Thermal neutron capture cross sections and neutron separation energies for ^{23}Na(n,γ)

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Prompt thermal neutron capture γ-ray cross sections σ_γ were measured for the ^{23}Na(n,γ) reaction with guided cold neutron beams at the Budapest Reactor. The ^{24}Na γ-ray cross sections were internally standardized with a stoichiometric NaCl target by using standard ^{35}Cl(n,γ)^{36}Cl γ-ray cross sections. Transitions were assigned to levels in ^{24}Na based primarily upon the known nuclear structure information from the literature, producing a nearly complete neutron capture decay scheme. The total radiative thermal neutron cross section σ_0 was determined from the sum of prompt γ-ray cross section populating the ground state as 0.540 (3) b, and from the activation γ-ray cross sections for the decay of ^{24}Na as 0.542 (3) b. The isomer cross section σ_0 (^{23}Na^m, $t_{1/2} = 20.20$ ms) = 0.501 (3) b and the ^{24}Na neutron separation energy $S_n = 6959.352\,(18)$ keV were also determined in these experiments. New level spins and parities were proposed on the basis of new transition assignments and the systematics of reduced transition probabilities for the primary γ rays.

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I. INTRODUCTION

Precise prompt thermal neutron capture γ-ray cross sections σ_γ have been measured for all elements with $Z = 1$–83, 90, and 92, except for He and Pm, at the Budapest Reactor [1]. These data have been evaluated together with additional information from the literature and compiled into the Evaluated Gamma-ray Activation File (EGAF) [2] and published in the *Handbook of Prompt Gamma Activation Analysis* [3]. For low-Z isotopes, where the decay schemes are completely measured, the total radiative thermal neutron capture cross section σ_0 can be determined by $\sigma_0 = \Sigma\sigma_\gamma(\mathrm{GS}) = \Sigma\sigma_\gamma(\mathrm{CS})$ using the transitions either feeding the ground state or deexciting the capture state. The total radiative thermal neutron capture cross sections can also be determined in these experiments from the activation γ-ray cross sections and their decay emission probabilities P_γ if the half-lives are sufficiently short. In this paper we report our determination of σ_0 for the ^{23}Na(n,γ) reaction.

II. EXPERIMENT

Neutron capture γ-ray cross sections were measured with cold guided neutron beams at the 10 MW Budapest Reactor [1]. Neutrons enter the evacuated target holder and continue to the beam stop at the rear wall of the guide hall. The target station is located ≈35 m from the reactor where both primary and secondary γ rays can be measured in low-background conditions. At the time of the experiment, the thermal-equivalent neutron flux was 5×10^7 n cm^{-2} s^{-1}.

Prompt γ rays from the target were measured with an n-type high-purity, 25% relative efficiency, germanium (HPGe) detector with closed-end coaxial geometry located 23.5 cm from the target. The detector is Compton suppressed by a bismuth-germanate (BGO) scintillator guard detector annulus surrounded by 10-cm-thick lead shielding. Energy resolution was 1.5 keV at 91 keV, 2.1 keV at 1.3 MeV, and 4.3 keV at 6.4 MeV. Counting efficiency was calibrated from 50 keV to 10 MeV with radioactive sources and (n,γ) reaction γ rays to a precision of better that 1% from 500 keV to 6 MeV and better than 3% at all other energies [4]. The γ-ray spectra were analyzed using the HYPERMET PC program [4,5].

The ^{24}Na thermal neutron capture γ-ray cross sections were internally calibrated with a stoichiometric, >99.5% pure NaCl target assuming the σ_γ(^{36}Cl, 1951.1 keV) = 6.51 (2) b [6] and using the relative ^{36}Cl γ-ray emission probabilities of Molnar *et al*. [7]. Besides the usual elements (H, B, C, N, F, Al, and Pb), whose concentrations did not exceed background levels, no other elements could be observed in the prompt γ-ray spectrum at the 0.1% level. For the homogenous target the measured cross section does not depend on the spatial distribution of the neutron flux. No target impurities were observed in the prompt γ-ray calibration spectrum. Both the chlorine and sodium isotopes have a $1/v$ cross-section energy dependence [2] so the respective γ-ray intensity ratios used in these cross-section calibrations are independent of neutron energy distribution. No fast neutrons were present in the guided neutron beam.

The total radiative neutron capture γ-ray cross section σ_0 for ^{23}Na was also determined by using the activation γ-ray cross sections, observed in both the prompt γ-ray data and after bombardment, with the γ-ray transition probabilities P_γ from the Decay Database Evaluation Project (DDEP) [8] database as shown in Eq. (1). The observed cross section is the corrected for

$$\sigma_0 = \frac{\sigma_\gamma}{P_\gamma b}, \tag{1}$$

the in-beam saturation b, as shown in Eq. (2), where t is

$$b = 1 - \frac{1 - e^{-\lambda t}}{\lambda t}, \tag{2}$$

the bombardment time and the decay constant $\lambda = \ln(2)/t_{1/2}$.

TABLE I. $^{23}Na(n,\gamma)$ thermal neutron capture γ-ray energies and cross sections measured in this work.

