We assume that the target nucleus is heavy enough to remain at rest in the center-of-mass system. The z-axis is taken in the direction of the incoming particle. Then the γ-angular distribution, with the outgoing particle unobserved, is given by

$$W(\vartheta)=\sum_{LL'ii'\nu}(-)^{i_2-i_2'+L_1-L_2+L_3+\nu}(2i_3+1)^{\frac{1}{2}}(2i_3'+1)^{\frac{1}{2}}\times(2i_2+1)(2i_2'+1)(2L_2+1)^{-1}c_\nu(L_1L_1')c_\nu(L_3L_3')\times W(L_1i_2L_1'i_2',i_1\nu)W(i_2i_3i_2'i_3',L_2\nu)W(L_3i_3L_3'i_3',i_4\nu)\times S_{L_2i_3,L_1i_1}{}^{(i_2)*}S_{L_2'i_3',L_1'i_1'}{}^{(i_2')}T_{i_4,i_3}{}^{(L_3)*}T_{i_4,i_3'}{}^{(L_3')}P_\nu(\cos\vartheta).$$

The numbers i_1 to i_4 mean the level spins of the target nucleus, the compound nucleus, the residual nucleus of the scattering process, and the final nucleus which later may coincide with i_1 except for its orientation. The L's are the total angular momenta of the incoming and the outgoing particle and the γ-radiation. The S-matrix elements are the radial parts of the probability amplitudes of the inelastic scattering, i.e., they are independent of magnetic quantum numbers. The relative probability of the γ-radiation is signified by $T_{i_4,i_3}{}^{(L_3)}$. The W's are the Racah coefficients.[1,2] The c_ν's are defined by

$$c_\nu(LL)=\Sigma_\mu(-)^{L'-\mu}(LL'-\mu\mu|\nu 0),$$

where μ is the z-projection of the particle spin and $(LL'-\mu\mu|\nu 0)$ is a Clebsch-Gordan coefficient. The triangular relations of the Racah coefficients restrict the degree of the Legendre polynomials $P_\nu(\cos\vartheta)$ to values $\leq(L+L', i_2+i_2', i_3+i_3', L_3+L_3')$.

The given expression for $W(\vartheta)$ describes the process with full generality. Without making further assumptions about the levels involved and the nature of the transitions, it cannot be simplified any further. In the case when the inelastic scattering process results in a short-lived isomer[3] with mass number >100, two essential simplifications seem to be possible. The γ-transition will, in general, be a pure multipole. Therefore, the product of the radiative transition probabilities $T_{i_4,i_3}{}^{(L_3)}$ can be dropped as a common factor. Furthermore, the statistical assumption[4] may be made for the compound nucleus of the scattering process which cancels interference terms and replaces the product of the S-matrix elements by the transmission for the incoming particle. Using channel spins for the scattering process, we get then for the γ-angular distribution

$$W_E(\vartheta)=\sum_{lji\nu}(-)^{l_2}T_{l_1}(E)(2i_2+1)^2(2l_1+1)^2(2l_2+1)^{-1}\times(l_1l_100|\nu 0)(L_3L_3-11|\nu 0)W(l_1i_2l_1i_2,j_1\nu)\times W(i_2j_3i_2j_3,l_2\nu)W(L_3i_3L_3i_3,i_4\nu)P_\nu(\cos\vartheta),$$

where E is the energy of the incoming particle and $T_{l_1}(E)$ is its transmission.[4]

Since odd Legendre polynomials in $W(\vartheta)$ arise from interference terms, the first requirement for the applicability of the formalism is the symmetry of the angular distribution.

We assume that the inelastic scattering that leads to the isomeric states listed below is neutron scattering. Then the coefficients for the Legendre polynomials of the angular distribution are given in Table I. Proton scattering or scattering of other particles would express itself in changed transmissions $T_{l_1}(E)$.

TABLE I. The coefficients of the γ-angular distribution $W_E(\vartheta)=P_0+a_2P_2(\cos\vartheta)+a_4P_4(\cos\vartheta)$. E is the energy of the incoming neutron; i_3 and i_4 are the spin numbers of the target and the final nucleus; i_3 is the one of the isomeric level.

