}} (\vec{\epsilon}_1\cdot\vec{\epsilon}_2) \langle D|\frac{f^2}{4\pi} r e^{-\mu r}|^3S_1\rangle$$

$$= \frac{\alpha}{18\pi^2\sqrt{\omega_1\omega_2}} (\vec{\epsilon}_1\cdot\vec{\epsilon}_2) \frac{f^2}{4\pi}\sqrt{8\pi\kappa}\ \frac{2-(\mu+\kappa)a_t}{(\mu+\kappa)^3}$$

This gives a 3% correction to the leading E1 - E1 matrix element. The energy spectrum is again of type I. Heavier meson exchanges should give even smaller effects.

b) <u>M1 - M1 case</u>

The magnetic dipole transitions can proceed from both the ^3S and the ^1S scattering states. Consider first the triplet case. The matrix element for the transition $^3S\to{}^1S\to D$ via an intermediate ^1S state is

$$M^t(M1,M1) =$$

$$= -\frac{1}{(2\pi)^6\sqrt{4\omega_1\omega_2}} \int d^3k \langle D|\frac{ie}{2M}(\mu_p-\mu_n)\frac{\vec{\sigma}_p-\vec{\sigma}_n}{2}\cdot(\vec{k}_2\times\vec{\epsilon}_2)|\vec{k}\rangle$$

$$\times \frac{1}{\omega_1+E_k} \langle\vec{k}|\frac{ie}{2M}(\mu_p-\mu_n)\frac{\vec{\sigma}_p-\vec{\sigma}_n}{2}\cdot(\vec{k}_1\times\vec{\epsilon}_1)|^3S_1\rangle + (1\leftrightarrow 2)$$

The integrals are evaluated in the scattering length approximation. After averaging over the initial spin, summation over the final spin, summation over photon polarizations and integration over one direction, the cross-section becomes

$$\frac{d\sigma}{d\omega_1\, d\Omega_{12}} = \frac{\alpha^2(\mu_p-\mu_n)^4}{4\pi v_n}\,\frac{B^2(\varkappa^{-1}-a_s)^2}{M^4\varkappa}$$
$$\times\ \omega_1\omega_2\left\{f^2\left(\frac{\omega_1}{B}\right)+f^2\left(\frac{\omega_2}{B}\right)+\frac{1+\cos^2\theta}{2}\, f\left(\frac{\omega_1}{B}\right) f\left(\frac{\omega_2}{B}\right)\right\}$$

with
$$f(x) = \frac{1-\sqrt{x}}{1-\varkappa a_s\sqrt{x}}$$

The energy spectrum is of type II with a maximum at $\omega_1 = 0.15$ MeV and a peak-to-valley ratio of 2.5. This spectral form is similar to the observed one. It is caused by the presence of a nearly bound state in the ^1S channel,

$$\frac{\hbar^2}{Ma_s^2} = 0.07\ \text{MeV} \ll B$$

The total cross-section is, however, only

$$\sigma = 0.06\ \alpha^2\,\frac{c}{v_n}\,(\mu_p-\mu_n)^4\left(\frac{B}{Mc^2}\right)^{9/2} a_t^2 = 0.9\cdot 10^{-7}\ mb$$

short of the measured value by almost seven orders of magnitude. It is smaller than the E1 - E1 cross-section by a factor of the order of

$$\left[\frac{\hbar(\mu_p-\mu_n)}{Mca_t}\right]^4 \approx 10^{-3}$$

because of the intrinsically slower rate of M1 photon emission.

