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1 Introduction

In this section we review the available data on gamma spectra following radiative capture of neutrons above 10 MeV. A few measurements below that energy are included. An important source for references to this topic is the CINDA compilation maintained by the IAEA in cooperation with three other major data centers. An additional useful source is the review article by Weller and Roberson [1], which treats capture reactions with neutrons, protons, and alpha particles. The following discussion refers only to data that are easily accessible through readily-available journals, reports, or the EXFOR database.

Most of the reported measurements were made for the purpose of determining cross sections for discrete states at the high energy end of the gamma spectra which are resolvable or nearly so. In only a few cases have cross sections been measured over a wide range of gamma energies. These measurements are first reviewed below, followed by a review of more detailed measurements such as angular distributions and analyzing powers. Neutron capture on hydrogen isotopes have not been included with the exception of a fairly recent measurement on deuterium [3]; see CINDA [2] for references to this specialized topic.

2 Absolute cross sections for gamma spectra induced by 14 MeV neutrons

We focus on three sets of measurements that have been carried out to measure absolute cross sections of the gamma spectra for neutrons in the neighborhood of 14 MeV. These spectra extend from the 12–14 MeV gamma region to the endpoint of the spectrum. Two of these sets measured the spectrum with a pair spectrometer, which is relatively insensitive to neutrons: these are the measurements of Stamatelatos *et al.* [4] and of the Ljubljana group [5, 6, 7, 8, 9, 10, 11]. The third data set, Rigaud *et al.* [12, 13, 14], used a NaI spectrometer. The pair spectrometer experiments used large targets surrounding the neutron source, leading to results that are very close to total (angle-integrated) cross sections. On the other hand, in the measurements of Rigaud *et al.*, the NaI measured gammas emerging perpendicular to the neutron beam, with the consequence that the measurements reported are actually 4π times the 90^o differential cross section. The targets included in each of these data sets are indicated in the following list:

- Pair spectrometer (Stamatelatos *et al.*): Cu, Zr, Sb
- Pair spectrometer (Ljubljana): Mg, ^{27}Al, Si, ^{31}P, S, Ca, ^{45}Sc, ^{51}V, Cr, ^{55}Mn, Fe, ^{59}Co, Cu, Se, Br, Sr, ^{89}Y, In, Sb, ^{127}I, Ba, ^{141}Pr, ^{165}Ho, ^{181}Ta, W, Tl, Pb, ^{209}Bi
- NaI spectrometer (Rigaud *et al.*): Si, ^{59}Co, Rb, Sr, Y, ^{93}Nb, ^{103}Rh, ^{133}Cs, ^{139}La, Ce, ^{159}Tb

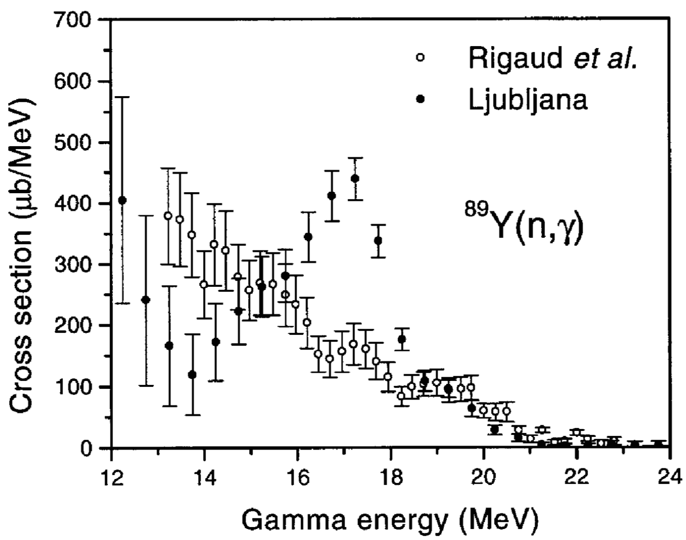

Figure 1: Gamma spectra from 14-MeV neutrons incident on ^{89}Y as measured by a pair spectrometer (Ljubljana) and a NaI spectrometer (Rigaud *et al.*).

We also note another measurement using NaI on ^{27}Al and ^{127}I targets [15]. However, the statistical accuracy is significantly poorer than that of the other NaI measurements.