Target nucleus	Isomeric level (kev)	E (kev)	i_1, i_4	i_3	a_2	a_4
Cd^{111}	247	330	$\frac{1}{2}+$	$\frac{5}{2}+$	−1.26	0.007
Er^{166}	80	170	$0+$	$2+$	1.07	0
Yb^{170}	84	170	$0+$	$2+$	1.07	0
Ta^{181}	134	210	$\frac{7}{2}+$	$\frac{1}{2}+$	0	0
Ta^{181}	345	430	$\frac{7}{2}+$	$\frac{3}{2}+$	−1.99	0
Os^{186}	137	220	$0+$	$2+$	−0.026	0.348
Hg^{197}	133	220	$\frac{1}{2}-$	$\frac{5}{2}-$	−0.279	0.006
Pb^{204}	374	450	$0+$	$2+$	0.071	1.27

The energy of the incoming neutron was chosen to be about 80 kev above the threshold. This means that l_2 is restricted to the values 0 and 1. Higher energies would quickly increase the number of l-values and would complicate the computation of $W_E(\vartheta)$ considerably.

Since the spin and parity assignments are well established by other experiments, an experimental check of the given angular distributions would show how well the statistical model accounts for the given situation.

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Internal Absorption of Fluorescent Light in Large Plastic Scintillators*

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THE preparation and performance of comparatively small plastic scintillators have been reported by several authors.[1-3] We have made some plastic scintillators of large dimensions by impregnating styrene monomer with various fluorescent substances before polymerization. No catalyst was used in the process. In a series of experiments, the samples had the form of a cylindrical rod 3.5 cm in diameter and 20 cm long. The pulse sizes were observed in an oscilloscope from the output of a 5819 photomultiplier attached to one end of the rod. Except for this end, the rod was wrapped with 0.133-mm thick aluminum foil as a reflecting surface in order to improve light collection. A narrow beam of γ-ray from a Co^{60} source passed through the rod perpendicularly to its axis at various distances from the surface of the photomultiplier. The results are summarized in Table I. Cosmic rays from a coincident counter telescope and a soft x-ray beam from a dental machine were also used as sources of irradiation and gave similar results. From the table we can see that there is little internal absorption of fluorescent light in the cases of a and c, while b shows considerable absorption at greater lengths. The concentration of the anthracene in polystyrene was about 3 percent. No great difference in internal absorption was observed in varying the concentration from 2–5 percent. The concentration of p-terphenyl in polystyrene was about 2 percent. The addition of about 0.01 percent diphenylhexatriene made no significant difference in the large internal absorption as shown in Table I. When the concentration of p-terphenyl was raised to 4 percent, some part of the plastic became less transparent in appearance. In the table the results for liquid phenylcyclohexane solution (plus 0.3 percent p-terphenyl and 0.001 percent diphenylhexatriene) of the same dimensions as the plastic rods are also included. An anthracene crystal 3 cm in diameter and 3.3 cm in length was also used and gave a pulse size of 5.4 (in the same units as used in Table I). A plastic scintillator consisting of 3 percent anthracene in polystyrene, 4.1 cm in diameter and 30 cm long (this is the maximum length that has been investigated), showed relatively small absorption (less than 15 percent) of the light output throughout the

TABLE I. Pulse sizes (in arbitrary units) observed with a Co^{60} source.

	Phosphor	Distance of the path of radiation through the sample from the surface of the photomultiplier: 1 cm	10 cm	20 cm
a	Anthracene in polystyrene	0.6	0.5	0.5
b	p-terphenyl in polystyrene	1.4	0.8	0.5
c	Phenylcyclohexane solution	1.6	1.6	1.5

whole length. This makes it possible to use scintillators of this kind (a) in cosmic-ray telescopes, (b) for triggering cloud chambers, and (c) for locating weak radioactive sources, etc. It might be mentioned that a sample of 2 percent pyrene in polystyrene was found to be comparable in performance to anthracene in polystyrene for small thicknesses of the scintillator. However, it showed greater internal absorption at greater lengths.

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Relative Yields of Photonuclear Reactions

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RELATIVE yields for 41 photonuclear reactions have been measured by the method of radioactive end-products. The yields were defined, following Perlman and Friedlander,[1] as "yield =saturation activity of product per milligram atom of parent isotope, divided by saturation activity of monitoring reaction."

