Effects of Isotopic Spin Selection Rules on Photonuclear Yields

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The effects of isotopic spin selection rules were taken into consideration in order to explain the observed high ratio of (γ,p) to (γ,n) cross sections. The recent experimental evidence on the separate giant resonances for (γ,p) and (γ,n) cross sections seems to support this viewpoint.

IT is known that with light nuclei ($Z\leq 20$) the (γ,p) reaction cross sections are about the same order of magnitude or sometimes even larger than the (γ,n) reaction cross sections for the same Z.[1–4] (See Table I.) For example, the $Al^{27}(\gamma,p)$ cross section is about the same order of magnitude as the $Al^{27}(\gamma,n)$ cross section. This might be explained by the fact that the (γ,p) threshold is about 5 Mev lower than the (γ,n) threshold, and therefore the suppression of proton emission by the Coulomb barrier is counter balanced by higher available energies for protons than neutrons and, also, possibly by there being more levels accessible for protons.

This argument does not hold when $Mg^{25}(\gamma,p)$ or $Mg^{26}(\gamma,p)$ yields are discussed. In these cases neutron thresholds are several Mev lower than the proton thresholds, and this might be expected to favor neutron emission strongly over proton emission. Experiments show, however, that the (γ,p) cross section appears to have the same order of magnitude as (γ,n) for these and other neighboring nuclides.

Recently it was shown by several authors that the isotopic spin selection rules hold with good approximation in nuclear reactions,[5] and especially it was shown that this is also true with photonuclear reactions in light nuclei involving photons in the range of electric dipole absorption.[6] Therefore, it seems to be necessary to take account of this effect when the magnitude of the photonuclear yield from light nuclei is estimated.

As an example, let us consider the case of the photonuclear reaction with Mg^{25} (Fig. 1).

The ground state of Mg^{25} has $T=\frac{1}{2}$, and by dipole absorption of γ rays the state with either $T=\frac{3}{2}$ or $T=\frac{1}{2}$ will be excited, since the selection rules allow $\Delta T=0$, 1 for dipole absorptions by nuclei for which $A\neq 2Z$.

The $T=\frac{3}{2}$ states can decay into either $T=1$ or $T=2$ states of neighboring nuclides, i.e., Na^{24} or Mg^{24} by proton or neutron emission, respectively. The $T=\frac{1}{2}$ states can decay into $T=0$ or $T=1$ states by nucleon emission.

The lowest $T=1$ state in Na^{24} is its ground state, and the lowest $T=1$ state in Mg^{24} lies about 9.4 Mev higher than its $T=0$ ground state. Above this lowest $T=1$ state the level scheme of Mg^{24} with $T\geq 1$ is identical with that of Na^{24} above its ground state, except for the Coulomb energy displacement of about 5 Mev.

Hence the decay from $T=\frac{3}{2}$ states in Mg^{25} is symmetric with regard to proton and neutron emission except for the difference in available energy for reaching the corresponding states in the two resulting nuclides, the suppressing of protons by the Coulomb barrier, and a factor $\frac{1}{2}$ for protons due to the coupling factor of isotopic spin. The first of these corrections enhances proton emission probability and the others suppress it. The situation is rather similar to the case of the (γ,p) and (γ,n) reactions in Mg^{24}. Here, product nuclides are mirror pairs whose level schemes are identical with each other and the decay of the photon-excited states (mostly $T=1$) by proton and neutron emission is symmetric in the sense mentioned above.

There are some reasons to suspect that proton emission can be more favored than neutron emission from $T=\frac{3}{2}$ states. The reason is as follows: The decay of the $T=\frac{3}{2}$ states in Mg^{25} is rather similar to that of the $T=1$ states in Mg^{24}, since the (γ,p) thresholds are about the same, and the (γ,n) threshold in Mg^{24} and the (γ,n) threshold from the $T=\frac{3}{2}$ states in Mg^{25} are about the same. Also the energy value of the (γ,n) peak of Mg^{24} is about the same as that of the (γ,p) peak of Mg^{25}. The (γ,p) reaction of Mg^{24} has not been measured, but guessing from the fact that the (γ,p) cross section on C^{12} is greater than the (γ,n) cross section on the same nuclide,[7] and also from the small magnitude of (γ,n) reaction on Mg^{24}, one may assume that the (γ,p) cross section probably exceeds the (γ,n) cross section with Mg^{24}, too. So, from the $T=\frac{3}{2}$ states of Mg^{25}, the proton emission can exceed the neutron emission.

From $T=\frac{1}{2}$ states in Mg^{25} neutrons compete strongly with protons, since by neutron emission the $T=0$ states in Mg^{24} can be attained. The decay into $T=1$ states of the product nuclides are symmetric in regard to proton and neutron emission but these transitions must compete with more favorable neutron emission which leads to the $T=0$ states, since the latter has a lower threshold than proton emission by about 5 Mev.