E_γ (keV)	σ_γ (b)	Placement (initial → final)	E_γ (keV)	σ_γ (b)	Placement (initial → final)
91.004 (15)	0.244 (3)	563 → 472	2414.33 (3)	0.02519(23)	2978 → 563
242.30 (9)[a]	0.000110 (11)	3656 → 3413	2426.44 (22)[b]	0.000143 (23)	4940 → 2513
373.24 (6)	0.000075 (7)	3745 → 3372	2431.74 (8)	0.000563 (23)	2904 → 472
387.98 (18)[b]	0.000028 (6)	3977 → 3589	2482.9 (5)[b]	0.000103 (20)	6073 → 3589
390.51 (15)[b]	0.000044 (6)	2904 → 2513	2505.26 (4)	0.01735 (19)	2978 → 472
464.47 (12)[b]	0.00018 (3)	4442 → 3977	2512.43 (13)	0.00107 (6)	2513 → 0
472.205 (14)	0.501 (4)	472 → 0	2517.54 (3)	0.0736 (7)	CS → 4442
499.363 (22)	0.01474 (22)	1846 → 1347	2521.92 (21)	0.00068 (6)	6111 → 3589
501.35 (4)	0.00308 (12)	1846 → 1345	2524.02 (7)[a]	0.00038 (5)	3866 → 1341
504.55 (5)	0.00140 (8)	1846 → 1341	2546.00 (19)	0.000145 (18)	5060 → 2513
543.94 (13)[b]	0.000042 (7)	4751 → 4207	2555.86 (7)	0.00046 (3)	4442 → 1885
551.21 (4)	0.000348 (13)	4207 → 3656	2565.2 (5)	0.00008 (3)	2565 → 0
552.721 (25)	0.0000605 (14)	CS → 6407	2574.9 (3)[b]	0.000106 (25)	6257 → 3682
563.171 (11)	0.00925 (8)	563 → 0	2588.38 (5)	0.00154 (3)	3933 → 1345
605.51 (3)	0.000159 (10)	3977 → 3372	2591.53 (5)	0.00181 (3)	3933 → 1341
617.84 (5)[b]	0.000143 (10)	4207 → 3589	2595.19 (4)	0.00520 (6)	4442 → 1846
685.54 (12)[b]	0.000229 (17)	3589 → 2904	2623.3 (4)[b]	0.000081 (19)	6251 → 3628
696.570 (20)[a]	0.00015 (17)	4442 → 3745	2630.31 (5)	0.00296 (4)	3977 → 1347
702.14 (3)	0.000312 (10)	CS → 6257	2635.36 (12)[b]	0.000208 (18)	3977 → 1341
708.051 (15)	0.001266 (16)	CS → 6251	2657.88 (19)	0.000156 (17)	6247 → 3589
711.865 (15)	0.00469 (4)	CS → 6247	2661.55 (14)[b]	0.000211 (16)	6251 → 3589
737.15 (7)[d]	0.00010 (3)	CS → 6222	2701.8 (14)	0.000259 (18)	4049 → 1347
773.685 (23)	0.000552 (12)	4751 → 3977	2715.71 (5)	0.00303 (4)	4562 → 1846
778.142 (13)	0.00602 (5)	1341 → 563	2752.13 (4)	0.0593 (11)	CS → 4207
781.295 (13)	0.01736 (14)	1345 → 563	2763.19 (4)	0.00234 (4)	CS → 4196
783.14 (4)[c]	0.00058 (4)	1347 → 563	2808.32 (4)	0.01644 (16)	3372 → 563
	0.00031 (4)	CS → 6172	2833.7 (3)[b]	0.000080 (12)	6247 → 3413
785.58 (7)	0.000206 (12)	4442 → 3656	2849.97 (5)	0.00137 (3)	3413 → 563
793.767 (15)	0.002119 (22)	4207 → 3413	2860.26 (4)	0.01821 (22)	4207 → 1347
813.36 (9)	0.000082 (10)	4442 → 3628	2865.4 (5)[c]	0.0121 (9)	4207 → 1341
835.259 (14)	0.01164 (10)	4207 → 3372		0.0029 (3)	4751 → 4751
852.25 (3)	0.000392 (13)	4442 → 3589	2875.55 (17)	0.000112 (13)	6247 → 3372
852.25 (3)		5060 → 4207	2899.410 (15)[a]	0.000110 (13)	3372 → 472
858.431 (24)[b]	0.00008 (3)	3372 → 2513	2903.819 (22)[a,c]	0.00062 (10)	2904 → 0
863.21 (5)[a]	0.00011 (5)	5060 → 4196	2904.55 (4)[c]	0.00543 (7)	4751 → 4751
869.173 (13)	0.1120 (15)	1341 → 472	2910.6 (8)	0.000332 (16)	CS → 4049
874.353 (13)	0.0796 (13)	1347 → 472	2940.74 (4)	0.00340 (4)	3413 → 472
886.729 (17)	0.00408 (4)	CS → 6073	2977.35 (7)	0.000554 (23)	2978 → 0
906.04 (4)[a]	0.00036 (9)	4562 → 3656	2981.98 (4)	0.01385 (14)	CS → 3977
943.4 (5)[b]	0.000046 (12)	6251 → 5309	2993.62 (11)	0.000214 (12)	6407 → 3413
992.40 (14)[c]	0.000010 (10)	4621 → 3628	3015.79 (10)	0.000437 (16)	CS → 3943
	0.000087 (15)	CS → 5967	3025.69 (8)	0.0094 (4)	3589 → 563
999.33 (15)	0.000080 (11)	3977 → 2978		0.0050 (4)	CS → 3933
1005.914 (21)[c]	0.00100 (3)	4751 → 3745	3092.64 (6)[c]	0.00073 (4)	3656 → 563
	0.00155 (3)	CS → 5953		0.00090 (9)	CS → 3866
1012.95 (5)[a]	0.000057 (15)	5455 → 4442	3094.808 (13)[a]	0.0029 (3)	4442 → 1347
1018.46 (15)	0.000077 (11)	2904 → 1885	3096.45 (4)	0.01965 (21)	4442 → 1345
1028.25 (4)	0.000360 (12)	4442 → 3413	3099.74 (4)	0.01519 (17)	4442 → 1341
1041.122 (23)	0.001535 (21)	CS → 5918	3116.86 (5)[b]	0.00470 (6)	3589 → 472
1050.4 (5)[a]	0.000032 (10)	2565 → 1514	3168.57 (11)	0.000244 (14)	6073 → 2904
1057.00 (4)	0.000355 (12)	2904 → 1846	3173.81 (9)	0.000313 (15)	5060 → 1885
1092.02 (3)	0.001667 (19)	2978 → 1885	3181.77 (6)	0.00133 (4)	3745 → 563
1094.86 (3)	0.000696 (12)	4751 → 3656	3183.52 (26)[a]	0.00029 (3)	3656 → 472
1097.2 (3)[d]	0.00020 (8)	CS → 5963	3198.75 (5)	0.001111 (22)	5045 → 1846
1108.12 (7)	0.000158 (10)	CS → 5851	3209.31 (5)	0.00378 (5)	3682 → 472
1131.35 (12)	0.000155 (22)	2978 → 1846	3214.2 (5)	0.00539 (7)	CS → 3745