The materials, in the form of thin metal foils, were irradiated in the x-ray beam from the 70-Mev Queen's synchrotron. Each foil was sandwiched between two thin polystyrene sheets, which monitored the exposure through the $C^{12}(\gamma, n)C^{11}$ reaction. Activities of the foils and monitors were measured by a thin end-window G-M tube in a standard geometry. The chemical purity of all samples was checked by spectrographic analysis. Some materials were used as simple compounds in powder form. Yields determined in the powder and foil arrangements were related by observing the $C^{12}(\gamma, n)C^{11}$ reaction in powdered and solid graphite and the $In^{115}(\gamma, n)In^{114}$ reaction in indium sesqui-oxide and indium foil. Short-lived activities were investigated with an apparatus which dropped the sample to a well-shielded counter below the x-ray beam.

Saturation activities were corrected for self-absorption of β-rays in the sample, absorption in the counter end-window, for alternative modes of decay such as K-capture, and for counts due to nuclear γ-rays, internal conversion electrons, etc. An estimation of the accuracy of the yields is sometimes very difficult due to the varied factors affecting each result. By giving careful attention to good monitoring, thorough determination of all activities present, reproduction of geometry, and accurate analysis for saturation activities, the standard deviation from the mean for individual runs was reduced to less than ± 3 percent (often for foil weights differing by as much as a factor of six). As each reported yield is the result of about eight experiments, the yield values should be accurate to about ± 2 percent. However, allowance must be made for possible large errors in individual cases due to poor corrections for K-capture, etc.

73 reactions were identified in these 22 elements; uncertainties or complications in decay schemes confined yield calculations to 44 of them. These yields are listed in Table I.

The definition of yield given above leads to the following expression for the relative yields Y_1 and Y_2 of two reactions:

$$\frac{Y_1}{Y_2}=\frac{{}^{P}R_1}{{}^{P}R_2}\frac{\int\sigma_1 dE}{\int\sigma_2 dE},$$

where ${}^{P}R$ represents the relative number of photons/Mev at the reaction resonance energy in the x-ray spectrum, and $\int\sigma dE$ is the integrated cross section of the reaction. A determination of the x-ray spectrum of this thick-target synchrotron, recently made by McDiarmid[2] using emulsion techniques, indicated that the photon spectrum is essentially flat in the region 10–30 Mev. Since this range includes the resonance energies of the common photonuclear reactions, the quantities ${}^{P}R_i$ should then be equal and the yields directly proportional to integrated cross sections. Assuming this to be the case, the value of $\int\sigma dE=0.047$ Mev barns for the $C^{12}(\gamma, n)C^{11}$ reaction, as measured by Haslam, Johns, and Horsley,[3] was used to calculate cross sections for all reactions (see Table I). Use of this reference standard and of the empirical spectrum introduces an added probable error of roughly ± 15 percent in the absolute values of the cross sections. The good agreement of our values with the best independently measured cross sections (column 6, Table I) is additional evidence for the flat photon spectrum.

TABLE I. Relative yields and integrated cross sections.

