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Cross Sections for n+^{89}Y for E_n < 20MeV

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Nuclear data collected in an experiment performed at LANSCE/WNR with the GEANIE spectrometer to measure the cross sections for $n+^{89}$Y for $E_n < 20$ MeV are reported. The estimated $(n, 2n)$ cross sections to the ground and isomeric states of ^{88}Y differ significantly from those listed in the RADCHEM data base. Folded with a fast neutron spectrum, these results lead to integral differences of +15%, +2%, and −70% *vs.* the RADCHEM evaluation.

I. EXPERIMENT

The experiment was performed using the GEANIE spectrometer located at the LANSCE/WNR facility. The 20 Compton-suppressed Ge detectors of GEANIE viewed a target of Y metal 2 mm thick positioned at the focal point of the array in the neutron beam. A ^{238}U fission chamber data was used to determine the neutron flux. The γ-ray detection efficiency used was that of McNabb *et al.* [1], verified by examining the relative efficiency curve extracted from the β-decay γ rays observed between the beam macropulses. A comparison of the cross sections extracted for the 847-keV ^{56}Fe $2^+ \rightarrow 0^+$ γ-ray from ^{nat}Fe foils placed on the Y sample were in excellent agreement with evaluated values, providing confidence in these results. The systematic uncertainty assigned to the Ge detector efficiency was 5%. Further details will be given in a longer report [2].

II. THEORY

Calculations using the Hauser-Feshbach code STAPRE were used to complement the experimental data where needed. This included corrections for unobserved neutron side-feeding, specifically for the ^{89}Y isomer and the ^{88}Y ground state and two isomeric states. In addition, the calculations were used to determine the partitioning of the "missing" cross section (defined in Sect. IV below) in the case of ^{88}Y. (Missing cross section is a concept introduced to quantify the influence of measured γ rays that could not be placed in the decay scheme and unobserved transitions.) The uncertainties assigned to the calculations are taken to be 10% for the neutron side-feeding and 30% for the partitioning of the "missing" cross section. The calculations used presently are from a set produced in Feb. 2003 done by W.E. Ormand.

III. POPULATION OF ^{89M}Y AND ^{88}Y

The measured sum of the partial γ-ray cross sections populating the ^{89}Y $9/2^+$ 16s isomer were corrected for the unobserved neutron side-feeding calculated with the STAPRE code. These results are presented in Table I. The first two columns give the mean and variance (width) of the neutron energy bin, the third column the deduced cross section, the fourth column the statistical uncertainty in the cross section, and the final column the addition in quadrature of the statistical and estimated systematic uncertainty. The systematic uncertainty includes 5% estimated for the efficiency and 10% estimated for the neutron side-feeding.

The observed cross sections for ^{88}Y for the 4^- ground state, and the two long-lived isomeric states at 392 keV (1^+) and 675 keV (8^+) were obtained by summing the cross sections of all γ rays observed to populate the specific levels. These observed cross sections were corrected for the neutron side-feeding obtained from the STAPRE calculations, and this forms the lower limit on the cross section. The summation of the lower limits of the cross sections to the ground state and the two isomeric states yields the observed lower limit to the total $(n, 2n)$ cross section. The total $(n, 2n)$ cross sections are known, and the RADCHEM evaluation reproduces the world data set extremely well. A "difference" cross section was formed by subtracting the presently observed lower limit from the RADCHEM evaluation. This "difference" cross section represents the unobserved portion in the GEANIE experiment. Experimentally, it is unclear how this "difference" cross section is apportioned to the ground state and the isomeric levels. Therefore, a very conservative approach was taken to form the upper limit; the "difference" cross section was added to each of the observed lower limits. In order to determine the best estimate of the cross section, the "difference" cross section was multiplied by a partial-to-total ratio obtained from the STAPRE calculations, and the resulting cross section was added to the lower limit. An estimated 30% systematic uncertainty was applied to the cross sections used in the partial-to-total ratios obtained from the STAPRE calculations. Tables II, III, and IV give the results obtained for the lower limits, upper limits, and best estimates using this procedure.

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REFERENCES

[1] D. McNabb, *et al.*, *Uncertainty Budget and the Efficiency Analysis for the* ^{239}Pu$(n, 2n\gamma)$ *Partial Reaction Cross-Section Measurements*, Tech. Rep. UCRL-ID-139906, LLNL (2000).