TABLE I. *(Continued.)*

E_γ (keV)	σ_γ (b)	Placement (initial → final)	E_γ (keV)	σ_γ (b)	Placement (initial → final)
1143.09 (14)	0.00026 (3)	3656 → 2513	3231.68 (13)	0.000164 (14)	5117 → 1885
1149.748 (19)	0.00580 (8)	CS → 5809	3244.31 (7)[a]	0.000027 (10)	6222 → 2978
1171.869 (21)[a]	0.00014 (4)	2513 → 1341	3270.47 (6)	0.000564 (15)	5117 → 1846
1183.8 (9)[b]	0.00007 (1)	CS → 5775	3277.45 (5)	0.00382(5)	CS → 3682
1208.34 (7)[a]	0.00023 (10)	4621 → 3413	3295.878 (24)[a]	0.000026 (11)	5809 → 2513
1219.95 (22)	0.000110 (14)	4196 → 2976	3303.26 (6)	0.001251 (22)	CS → 3656
1225.0 (6)	0.000087 (22)	5918 → 4694	3330.6 (5)	0.00134 (3)	CS → 3628
1229.26 (4)	0.00153 (3)	4207 → 2978	3343.02 (5)	0.001168 (24)	6247 → 2904
1231.65 (15)	0.000191 (21)	3745 → 2513	3369.84 (6)	0.0008 (4)	3933 → 563
1247.37 (5)	0.001186 (20)	5809 → 4562		0.0140 (2)	CS → 3589
1218.59 (5)[a]	0.000129 (22)	4196 → 2978	3409.15 (5)	0.00237 (4)	4751 → 1341
1282.714 (21)	0.00551 (5)	1846 → 563	3413.74 (5)	0.00449 (6)	3977 → 563
1292.4 (3)[b]	0.000037 (11)	4196 → 2904	3471.27 (7)	0.00136 (6)	3943 → 472
1314.55 (5)	0.000308 (11)	5060 → 3744	3492.8 (6)	0.000454 (13)	5339 → 1846
1322.202 (19)	0.00632 (5)	1885 → 563	3504.78 (5)	0.00718 (8)	3977 → 472
1330.52 (19)[b]	0.000075 (11)	3216 → 1885	3545.89 (5)	0.00492 (6)	CS → 3413
1337.646 (19)	0.00332 (3)	4751 → 3413	3576.4 (3)	0.00025 (4)	4049 → 472
1340.98 (22)	0.000098 (15)	1341 → 0	3587.4 (5)	0.0619 (17)	CS → 3372
1344.475 (19)	0.02119 (17)	1345 → 0	3627.97 (7)	0.000766 (19)	3628 → 0
1373.654 (20)	0.00818 (9)	1846 → 472	3632.62 (8)[c]	0.00055 (7)	4196 → 563
1378.80 (12)	0.00038 (4)	4751 → 3372		0.000430 (18)	5479 → 5479
1387.83 (8)	0.000278 (22)	CS → 5571	3643.55 (6)	0.00735 (8)	4207 → 563
1412.4 (8)	0.000075 (17)	1885 → 472	3697.8 (11)	0.00100 (3)	5045 → 1347
1415.8 (10)	0.000045 (17)	5045 → 3628	3703.07 (12)	0.00224 (4)	5045 → 1341
1420.00 (18)[b]	0.000117 (18)	3933 → 2513	3713.47 (25)	0.000198 (20)	5060 → 1345
1455.65 (3)[a]	0.00019 (11)	5045 → 3589	3723.47 (12)	0.00165 (4)	4196 → 472
1470.0 (3)[b]	0.000043 (9)	5060 → 3589	3734.17 (15)	0.00055 (3)	4207 → 472
1477.14 (15)	0.000089 (13)	5455 → 3977	3744.04 (24)	0.000217 (21)	3745 → 1
1480.32 (4)	0.001802 (22)	CS → 5479	3770.51 (17)	0.000529 (17)	5117 → 1345
1486.05 (4)[b]	0.001271 (17)	3372 → 1885	3775.7 (3)	0.000091 (12)	5117 → 1341
1504.76 (4)	0.00255 (3)	CS → 5455	3866.20 (14)[b]	0.000324 (17)	3866 → 0
1514.7 (4)	0.000101 (20)	1514 → 0	3878.1 (5)	0.02316 (25)	4442 → 563
1525.79 (15)	0.000093 (12)	3372 → 1846	3934.34 (25)	0.000096 (13)	6448 → 2513
1559.22 (4)	0.001488 (24)	2904 → 1345	3942.84 (8)	0.000434 (16)	3943 → 0
1562.36 (4)	0.00257 (4)	2904 → 1341	3964.13 (15)[b]	0.000204 (15)	5309 → 1345
1567.10 (5)	0.000537 (15)	3413 → 1846	3969.07 (6)	0.00235 (4)	4442 → 472
1578.0 (6)[a]	0.000064 (10)	4143 → 2565	3981.35 (5)	0.0723 (8)	CS → 2978
1584.05 (14)	0.000260 (11)	4562 → 2978	3997.57 (6)	0.00170 (3)	5339 → 1341
1620.39 (3)	0.00297 (3)	CS → 5339	4055.23 (6)	0.00340 (18)	CS → 2904
1631.19 (6)[b]	0.00086 (6)	2978 → 1347	4058.47 (19)	0.00033 (4)	4621 → 563
1633.223 (24)	0.00834 (9)	2978 → 1345	4089.36 (7)	0.00216 (11)	4562 → 472
1636.21 (3)	0.02511 (22)	2978 → 1341	4106.92 (4)[a]	0.000158 (22)	5953 → 1885
1646.16 (13)[b]	0.000130 (12)	5060 → 3413	4108.1 (3)	0.000064 (10)	5455 → 1347
1651.08 (12)[b]	0.00136 (13)	CS → 5309	4132.55 (19)	0.000171 (13)	5479 → 1345
1683.1 (3)[b]	0.000101 (14)	4196 → 2513	4137.03 (7)	0.000836 (22)	5479 → 1341
1685.7 (3)[b]	0.000079 (15)	6247 → 4562	4142.6 (6)	0.000064 (10)	4143 → 0
1693.677 (22)[a]	0.00064 (7)	4207 → 2513	4187.39 (6)[c]	0.00795 (9)	4751 → 563
1711.16 (16)[b]	0.00028 (3)	5918 → 4207		0.00014 (6)	6073 → 6073
1714.2 (4)[a]	0.00043 (3)	4694 → 2978	4226.17 (13)	0.000174 (11)	6073 → 1846
1743.26 (8)	0.000444 (17)	3589 → 1846	4278.59 (24)	0.000084 (10)	4751 → 472
1766.92 (5)	0.000321 (11)	CS → 5192	4361.38 (25)	0.000097 (11)	6247 → 1885
1770.18 (6)	0.000332 (12)	3656 → 1885	4376.05 (12)	0.00060 (3)	4940 → 563
1773.02 (3)	0.001007 (20)	4751 → 2978	4394.9 (5)	0.000055 (10)	CS → 2565
1809.96 (9)	0.000189 (13)	3656 → 1846	4405.06 (17)	0.000305 (19)	6251 → 1846
1831.87 (5)	0.00092 (7)	5809 → 3977	4433.8 (3)	0.000069 (9)	5776 → 1341
1841.92 (3)	0.00246 (19)	CS → 5117	4445.69 (7)	0.00249 (3)	CS → 2513