Z	Reaction	Half-life	Relative yield	Calculated values $\int\sigma dE$ (Mev-barns)	Previous values $\int\sigma dE$ (Mev-barns)
6	$C^{12}(\gamma, n)C^{11}$	20.5 min	0.100	0.047	0.047[a,b]
7	$N^{14}(\gamma, n)N^{13}$	10.1 min	0.035	0.017	
8	$O^{16}(\gamma, n)O^{15}$	118 sec	0.400	0.18	
9	$F^{19}(\gamma, n)F^{18}$	112 min	0.382	0.11	
12	$Mg^{24}(\gamma, n)Mg^{23}$	11.4 sec	0.152	0.072	
13	$Al^{27}(\gamma, n)Al^{26}$	6.3 sec	0.170	0.080	
17	$Cl^{35}(\gamma, n)Cl^{34}$	33 min	0.123	0.058	
19	$K^{39}(\gamma, n)K^{38}$	7.5 min	0.162	0.076	
22	$Ti^{46}(\gamma, n)Ti^{45}$	2.9 hr	0.925	0.44	
26	$Fe^{54}(\gamma, n)Fe^{53}$	8.9 min	0.836	0.39	0.42[c]
28	$Ni^{58}(\gamma, n)Ni^{57}$	36.7 hr	0.497	0.23	0.33[c]
29	$Cu^{63}(\gamma, n)Cu^{62}$	10.1 min	1.37	0.64	0.63[a,b]
	$Cu^{65}(\gamma, n)Cu^{64}$	12.9 hr	2.47	1.16	1.2[a,d]
30	$Zn^{64}(\gamma, n)Zn^{63}$	38 min	1.27	0.60	0.83[c]
41	$Nb^{93}(\gamma, n)Nb^{92}$	10.1 day, 21.6 hr	0.111	0.052	
42	$Mo^{92}(\gamma, n)Mo^{91}$	15.5 min	2.28	1.07	
	$Mo^{100}(\gamma, n)Mo^{99}$	68 hr	3.54	1.67	
45	$Rh^{103}(\gamma, n)Rh^{102}$	210 day	>1.42	>0.67	
46	$Pd^{110}(\gamma, n)Pd^{109}$	13.8 hr	8.64	4.1	
47	$Ag^{107}(\gamma, n)Ag^{106}$	24.6 min	3.27	1.54	
	$Ag^{109}(\gamma, n)Ag^{108}$	2.4 min	3.53	1.66	1.65[a,d]
49	$In^{115}(\gamma, n)In^{114}$	72 sec, 50 day	7.10	3.3	
78	$Pt^{198}(\gamma, n)Pt^{197}$	3.4 day, 18 hr	10.2	4.8	
79	$Au^{197}(\gamma, n)Au^{196}$	5.6 day, 14 hr	8.65	4.1	
12	$Mg^{26}(\gamma, p)Na^{25}$	59 sec	0.196	0.092	
12	$Mg^{25}(\gamma, p)Na^{24}$				
12	$Mg^{26}(\gamma, pn)Na^{24}$	14.9 hr	0.486	0.23	
22	$Ti^{48}(\gamma, p)Sc^{47}$	3.4 day	0.416	0.20	
22	$Ti^{50}(\gamma, p)Sc^{49}$	54 min	0.244	0.12	
26	$Fe^{57}(\gamma, p)Mn^{56}$	2.8 hr	0.586	0.28	
28	$Ni^{62}(\gamma, p)Co^{61}$	1.7 hr	0.378	0.18	
30	$Zn^{68}(\gamma, p)Cu^{67}$	58 hr	0.40	0.19	
42	$Mo^{98}(\gamma, p)Nb^{97}$	68 min	0.359	0.17	
46	$Pd^{108}(\gamma, p)Rh^{107}$	25.7 min	0.326	0.15	
26	$Fe^{54}(\gamma, pn)Mn^{52}$	21 min	0.222	0.11	
30	$Zn^{64}(\gamma, pn)Cu^{62}$	10.1 min	0.25	0.12	
30	$Zn^{66}(\gamma, pn)Cu^{64}$	12.9 hr	0.65	0.31	
42	$Mo^{92}(\gamma, pn)Nb^{90}$	16.5 hr	0.622	0.29	
29	$Cu^{63}(\gamma, 2n)Cu^{61}$	3.4 hr	0.154	0.073	
30	$Zn^{64}(\gamma, 2n)Zn^{62}$	9.5 hr	0.073	0.034	
13	$Al^{27}(\gamma, 2p)Na^{25}$	59 sec	0.00476	0.0022	
45	$Rh^{103}(\gamma, 2p)Tc^{101}$	16 min	0.0050	0.0024	
13	$Al^{27}(\gamma, 2pn)Na^{24}$	14.9 hr	0.0065	0.0031	
27	$Co^{59}(\gamma, 2pn)Mn^{56}$	2.7 hr	0.0047	0.0022	

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A striking feature of these results is that (γ, pn) yields, previously considered to be small,[4] are of the same order as (γ, p) yields; similarly, $(\gamma, 2pn)$ yields are of the same order as $(\gamma, 2p)$ yields.

A more detailed account of these experiments will be published in the near future. The work was carried out at the suggestion of Dr. J. A. Gray, and grateful acknowledgment is made for his interest and advice throughout; also to the National Research Council of Canada and the Ontario Research Council for bursaries held by the authors.

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