Additional spectral measurements using a NaI spectrometer have been made at Los Alamos on targets of Gd, Ho, Ta, Au, ^{208}Pb, and ^{238}U [16]. These measurements

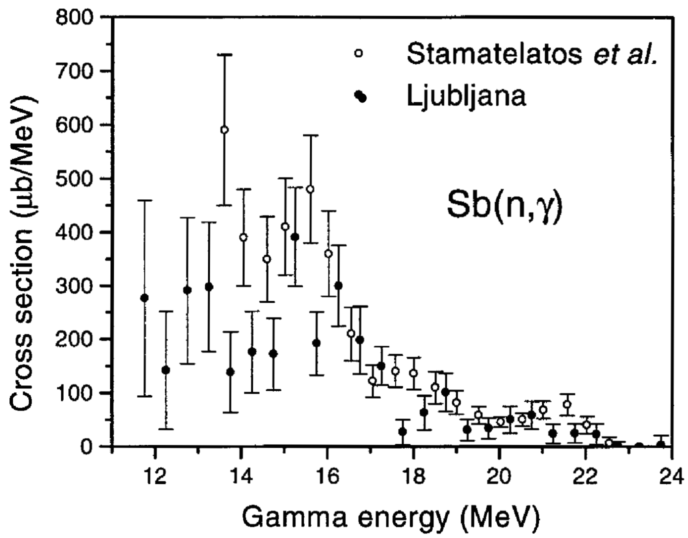

Figure 2: Gamma spectra from 14-MeV neutrons incident on Sb as measured in two pair spectrometer experiments.

were important in showing that the energy-integrated cross section from 14 MeV to the endpoint is approximately 1 mb over a wide mass range (approximately 40 to 240). This work eventually led to the conclusion that activation measurements of this same quantity, which in some cases were an order of magnitude larger, were faulty because of contamination by lower-energy neutrons. Although spectra with an absolute cross section normalization have not been made available, the unnormalized spectra for Ho, ^{208}Pb, and ^{238}U shown in Ref. [16] may be used with the integrated values of the spectra above 14 MeV to obtain an absolute normalization.

There are important discrepancies among the three principal data sets listed above. Examples of these discrepancies are shown in Figs. 1 and 2. In Fig. 1 the comparison of pair spectrometer (Ljubljana) and NaI (Rigaud *et al.*) measurements on ^{89}Y show the significantly lower values of the pair spectrometer measurements in the 14-MeV gamma energy region compared to the NaI results. This appears to be a systematic difference between these two data sets. Results for Sb of the two pair spectrometer measurements are shown in Fig. 2. The Ljubljana measurements appear to be lower than those of Stamatelatos *et al.* below 15 MeV. There is rather better agreement among the various data sets for the gammas within a few MeV of the endpoint of the spectrum. While the discrepancies among these data sets are not understood, it may be useful to note that neutrons interacting in the spectrometer are a potential problem in all of these measurements. Such backgrounds, if present in spite of measures taken to reduce them, are more likely to be a problem in the low-energy part of the spectrum than near the endpoint.

Spectral Shape Measurements		
Target	Reference	Neutron Energies (MeV)
S	[17]	6.8, 10.9, 15
^{40}Ca	[18]	10.2, 11.2, 12.2, 13.2, 14.2, 15.2
^{89}Y	[19]	7.2, 8.9, 10.7, 10.9, 12.9, 15.6
^{140}Ce	[19]	7.2, 8.9, 10.7, 10.9, 12.9, 15.6
^{165}Ho	[20]	10.7
^{208}Pb	[21],[22]	9.2, 10.2, 11.2, 12.2, 13.2, 14.7
^{238}U	[20]	10.7

Table 1: Spectral shape measurements taken with NaI at indicated energies. All measurements were made with a NaI spectrometer.

90^o Differential Cross Section Measurements (also see references in Table 1)		
Target	Reference	Neutron Energies (MeV)
^{3}He	[23]	6–17
^{40}Ca	[24]	0.5–11
^{58}Ni	[25]	0.9–8.3
^{58}Ni	[24]	0.5–11
^{89}Y	[24]	0.5–11
^{206}Pb	[26]	1.5–8.5
^{208}Pb	[24]	0.5–11
^{209}Bi	[25]	4.7–8.3

Table 2: Measurements of 90^o differential cross sections taken with NaI spectrometers

3 Variation of the spectral shape with neutron energy

A number of the papers reporting excitation functions of the discrete gammas at the high end of the spectrum have also shown unnormalized spectra at selected energies. These spectra were measured at 90^o with NaI spectrometers. The experimental resolution has not been unfolded from the spectra, although usually the energy variation of the efficiency has been corrected for. In most cases an absolute cross section can be guessed (though with limited accuracy) by noting the absolute cross sections for the discrete transitions reported in these papers. These results are shown in Table 1.