TABLE I. *(Continued.)*

E_γ (keV)	σ_γ (b)	Placement (initial → final)	E_γ (keV)	σ_γ (b)	Placement (initial → final)
1846.67 (8)	0.00041 (4)	4751 → 2904	4462.43 (8)	0.000747 (16)	5809 → 1347
1859.2 (8)	0.00034 (4)	3745 → 1885	4466.96 (7)	0.001558 (24)	4940 → 472
1876.24 (5)[a]	0.00034 (3)	6073 → 4196	4481.4 (7)	0.001005 (18)	5045 → 563
1885.35 (3)	0.00347 (4)	1885 → 0	4496.02 (7)	0.00216 (3)	5060 → 563
1899.15 (3)[c]	0.0021 (3)	3745 → 1846	4521.3 (3)	0.000070 (8)	5863 → 1341
	0.0047 (3)	CS → 5060	4553.79 (15)	0.000389 (24)	5117 → 563
1914.31 (3)	0.00602 (6)	CS → 5045	4562.57 (25)	0.000125 (12)	6448 → 1885
1928.15 (3)[b]	0.00471 (5)	4442 → 2513	4571.76 (10)[c]	0.00044 (7)	5045 → 472
1950.03 (3)	0.00894 (8)	2513 → 563		0.00070 (7)	5918 → 5918
1964.3 (4)	0.000026 (12)	6407 → 4442	4586.99 (11)	0.000808 (20)	5060 → 472
2009.76 (9)[a]	0.00093 (10)	5953 → 3943	4619.1 (18)[a]	0.000012 (4)	5967 → 1347
2019.74 (3)[b,c]	0.0023 (2)	CS → 4940	4628.72 (14)	0.000226 (13)	5192 → 563
	0.0009 (2)	3866 → 1846	4644.47 (18)	0.000296 (13)	5117 → 472
2024.97 (3)	0.0318 (3)	3372 → 1347	4725.94 (12)	0.000625 (22)	6073 → 1347
2027.02 (4)	0.00415(9)	3372 → 1345	4727.601 (13)[a]	0.00012 (4)	6073 → 1345
2030.15 (3)	0.02094 (18)	3372 → 1341	4730.75 (11)	0.00177 (4)	6073 → 1341
2040.9 (3)[b]	0.000078 (19)	5455 → 3413	4775.3 (13)	0.000919 (21)	5339 → 563
2047.91 (9)	0.000534 (20)	4562 → 2513	4829.68 (18)	0.000151 (12)	6176 → 1347
2051.29 (26)	0.000098 (17)	CS → 4908	4836.06 (24)[b]	0.000113 (11)	5309 → 472
2066.4 (3)	0.001300 (21)	3413 → 1347	4866.0 (9)	0.00008 (5)	5339 → 472
2071.58 (3)	0.00567(6)	3413 → 1341	4875.18 (7)[a]	0.000032 (5)	6222 → 1347
2087.44 (4)	0.000707(15)	3933 → 1846	4890.69 (19)	0.0017 (7)	5455 → 563
2107.7 (3)	0.000062 (13)	5479 → 5479	4900.356 (13)[a]	0.0007 (2)	6247 → 1347
2108.12 (7)[a]	0.00013 (5)	4621 → 2513	4902.0 (3)	0.0010 (4)	6247 → 1345
2117.91 (12)[a]	0.00009 (4)	5863 → 3744	4905.517 (13)[a]	0.000016 (5)	6247 → 1341
2130.92 (12)	0.000167 (15)	3977 → 1846	4914.7 (4)	0.00020 (8)	5479 → 563
2139.22 (9)	0.000210 (16)	5117 → 2978	4981.79 (21)	0.00035 (11)	5455 → 472
2208.25 (3)	0.02682 (24)	CS → 4751	5006.32 (21)	0.00024 (8)	5479 → 472
2219.84 (6)	0.00080 (5)	5809 → 3589	5059.75 (20)	0.000113 (9)	5060 → 0
2237.55 (7)	0.00121 (5)	4751 → 2513	5073.33 (8)	0.00237 (3)	CS → 1885
2243.27 (15)	0.0041 (3)	3589 → 1345	5112.79 (8)	0.00289 (4)	CS → 1846
2247.38 (12)	0.00059 (3)	3589 → 1341	5191.5 (15)	0.000037 (9)	5192 → 0
2265.70 (21)	0.00022 (3)	CS → 4694	5245.5 (5)	0.000051 (10)	5809 → 563
2271.0 (3)[c]	0.00012 (3)	5953 → 3682	5336.7 (3)	0.000068 (9)	5809 → 472
	0.00012 (3)	6247 → 3977	5445.28 (12)	0.000855 (18)	5918 → 472
2279.5 (3)[a]	0.000035 (4)	6257 → 3977	5493.8 (3)	0.000066 (9)	5967 → 472
2281.65 (24)[a]	0.000261 (25)	3628 → 1347	5508.4 (6)	0.000041 (9)	6073 → 563
2286.33 (7)	0.00086 (4)	3628 → 1341	5599.73 (10)	0.000694 (18)	6073 → 472
2297.04 (17)[b]	0.000293 (27)	4143 → 1846	5612.75 (17)	0.00132 (12)	CS → 1347
2309.17 (3)[a]	0.00018 (4)	3656 → 1347	5617.14 (8)	0.0228 (3)	CS → 1341
2310.79 (5)[a]	0.00019 (4)	4196 → 1885	5658.41 (7)[a]	0.000032 (5)	6222 → 563
2314.33 (3)[a]	0.000163 (24)	3656 → 1343	5683.592 (12)[a]	0.00005 (3)	6247 → 563
2334.71 (21)	0.000132 (17)	3682 → 1347	5703.91 (18)	0.000162 (12)	6176 → 472
2337.83 (8)	0.000570 (20)	CS → 4621	5774.59 (13)	0.001367 (24)	6247 → 472
2340.48 (18)	0.000178 (20)	2904 → 563	5784.16 (25)	0.000125 (11)	6257 → 472
2349.78 (12)	0.000288 (17)	4196 → 1846	6111.1 (3)	0.000082 (12)	6111 → 0
2360.89 (3)	0.00834 (8)	4207 → 1846	6246.641 (12)[a]	0.000014 (5)	6247 → 0
2376.8 (13)[a]	0.000009 (3)	5967 → 3589	6395.48 (9)	0.1005 (11)	CS → 563
2397.24 (4)	0.00586 (9)	CS → 4562	6406.4 (7)	0.000042 (9)	6407 → 0
2400.18 (6)	0.00126 (3)	3745 → 1345	6486.35 (11)	0.00233 (3)	CS → 472
2403.31 (4)	0.00154 (3)	3745 → 1341	6958.8 (5)	0.000015 (3)	CS → 0