[2] P. Garrett, *et al.*, *Measurements of the* $n+^{89}Y$ *cross sections for* $E_n < 20$ *MeV*, Tech. Rep. to be published, LLNL (2003).

TABLE I: Cross section for population of ^{89}Y isomer via the (n, n') reaction. The variance on the neutron energy represents the width of the neutron-energy bin. The final two columns give the 1σ uncertainty on the cross section; the first column the statistical contribution only and the second the statistical + systematic.

E_n (MeV)	var.E_n (MeV)	σ (b)	$\delta\sigma$ (b) stat.	$\delta\sigma$ (b) stat.+sys.
1.010	0.012	0.099	0.003	0.010
1.031	0.011	0.111	0.004	0.011
1.053	0.013	0.122	0.003	0.012
1.075	0.013	0.132	0.004	0.013
1.101	0.013	0.143	0.003	0.014
1.122	0.013	0.154	0.003	0.015
1.148	0.014	0.168	0.004	0.017
1.174	0.014	0.178	0.003	0.018
1.200	0.015	0.191	0.004	0.019
1.228	0.015	0.203	0.003	0.020
1.255	0.015	0.214	0.003	0.021
1.283	0.016	0.226	0.003	0.022
1.314	0.017	0.239	0.003	0.024
1.346	0.018	0.251	0.004	0.025
1.379	0.018	0.261	0.003	0.026
1.412	0.019	0.273	0.004	0.027
1.447	0.019	0.281	0.003	0.028
1.483	0.021	0.292	0.004	0.029
1.522	0.021	0.301	0.004	0.030
1.560	0.022	0.304	0.003	0.030
1.600	0.023	0.311	0.004	0.031
1.644	0.024	0.316	0.003	0.031
1.687	0.025	0.319	0.004	0.031

E_n (MeV)	var.E_n (MeV)	σ (b)	$\delta\sigma$ (b) stat.	$\delta\sigma$ (b) stat. + sys.
1.733	0.026	0.322	0.004	0.031
1.781	0.027	0.322	0.003	0.031
1.830	0.027	0.319	0.003	0.031
1.883	0.029	0.317	0.003	0.031
1.935	0.030	0.316	0.003	0.031
1.991	0.032	0.315	0.003	0.031
2.051	0.033	0.316	0.003	0.031
2.113	0.034	0.317	0.003	0.031
2.177	0.036	0.315	0.003	0.031
2.243	0.037	0.320	0.003	0.031
2.313	0.040	0.353	0.003	0.031
2.388	0.042	0.385	0.004	0.031
2.465	0.043	0.408	0.005	0.031
2.546	0.046	0.437	0.006	0.031
2.633	0.048	0.466	0.007	0.030
2.721	0.050	0.521	0.009	0.031
2.815	0.053	0.560	0.011	0.032
2.914	0.056	0.587	0.012	0.032
3.020	0.059	0.606	0.013	0.033
3.128	0.062	0.655	0.015	0.035
3.246	0.067	0.639	0.015	0.034
3.371	0.069	0.625	0.015	0.033
3.498	0.074	0.639	0.016	0.033
3.639	0.078	0.687	0.018	0.036
3.784	0.083	0.752	0.020	0.039
3.939	0.088	0.800	0.022	0.042
4.107	0.093	0.786	0.022	0.042
4.279	0.099	0.761	0.022	0.041
4.469	0.107	0.767	0.023	0.042
4.667	0.114	0.778	0.024	0.043
4.882	0.120	0.851	0.027	0.048
5.111	0.131	0.899	0.029	0.052
5.357	0.140	0.929	0.030	0.054
5.620	0.150	0.941	0.031	0.055
5.902	0.160	0.971	0.032	0.057
6.208	0.176	0.996	0.033	0.059
6.540	0.189	1.047	0.034	0.062
6.897	0.203	1.061	0.034	0.063
7.281	0.221	1.050	0.034	0.062
7.699	0.241	1.036	0.034	0.062
8.170	0.267	1.067	0.035	0.064
8.666	0.284	1.056	0.035	0.063
9.212	0.318	1.042	0.034	0.062
9.821	0.348	1.047	0.034	0.063
10.477	0.381	1.034	0.034	0.062
11.216	0.428	1.076	0.036	0.064
12.036	0.473	1.027	0.034	0.062
12.949	0.529	0.800	0.027	0.048
13.967	0.594	0.555	0.019	0.033
15.138	0.677	0.363	0.013	0.022
16.451	0.757	0.271	0.010	0.017
17.926	0.881	0.222	0.009	0.014
19.570	0.939	0.199	0.008	0.013