For a process starting from the singlet scattering state, the first M1 transition takes the np system to a ^3S state. The second M1 operator can only rotate the angular momentum vector, and the intermediate state must therefore be the deuteron. The matrix element for this $^1S \to D \to D$ reorientation transition is

$$M^s(M1,M1) = -\frac{1}{(2\pi)^3\sqrt{4\omega_1\omega_2}}\left\langle D\left|\frac{ie}{2M}(\mu_p+\mu_n)\frac{\vec{\sigma}_p+\vec{\sigma}_n}{2}\cdot(\vec{k}_2\times\vec{\varepsilon}_2)\right|D\right\rangle$$
$$\times\frac{1}{\omega_1-B}\left\langle D\left|\frac{ie}{2M}(\mu_p-\mu_n)\frac{\vec{\sigma}_p-\vec{\sigma}_n}{2}\cdot(\vec{k}_1\times\vec{\varepsilon}_1)\right|{}^1S_0\right\rangle + (1\leftrightarrow 2)$$

and the cross-section

$$\frac{d\sigma}{d\omega_1 d\Omega_{12}} = \frac{\alpha^2(\mu_p^2-\mu_n^2)^2}{16\pi v_n} \frac{(\varkappa^{-1}-a_s)^2}{M^4\varkappa} \cdot \omega_1\omega_2(\omega_1-\omega_2)^2 \cdot (3-\cos^2\theta)$$

$$\sigma = \frac{1}{90}\alpha^2 \frac{c}{v_n}(\mu_p^2-\mu_n^2)^2 \left(\frac{B}{Mc^2}\right)^{9/2} (\varkappa^{-1}-a_s)^2 = 0.2 \cdot 10^{-7}\,\mathrm{mb}$$

The energy spectrum is of type III with a zero at $\omega_1 = \omega_2 = 1.11$ MeV. The total cross-section is even smaller than in the preceding case.

Since the physical process $\pi^0 \to 2\gamma$ exists, one may wonder whether a virtual π^0 may contribute significantly. A virtual π^0 can be emitted when the np system makes a transition from the $T=1$ ^1S state to the $T=0$ deuteron. The small phase space and the centrifugal barrier reduces the cross-section for π^0 emission followed by 2γ decay to only 10^{-11} of the experimentally observed value, which is negligible.

At this point one must clearly envisage either a wrong experiment or an unconventional interpretation. From experimental colleagues we understand that the experiment [1] contains no manifest weaknesses. However, there is no compelling proof that the normal one-gamma decay cannot produce the observed signal. In particular, there is the possibility that a double Compton process in, or near, the target region could simulate the effect.

If the experimental results are confirmed one must consider unconventional explanations. Without entering into detailed speculations, we now show that two general classes of such interpretations can be heavily restricted.

1) A previously unknown non-derivative short-range coupling to two photons. This explanation is ruled out since the energy distribution of the photons is of phase space type I, contrary to observation. This conclusion is independent of the strength of the interaction. In particular, the Adler suggestion [11], which originally motivated the experiment, is untenable.

2) A light boson decaying into two photons. A way to avoid the phase space distribution is by assuming the emission of a boson with mass $m < B = 2.23$ MeV, subsequently decaying into two photons. An isotropic decay of such a boson in its rest frame gives rise to the usual Doppler-shifted energy distribution (Fig. 1). This is still at variance with the observed energy distribution. Therefore, spin 0 bosons are strictly ruled out. If the photons are emitted preferentially along the direction of motion of the boson, the resulting spectrum will be of type II.

One notes that a 1^+ boson with isospin 1 content would naturally couple strongly between the ^1S state and the deuteron with a similar matrix element as the strong M1 gamma ray. A 10^{-3} branching ratio would only require a coupling of $10^{-3}\,\alpha$, which could easily have gone undetected. Spin 1 bosons are, however, ruled out because they cannot decay into two physical photons. Higher spins would require strong couplings because they involve either emission in $\ell \neq 0$ partial waves or the $^3S \rightarrow D$ transition with its low intrinsic overlap. Such bosons would then be copiously produced in other nuclear decays, which is not observed. Before confirmation of the experiment, we feel that further speculation is idle.