[a]From ^{24}Na Adopted Levels Gammas [9], intensity normalized to adopted branching ratios.
[b]Placed on the basis of energy sums and consistency with the level scheme.
[c]Transition multiply placed. Intensity divided on the basis of adopted γ-ray branching ratios [9] and level scheme.
[d]Transition adopted from Hungerford *et al*. [10].

TABLE II. Cross sections populating and depopulating levels in ^{24}Na from the (n,γ) reaction. Level energies are calculated from a least-squares fit of the γ-ray energies to the level scheme. The J^{π} values are from the Evaluated Nuclear Structure Data File (ENSDF) [11], modified as discussed in the text.

Level energy keV	J^{π}	In (b)	Out (b)	Net[a] (b)	Level energy eV	J^{π}	In (b)	Out (b)	Net[a] (b)
0	4^+	0.540 (3)	0.0	0.540 (3)	4561.94 (4)	2^-	0.0071 (1)	0.0063 (2)	0.0008 (2)
472.208 (14)	1^+	0.500 (4)	0.501 (3)	−0.001 (5)	4621.50 (7)	$(2)^+$	0.00057 (2)	0.00070 (12)	0.00013 (12)
563.189 (12)	2^+	0.252 (2)	0.254 (3)	0.002 (3)	4693.4 (3)	(3^-)	0.00031 (4)	0.00011 (4)	0.00020 (6)
1341.426 (17)	2^+	0.121 (1)	0.118 (2)	−0.003 (2)	4750.876 (24)	2^-	0.0268 (2)	0.0274 (3)	−0.0005 (4)
1344.512 (17)	3^+	0.0386 (5)	0.0386 (2)	−0.0000 (5)	4908.022 (16)	2^+,3	0.00010 (2)	0.0	000010 (2)
1346.591 (17)	1^+	0.0814 (6)	0.0802 (13)	−0.0012 (14)	4939.55 (4)	1^-	0.0023 (2)	0.0023 (1)	0.0000 (2)
1514.5 (5)	5^+	0.00003 (1)	0.00010 (2)	0.00007 (2)	5044.96 (3)	$(1)^-$	0.00602 (6)	0.00603 (14)	−0.0.00001 (15)
1845.978 (22)	2^+	0.0342 (4)	0.0329 (3)	0.0013 (5)	5059.55 (5)	3^-	0.0047 (3)	0.0047 (1)	0.0000 (3)
1885.438 (24)	3^+	0.0087 (3)	0.0099 (1)	0.0012 (3)	5117.34 (5)	(2^-)	0.0025 (2)	0.0022 (1)	0.0002 (2)
2513.276 (22)	3^+	0.0108 (1)	0.0102 (1)	0.0006 (2)	5192.37 (8)	3^-	0.00032 (1)	0.0026 (2)	0.00006 (2)
2564.6 (3)	4^+	0.00012 (1)	0.00022 (4)	−0.00010 (4)	5308.6 (3)	$2(^+)$	0.00018 (2)	0.00032 (2)	−0.00014 (3)
2903.81 (4)	3^+	0.0055 (2)	0.0059 (1)	−0.0004 (2)	5339.02 (8)	2^-	0.00297 (3)	0.00315 (6)	−0.00018 (7)
2977.681 (25)	2^+	0.0757 (8)	0.0752 (4)	0.0005 (9)	5454.52 (5)	$1^-,2^-$	0.0025 (1)	0.0023 (7)	−0.0002 (7)
3216.0 (3)	(4^+)	0.0	0.000075 (11)	0.000075 (11)	5478.95 (5)	1^-	0.00180 (2)	0.0019 (1)	−0.0001 (1)
3371.696 (20)	2^-	0.0743 (17)	0.0748 (4)−	0.0005 (17)	5571.48 (9)	(2^+)	0.00028 (2)	0.0	0.00028 (2)
3413.195 (23)	1^+	0.0116 (1)	0.0123 (1)	−0.0007 (2)	5775.7 (4)	(3^+)	0.00007 (8)	0.00007 (1)	0.00000 (8)
3589.26 (3)	1^+	0.0161 (2)	0.0169 (4)	0.0008 (5)	5809.40 (4)	2^-	0.0058 (1)	0.0038 (1)	0.0020 (1)
3628.29 (8)	3^+	0.00156 (4)	0.00189 (5)	0.00033 (7)	5851.26 (8)	(2^+)	0.00016 (1)	0.0	0.00016 (1)
3655.89 (3)	$(1)^+$	0.0029 (1)	0.0022 (1)	0.0007 (1)	5862.85 (17)	(2^+)	0.00020 (8)	0.00016 (4)	0.00004 (9)
3681.71 (6)	0^+	0.00405 (6)	0.00391 (5)	−0.00013 (8)	5918.21 (4)	(2^-)	0.00154 (2)	0.00192 (8)	−0.00039 (8)
3744.94 (3)	3^-	0.00700 (9)	0.0071 (3)	0.0001 (3)	5953.39 (3)	(1^-)	0.00155 (3)	0.00121 (11)	0.00034 (11)
3865.81 (5)	(3^-)	0.0009 (1)	0.0016 (2)	−0.0007 (2)	5966.88 (20)	0^+	0.00009 (2)	0.00009 (1)	0.00000 (2)
3933.33 (7)	$1^+,2^+$,3	0.0050 (4)	0.0050 (4)	0.0000 (4)	6072.611 (22)	1^+	0.00408 (4)	0.00406 (10)	0.00002 (11)
3943.38 (9)	$(2,3)^+$	0.00137 (10)	0.00179 (6)	0.00043 (12)	6176.20 (6)	$(1^-,2^-)$	0.00031 (4)	0.00031 (2)	0.0000 (4)
3977.18 (3)	2^+	0.0158 (2)	0.0153 (1)	0.0005 (2)	6222.26 (6)	$(1^+,2^+)$	0.00010 (3)	0.000091 (12)	0.000009 (3)
4048.58 (11)	0^-	0.00033 (2)	0.00051 (4)	−0.00018 (5)	6247.492 (14)	2^-	0.00469 (4)	0.0050 (5)	−0.0003 (5)
4143.09 (25)	(4^+)	0.0	0.00042 (3)	−0.00042 (3)	6251.29 (3)	(2^-)	0.00127 (2)	0.00064 (3)	0.00062 (4)
4196.28 (5)	(2^+)	0.0026 (1)	0.0028 (1)	−0.0002 (1)	6257.19 (5)	(2^-)	0.00031 (1)	0.00027 (3)	0.00005 (3)
4206.990 (20)	2^-	0.0600 (10)	0.0630 (9)	−0.0030 (14)	6406.62 (4)	(2^-)	0.00060 (1)	0.00033 (2)	0.00027 (3)
4441.532 (24)	2^-	0.0737 (7)	0.0751 (5)	−0.0014 (9)	6959.352 (18)	1^{+}[b]	0.0	0.537 (3)	0.537 (3)