The foregoing discussion may be crudely summarized

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by stating that the $T=\frac{3}{2}$ states contribute principally to proton emission and the $T=\frac{1}{2}$ states give mostly neutrons. Thus the (γ,p) to (γ,n) ratio depends on the ratio of the probability of formation of $T=\frac{3}{2}$ states and $T=\frac{1}{2}$ states, rather than solely on the values of proton and neutron thresholds, as is assumed in the statistical model.

It is interesting to look at the recent measurements of (γ,p) and (γ,n) cross sections reported by the Saskatchewan group[4] from this point of view. With Mg^{25}, Mg^{26}, Si^{29+30}, and A^{40} the (γ,p) resonances were found to have considerably higher energy than (γ,n) resonances. With magnesium the position of the (γ,p) peaks of Mg^{25} and Mg^{26} appear very close to that of the (γ,n) peak of Mg^{24} and the (γ,n) peaks of the former nuclides lie several Mev lower. It is hard to explain these differences by mere Coulomb barrier effect on the protons. It is very tempting to attribute the proton giant resonances to higher T excitation and the neutron resonances to lower T excitation.

A very clear-cut example which might support this view has already been shown by Nathans and Halpern[8] with the case of $Be^9(\gamma,n)$ reaction, where the cross section has two distinct peaks and the higher peak coincides with the (γ,p) peak. The interpretation has been given that the lower peak is due to the odd-neutron excitation and the higher peak is due to the core excitation. The odd-neutron excitation must correspond to $T=\frac{1}{2}$ states; $T=\frac{3}{2}$ states are made only by exciting the core.

The clarity of the situation with Be^9 should be obscured in the case of higher Z, since the binding energy of the odd neutron becomes higher and it becomes more difficult experimentally to find the second peak.

The discussion with Mg^{25} can be extended to the case of Mg^{26}, but in the case of Al^{27} some caution is necessary. From the low proton threshold, it must not be concluded that there is a loosely bound odd proton. Protons are emitted both from $T=\frac{3}{2}$ and $T=\frac{1}{2}$ states, but there is no odd-proton excited state corresponding to odd-neutron excited states in Mg^{25}. Indeed, experiment shows that the (γ,p) peak is as high as 21 Mev even though the (γ,p) threshold is only 7.4 Mev.[7]

The possibility of explaining the separate giant resonances indicates the validity of isotopic spin selection rules in the reaction through highly excited states of light nuclei. The analysis presented here includes higher Z than considered by Gell-Mann and Telegdi.[6] The fact that the (d,α) reaction on Si^{28} with 7-Mev deuterons failed to find the lowest $T=1$, $J=0$ state in Al^{26},[9] also indicated that the isotopic spin selection rules hold in the reaction through 19-Mev states of P^{30}.

Since level spacings are expected to be quite narrow in such high energy states of a nucleus with A as high as 30, it is rather surprising to see the isotopic spin selection rules hold. Probably it is due to the following reasons:

(1) The population of states which have different isotopic spin and which can mix with the state under consideration is much less than the total population of states, since only those states with the same J, L, S, and parity are mixed by Coulomb perturbation.

(2) The perturbation starts as soon as the incident particle or quantum hits the target nucleus. The isotopic spin before the encounter is very well defined since the mixture of higher isotopic spin states in the ground

TABLE I. Measured (γ,p) and (γ,n) cross sections.

	Lithium γ rays[a] (17.6, 14.8 Mev) ratio to $Cu^{63}(\gamma,n)$ yield (reference 1)		Integrated cross section from 26-Mev bremsstrahlung (Mev-barn)[b]		Integrated cross section from 70-Mev bremsstrahlung (Mev-barn)[c]	
	(γ,n)	(γ,p)	(γ,n)	(γ,p)	(γ,n)	(γ,p)
$Mg^{24}(\gamma,n)$	1.1(16.4)[d]		0.057		0.072	
$Mg^{25}(\gamma,p)$		2.83(12.3)		0.10		0.23[e]
$Mg^{26}(\gamma,p)$		1.56(13.0)		0.085		0.092
$Al^{27}(\gamma,n)$[f]	4.0(14.4)		0.045			0.080
$Al^{27}(\gamma,p)$				0.12[g]		
$Si^{29}(\gamma,p)$		3.45(11.7)				
$Si^{30}(\gamma,p)$		1.26(13.7)				
$P^{31}(\gamma,n)$			0.129			

[a] Values in this column should not be taken seriously since the γ rays used are almost monochromatic and the energies are not high enough, so the discussion does not apply so well.
[b] See reference 2.
[c] See reference 3.
[d] The number in parentheses is the threshold value for the reaction.
[e] This value contains a contribution from the $Mg^{26}(\gamma,pn)$ reaction and therefore should be read as about half of this value.
[f] The values cited here are measured by the 6.3-sec activity which is not all of the (γ,n) product. The value must be multiplied by 3. R. Montalbetti and L. Katz, Phys. Rev. 91, 659 (1953).
[g] This value was taken from reference 7.