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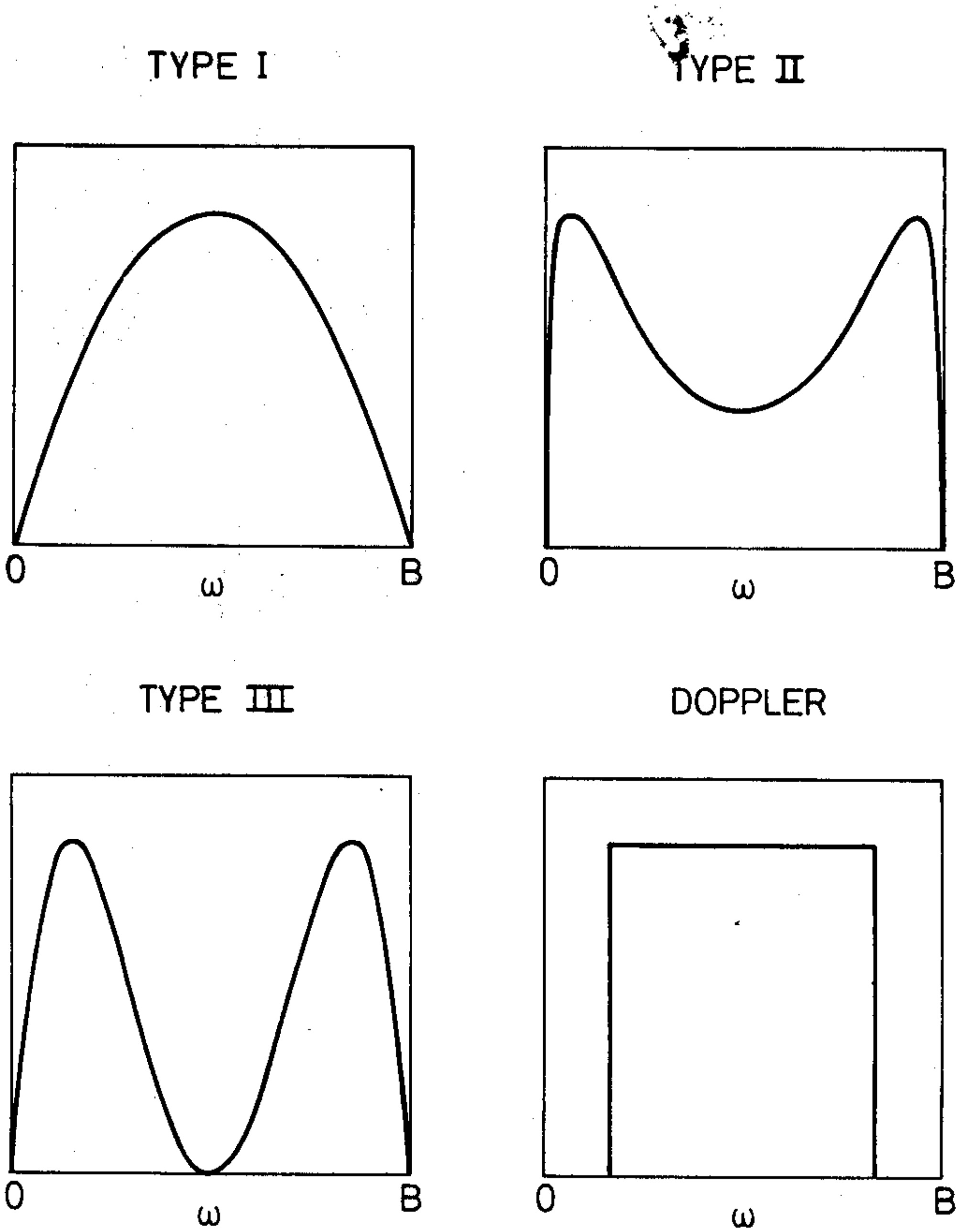

Fig. 1 Photon energy spectra in $n + p \rightarrow D + 2\gamma$