[a]Net level feeding σ_{γ}(In)-σ_{γ}(Out).
[b]The composite spin is $\approx 96.5\%\ 1^+ + \approx 3.5\%\ 2^+$.

III. RESULTS

A pure ^{23}Na(n,γ) γ-ray spectrum was acquired using an 0.16 g Na metal target contained in an evacuated target chamber. The γ-ray intensities were renormalized to cross sections using the NaCl standardization described above. The Na γ-ray energies and cross sections measured in this work and placed in the ^{24}Na level scheme are listed in Table I. A total of 326 γ rays were placed in the level scheme depopulating 59 levels including the neutron capture state. Level energies have been calculated by a least-squares fit to the connecting γ-ray energies observed in this experiment.

A. Prompt γ-ray cross section

The cross-section balance through the level scheme is shown in Table II. The level scheme is nearly complete with 0.538(3) barns observed deexciting the neutron capture state and 0.540(3) barns populating the ground state. A total cross section of $\Sigma \frac{E_{\gamma}}{S_n}\sigma_{\gamma} = 0.537(6)$ barns was calculated suggesting that the decay scheme is ≈99% complete. The population and depopulation of intermediate levels is generally well balanced although clearly numerous weak transitions are missing.

The cross section calculated from the transition deexciting the short-lived isomeric first-excited state in ^{24}Na at 472.214 keV, with $t_{1/2} = 20.18(10)$ ms, is 0.501(3) barns, as measured in the prompt γ-ray spectrum. This value is significantly higher than than previous measurements of 0.39(6) b by Groshev [12] and 0.40(3) b by Alexander [13] and adopted by Mughabghab [40], but more consistent with 0.476(11) b by Matsue and Yonezawa [14] and 0.504(11) by Szentmiklosi *et al.* [15]. $P_{\gamma}(472.2) = 0.904 \pm 0.006$ from ENSDF for ^{23}Na(n,γ) would give a total cross section of $\sigma_0(^{24}\text{Na}^{m+g}) = 0.44$ b from Mughabghab's adopted isomeric cross section which is inconsistent with all later measured values, indicating that the early measurements are significantly discrepant for unknown reasons.

B. Activation γ-ray cross section

The ^{23}Na(n,γ) total radiative cross section was also determined from the ^{24}Na^{m+g} β^-decay scheme, shown in Fig. 1,

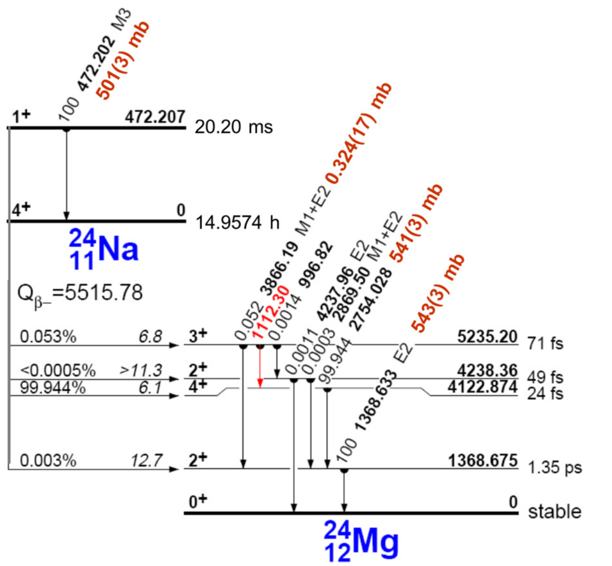

FIG. 1. (Color online) The ^{24}Na^{m+g} decay scheme from the Table of Isotopes [41]. The γ-ray cross sections have been added from this work. Transition and level energies are in keV.