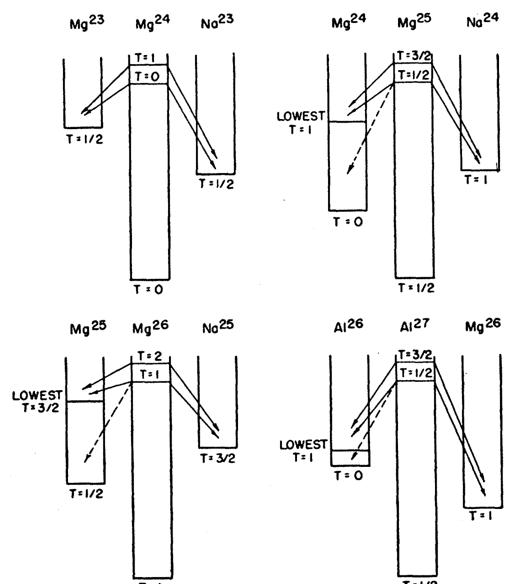

FIG. 1. Schematic diagram showing (γ,p) and (γ,n) reactions from Mg^{24}, Mg^{25}, Mg^{26}, and Al^{27}. The solid arrows show decay to the symmetrical parts of product nuclides. The broken arrows are to the asymmetric part which is reached only by neutron emission.

[8] R. Nathans and J. Halpern, Phys. Rev. 92, 940 (1953).

[9] C. P. Browne, Phys. Rev. 95, 860 (1953).

states is small.[10] A time-dependent perturbation causes the transition of the isotopic spin state, and if H_c is the Coulomb interaction and $\hbar\omega = E_1 - E_2$ is the difference in energy between the mixing states, the amplitude of mixing is

$$a(t) = \frac{H_c \sin\omega t}{\hbar\omega}$$

$$\approx \frac{H_c t}{\hbar} = \frac{H_c}{\Gamma} \cdot \frac{t}{T} \text{ (when } t \ll 2\pi/\omega).$$

[10] L. A. Radicati, Proc. Phys. Soc. (London) **A66**, 139 (1953); **A67**, 39 (1954).

Here $\Gamma = h/T$, where T is the life of the decaying state; if this is much larger than H_c, decay takes place before mixing proceeds. Γ is of order 1 Mev or more and H_c is probably a fraction of one Mev. Hence the isotopic spin purity is not affected by close-lying intermixable levels, which would cause considerable mixing in the case of a stationary perturbation.

Further studies on this subject are in progress.

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Energy of the Ground State of Li^6

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The binding energy of Li^6 is calculated by using a wave function of the exponential type with a central Yukawa interaction, both neutral and symmetric exchange characters being considered. The neutral interaction leads to a large excess binding energy whereas the symmetric case gives much too small a value, for a particular set of nuclear parameters. The contribution to the energy from the central part of the neutral and symmetric types of Pease-Feshbach interaction is also determined.

1. INTRODUCTION

In this paper, the energy of the ground state of Li^6 is determined by using a wave function of the exponential type for a central Yukawa interaction, both the neutral and symmetric cases being considered. The contribution to the energy of the central part of the Pease-Feshbach[1,2] type of interaction—neutral and symmetric—is also evaluated. The justification for dealing only with the central part of the interaction at this stage arises from the treatment of H^3 and He^4, where it is necessary to construct as good a wave function as possible for the S-state,[3] before taking into account the tensor part of the interaction.

It has previously been established that a two-body interaction, involving a mixture of central and tensor forces with a Yukawa well-shape, can give, for a set of nuclear parameters which fits the low-energy two-body data, reasonable values for the binding energies of both the triton[1,2] and the alpha particle.[3] Since the results for the two-body problem are independent of the exchange nature of the forces and the three- and four-body energy values differ very little if a neutral or symmetric interaction is used, it is of importance to determine whether the effect of both neutral and symmetric interactions of the above type is the same for the lightest bound p-shell nucleus, Li^6.

If the nuclear interaction is assumed to be of the two-body type, saturation requirements for heavy nuclei indicate that the interaction is of a symmetric character. Kronheimer[4] has in fact shown that the exchange nature of the interaction is evident in the case of the light nucleus Be^9. Using single-particle Gauss wave functions and taking only the lowest state (^2P) of highest orbital symmetry of the $(1s)^4(2p)^5$ configuration, he has obtained an excess binding energy with the neutral Pease-Feshbach type of interaction. For the charge-symmetric interaction on the other hand, the $(1s)^4(2p)^5$ term does not describe a bound state. Edwards[5] has found, in the case of the Be^8 nucleus, that for a symmetric central interaction with a Gauss well-shape the system is not bound. Morpurgo,[6] using a similar interaction, has calculated the energy of Li^6, treating the system as composed of a deuteron and an alpha particle. He finds that the energy is a minimum when the deuteron is at infinity, that is, the system is not bound.

Other calculations on the binding energy of Li^6 have been carried out by Inglis,[7] Margenau,[8] and Tyrrell,[9] using a central two-body Gauss interaction, and by

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