TABLE II: Cross section for population of ^{88}Y ground state via the $(n, 2n)$ reaction. The variance on the neutron energy represents the width of the neutron-energy bin. The next four columns list the lower (LL) and upper limits (UL) with their 1σ statistical uncertainties, while the final three columns list the best estimate (BE) of the cross section together with the statistical and the combined statistical+systematic 1σ uncertainties.

E_n (MeV)	var.E_n (MeV)	σ_{LL} (b)	$\delta\sigma_{LL}$ (b)	σ_{UL} (b)	$\delta\sigma_{UL}$ (b)	σ_{BE} (b)	$\delta\sigma_{BE}$ (b)	$\delta\sigma_{BE}$(stat.+sys.) (b)
11.882	0.464	0.0657	0.0027	0.0657	0.0040	0.0657	0.0027	0.0043
12.776	0.519	0.3498	0.0053	0.3498	0.0076	0.3498	0.0053	0.0224
13.774	0.580	0.5813	0.0116	0.5939	0.0168	0.5909	0.0148	0.0327
14.915	0.663	0.7244	0.0178	0.8161	0.0257	0.7877	0.0219	0.0400
16.205	0.743	0.7349	0.0205	0.9610	0.0296	0.8808	0.0247	0.0455
17.637	0.852	0.7027	0.0211	1.0426	0.0306	0.9124	0.0251	0.0508
19.280	0.920	0.6872	0.0214	1.0814	0.0310	0.9205	0.0252	0.0545

TABLE III: Cross section for population of first isomeric state in ^{88}Y via the $(n, 2n)$ reaction. See caption to Table II.

E_n (MeV)	var.E_n (MeV)	σ_{LL} (b)	$\delta\sigma_{LL}$ (b)	σ_{UL} (b)	$\delta\sigma_{UL}$ (b)	σ_{BE} (b)	$\delta\sigma_{BE}$ (b)	$\delta\sigma_{BE}$(stat.+sys.) (b)
11.882	0.464	0.0017	0.0013	0.0017	0.0032	0.0017	0.0013	0.0013
12.776	0.519	0.0511	0.0015	0.0511	0.0057	0.0511	0.0015	0.0036
13.774	0.580	0.1219	0.0031	0.1346	0.0125	0.1239	0.0036	0.0070
14.915	0.663	0.1632	0.0048	0.2549	0.0191	0.1776	0.0057	0.0104
16.205	0.743	0.1776	0.0060	0.4037	0.0222	0.2136	0.0069	0.0158
17.637	0.852	0.1750	0.0064	0.5149	0.0230	0.2271	0.0072	0.0200
19.280	0.920	0.1641	0.0062	0.5583	0.0232	0.2200	0.0070	0.0209

TABLE IV: Cross section for population of second isomeric state in ^{88}Y via the $(n, 2n)$ reaction. See caption to Table II.

E_n (MeV)	var.E_n (MeV)	σ_{LL} (b)	$\delta\sigma_{LL}$ (b)	σ_{UL} (b)	$\delta\sigma_{UL}$ (b)	σ_{BE} (b)	$\delta\sigma_{BE}$ (b)	$\delta\sigma_{BE}$(stat.+sys.) (b)
11.882	0.464	0.0001	0.0000	0.0001	0.0030	0.0001	0.0000	0.0000
12.776	0.519	0.0068	0.0000	0.0068	0.0055	0.0068	0.0000	0.0007
13.774	0.580	0.0299	0.0010	0.0425	0.0121	0.0310	0.0014	0.0032
14.915	0.663	0.0525	0.0011	0.1442	0.0185	0.0665	0.0030	0.0073
16.205	0.743	0.0586	0.0013	0.2848	0.0214	0.1028	0.0044	0.0153
17.637	0.852	0.0528	0.0016	0.3927	0.0222	0.1309	0.0053	0.0242
19.280	0.920	0.0459	0.0018	0.4400	0.0225	0.1509	0.0062	0.0308