using the decay γ-ray cross sections, after correction for saturation, and the DDEP transition probabilities [8]. For the 1368.626(5) keV γ ray with $P_\gamma = 0.999\,935\,3\,(5)$ we get $\sigma_0 = 0.544(5)$ barns in the prompt spectrum and $\sigma_0 = 0.542(3)$ barns in the decay spectrum. For the 2754.007(11) keV γ ray with $P_\gamma = 0.99872(8)$ we get $\sigma_0 = 0.540(3)$ barns in the prompt spectrum and $\sigma_0 = 0.542(3)$ barns in the decay spectrum. The average total radiative thermal neutron cross section from decay, $\sigma_0 = 0.542(3)$ b is consistent with the value determined from the prompt γ rays and we recommend $\sigma_0 = 0.541(3)$ b from the weighted average of all values. This value is compared with earlier measurements in Table III. The new measurements are consistent with most previous values but inconsistent with Mughabghab's [40] recommended value of 0.517(4) barns. The weighted average value from all previous experiments gives $\sigma_0 = 0.527(20)$ b which is consistent with our new value. We note that most previous measurements were performed by neutron activation which can be subject to significant summing corrections for the two intense coincident decay γ rays that would lead to an underestimating the total cross section when the source or detector distance is too small.

C. Neutron separation energy

The HPGe detector was calibrated offline with γ rays from the ^{14}N(n,γ) [42] and ^{35}Cl(n,γ) [7] reactions. A total of 55 primary γ rays with energies from 553 to 6959 keV, which were observed to deexcite the capture state, were used to determine a neutron separation energy $S_n = 6959.352(18)$ keV after correction for nuclear recoil. The consistency of S_n over a wide range of primary γ-ray energies demonstrates the stability of our energy calibration over the time of the experiment. Our S_n value is slightly lower than the recommended values of 6959.42(4) keV from the AME2012 Atomic Mass Evaluation [43].

TABLE III. Comparison of ^{23}Na(n,γ) total radiative cross section σ_0 measurements from this work.

Author (year)	σ_0 (b)	Method
	^{24}Na^m	
Groshev (1955) [12]	0.39 ± 0.06[a]	Activation
Alexander (1963) [13]	0.40 ± 0.03	Activation
Matsue (2004) [14]	0.476 ± 0.11	PGAA
Szentmiklosi (2010) [15]	0.504 ± 0.011	PGAA
Mughabghab (2006)	0.40 ± 0.03	
This work	0.501 ± 0.003	
	^{24}Na^{m+g}	
Meadows (1961) [16]	0.47 ± 0.06	Pile oscillator
Pomerance (1951) [17]	0.49 ± 0.05[b]	Pile oscillator
Brooksbank (1955) [18]	0.50 ± 0.05	Activation
Koehler (1963) [19]	0.50 ± 0.02	Activation
Yamamuro (1970) [20]	0.50 ± 0.03	Transmission
Harris (1953) [21]	0.511 ± 0.005[b]	Pile oscillator
De Corte (2003) [22]	0.513 ± 0.006	Activation
Kennedy (2003) [23]	0.515 ± 0.021	Activation
Grimeland (1955) [24]	0.52 ± 0.03	Activation
Heft (1978) [25]	0.523 ± 0.005	Activation
Ryves (1970) [26]	0.527 ± 0.005	Activation
Szentmiklosi (2006) [27]	0.527 ± 0.008	PGAA
Jozefowicz (1963) [28]	0.53 ± 0.01	Activation
Wolf (1960) [29]	0.531 ± 0.008	Activation
Cocking (1957) [30]	0.536 ± 0.006	Activation
Rose (1958) [31]	0.536 ± 0.008	Pile oscillator
Kappe (1966) [32]	0.536 ± 0.027	Activation
Popovic (1955) [33]	0.538 ± 0.027[b]	Activation
Gleason (1975) [34]	0.539 ± 0.020	Activation
Bartholomew (1953) [35]	0.562 ± 0.034[b]	Activation
Grimeland (1952) [36]	0.57 ± 0.04[b]	Activation
Kaminishi (1982) [37]	0.577 ± 0.008	Activation
Coltman (1946) [38]	0.60 ± 0.05[b]	Transmission
Seren (1947) [39]	0.65 ± 0.13[b]	Activation
Average[c]	0.527 ± 0.020	
Mughabghab (2006)	0.517 ± 0.004	
This work	0.541 ± 0.003	

[a]Measured assuming $\sigma_0(^{24}\text{Na}^g = 530)$ mb.
[b]Corrected for standardization value from Mughabghab [40].
[c]Weighted average of all values with external error.

IV. NUCLEAR STRUCTURE

The level spins and parities shown in Table II are mainly derived from the ^{24}Na ENSDF Adopted Levels [9] and the (d,p) reactions assignments of Tomandl *et al.* [44]. We have revised some of these spin and parity assignments on the basis of newly assigned γ-ray transitions and the primary γ-ray reduced transition probabilities shown in Fig. 2. Transitions to levels with $J^\pi = 1^-, 2^-$ are consistently about an order of magnitude stronger than all other transitions making this indicator a strong argument for these spin assignments. Although s-wave neutron capture on the ^{23}Na $J^\pi = 3/2^+$ target can populate a capture state with an admixture of spins 1^+ and 2^+, the dominant observed spin is 1^+, predominantly due to a 1^+ resonance at 2.787 keV [40]. This is consistent with the weak feeding observed to 3^- resonances. The admixture