Angular Distributions with Unpolarized Neutrons						
Tgt	Final States	Ref.	Neutron Energies (MeV)	Angles (degrees)	Absolute Cross Sections	Comments
^{2}H	0	[3]	9,10.8,14	various	yes	
^{3}He	0	[23]	9	various	yes	
^{10}B	0	[27]	14	55,90,125	no	
^{12}C	0	[27]	14	55,90,125	no	
^{28}Si	1	[27]	14	55,90,125	no	
^{40}Ca	0	[27]	14	55,90,125	no	
^{40}Ca	0	[28]	8, 12	several	no	
^{40}Ca	0	[29]	6–13	several	yes	
^{40}Ca	0	[30]	20–28	55,90,125	yes	
^{40}Ca	0	[31]	8–44	55,90,125	yes	BGO crystal spectrometer
^{88}Sr	—	[32]	7–11	55,90,125	no	two s.p. final configurations
^{89}Y	—	[32]	7–11	55,90,125	no	two s.p. final configurations
^{89}Y	—	[33]	12–27	55,90,125	no	several s.p. final configurations
^{208}Pb	0	[34]	7–20	55,125	no	
^{208}Pb	—	[34]	20	55,125	no	γ spectrum measured
^{208}Pb	0	[35]	0.8–7.7	?	?	
^{208}Pb	0,1	[36]	7–13	several	yes	
^{209}Bi	0-5	[37]	17.7–22	55,125	no	some final states unresolved

Table 3: Angular distribution measurements taken with NaI spectrometers unless otherwise indicated.

4 90^o differential cross section, angular distribution, and analyzing power measurements

Absolutely-normalized measurements of excitation functions of 90^o differential cross sections to low-lying states or groups of states in the final nucleus have been important in the establishment of the direct-semidirect capture model. Most of the references in Table 1 contain data of this type. Additional measurements are noted in Table 2.

There has been a large number of angular distribution measurements to discrete final states. The majority of these have been measured at only two or three angles, either 55^o and 125^o, or 55^o, 90^o, and 125^o. These measurements of the fore-aft asymmetry in the cross sections have been important in elucidating the properties of collective E2 radiation, since direct E2 is highly suppressed by an effective charge factor. Most of the results of the experiments indicated in Table 3 have reported the results in the form of Legendre coefficients, although in a few cases the angular distributions themselves are shown. In the column indicating final states, 0 is the ground state, 1 is the first excited state, and so on. When the final states are not specified, the final states are unresolved and the spectrum is assumed to be dominated by one or more single-particle final state configurations that produce the observed structure.

Observation of analyzing powers in measurements with polarized beams provides extra information and constraints on the multipolarities and amplitudes contributing to the reactions. These measurements are indicated in Table 4. In all cases the transition to the ground state of the residual nucleus was measured.

Measurements with Polarized Neutrons				
Target	Reference	Neutron Energies (MeV)	Angles (degrees)	Absolute Cross Sections
^{2}H	[3]	9	various	yes
^{12}C	[38]	20–35	55,90,125	no
^{12}C	[39]	16–22.3	various	no
^{13}C	[40]	5.6–17	various	no
^{40}Ca	[41]	10	various	no

Table 4: Measurements of analyzing powers taken with NaI spectrometers.

5 Isospin tests

A few measurements in light nuclei have been carried out to test isospin conservation by comparison with proton capture reactions. For a ^{12}C target, the excitation function of the ^{12}C(n,γ_0) reaction at 90^o at neutron energies 7–19.5 MeV [42] and 5.6–13 MeV

[43] has been compared with the $^{12}C(p,\gamma_0)$ reaction. The 90° excitation function of the $^{14}N(n,\gamma_0)$ reaction in the 5.6–13 MeV neutron energy range has been measured in [44] and compared with the $^{14}C(p,\gamma_0)$ and $^{14}N(p,\gamma_0)$ reactions. Angular distributions at seven energies were also measured in [44].

6 Conclusions

The measurements compiled above show that the behavior of the capture reaction for gammas near the high energy end of the gamma spectrum is reasonably well characterized up to 20 to 30 MeV, although the choice of targets is rather limited. These results have been useful in the development of direct-reaction models (such as direct-semidirect) for capture, since there is little competition from statistical reaction mechanisms. Angular distribution and analyzing power measurements in this part of the spectrum have also been important in elucidating the properties of E2 radiation in neutron capture.

On the other hand, spectral measurements over a wide energy range are in a much less satisfactory state, since there are discrepancies between the various measurements of absolute cross sections at 14 MeV, and measurements at other energies have been reported without an absolute energy scale. New measurements would be desirable to provide an adequate data base for the testing of models that include statistical reactions or direct reactions to highly excited states (see, *e.g.*, the discussion of extensions to the DSD model earlier in this report).

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