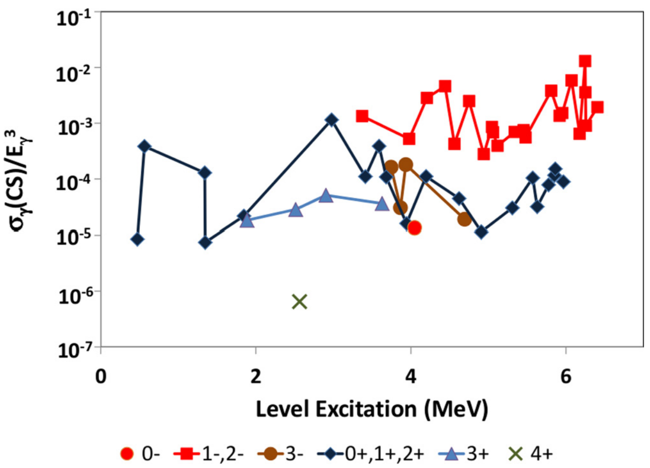

FIG. 2. (Color online) Reduced transition probabilities, σ_γ/E^3, for thermal neutron capture primary γ-ray transitions in ^{24}Na. Transitions to levels with $J^\pi = 1^-, 2^-$ are significantly stronger than transitions to other states. The lines connecting states of the same spin and parity are provided to guide the eye.

of $J^\pi = 2^+$ to the capture state can be estimated from the average strength populating 3^- levels which is ≈3.5% of that populating the 1^-, 2^- states. This population is larger than ≈1.6% estimated feeding the 2^+ bound state near ≈176 keV below the neutron separation energy, reported by Mughabghab [40], but consistent with contributions from the higher-lying 2^+ resonances at 35.295 and 52.973 keV.

3933.33 level. This level has no spin assignment in ENSDF and is loosely restricted to $J = 1$–4 by Tomandl. It decays only to levels with $J^\pi = 2^+,3^+$ and is weakly populated by a primary γ ray limiting likely spins to $J^\pi = 1^+,2^+,3$.

4048.58 level. This level is assigned as $J^\pi = 0^-$ and is expected to be strongly populated by a primary transition, yet it is populated nearly two orders of magnitude more weakly than expected for a favored transition. Although this transition may be anomalous due to nuclear structure considerations, the spin assignment of this state should be reexamined.

4143.09 level. Assignment as (4^-) in ENSDF is inconsistent with γ rays deexciting this level to a 2^+ state. Tomandl assigns this level as $J^\pi = 3^+$–6^+ and since no primary γ ray is observed feeding this level, which is weakly populated, a (4^+) spin assignment has been adopted.

4196.28 level. The spin proposed by Tomandl is $J^\pi = 1^-,2^-$. The 1^- spin is unlikely since this level deexcites to a 3^+ state. This level is only weakly populated by a primary γ ray, suggesting the parity is more likely positive. $J^\pi = (2^+)$ has been adopted for this level.

4206.991 level. This level is assigned $J^\pi = 2^+$ in ENSDF and $J^\pi = 1^-,2^-$ by Tomandl. The γ ray deexciting this level to a 3^+ state eliminates the 1^- assignment, and very strong population by a primary γ ray favors the 2^- assignment.

4561.94 level. This level is assigned $J^\pi = 1^-$ in ENSDF and $J^\pi = 1^+,2,3^+$ by Tomandl. The γ ray deexciting this level to a 3^+ state eliminates the 1^- assignment, and strong population by a primary γ ray favor a 2^- assignment.

4908.022 level. This level is assigned $J^\pi = 2^+$–6^+ by Tomandl. Weak population by a primary γ ray is most consistent with $J^\pi = 2^+,3$

5044.96, 5809.40 levels. These levels are assigned $J^\pi = 1^-,2^-$ by Tomandl. The 1^- assignments are eliminated by transitions deexciting these levels to 3^+ states.

5117.34 level. This level is assigned $J^\pi = 1^-$ in ENSDF and $J^\pi = 1^+,2^+$ by Tomandl. The γ ray deexciting this level to a 3^+ state eliminates the 1^- assignment; however, the strong population by a primary γ ray favors a 2^- assignment.

5308.6 level. This level is assigned $J^\pi = 1^-$–3^- by Tomandl. γ rays populating 1^+ and 3^+ eliminate the 1^- and 3^- assignments. Weak population by a primary γ ray favors a $2^{(+)}$ assignment.

5454.52 level. This level is assigned $J^\pi = 1,2,(3^+)$ by Tomandl. Strong population by a primary γ ray favors $J^\pi = 1^-,2^-$.

5571.48 level. This level is assigned $J^\pi = 2^+$–4^+ by Tomandl. Population by a weak primary γ ray is consistent with an assignment of $J^\pi = (2^+)$.

5775.5, 5851.32 levels. This level is assigned $J^\pi = 1^-$–3^- by Tomandl. Very weak feeding by a primary γ ray is consistent with a (2^+) assignment.

5862.85 level. No spin assignment has been previously recommended for this level. Weak population of this level by a primary γ ray and deexcitation to a 3^- level suggest a (2^+) assignment.

5918.21 level. This level is assigned $J^\pi = 2^+,(1^+)$ by Tomandl. 1^+ is eliminated by a γ ray feeding a 3^- level. While this would suggest the 2^+ assignment, this level is very strongly fed by a primary γ ray and has been tentatively assigned as (2^-) in this work.

5953.39 level. No spin assignment has been previously recommended for this level. Strong population by a primary γ ray and deexcitation to a 0^+ level favors a (1^-) assignment.

6072.611 level. This level is assigned $J^\pi = 1^+$ in ENSDF and $J^\pi = 2^+,(3^+)$ by Tomandl; however, it is very strongly fed by a primary γ ray suggesting negative parity. Depopulation to a 3^+ level suggests that (2^-) is a more likely assignment.

6222.26 level. No spin assignment has been previously recommended for this level. Weak population by a primary γ ray suggests a $(1^+,2^+)$ assignment.

6251.29 level. This level is assigned $J^\pi = 0^+,1,2$ by Tomandl. Strong feeding by a primary γ ray and deexcitation to a 3^+ level suggest a (2^-) assignment.

6257.19 level. This level is assigned $J^\pi = 1^-,2^-$ by Tomandl. A γ ray to a 0^+ level eliminates the 2^- possibility.

6406.62 level. New level assigned in this work. Strong feeding by a primary γ ray and a weak (M2) γ ray deexciting to a 4^+ level suggests a 2^- assignment.

V. DISCUSSION

A new, nearly complete ^{23}Na$(n,\gamma)^{24}$Na thermal neutron capture γ-ray decay scheme has been measured in this work. Self-consistent total radiative neutron cross section, $\sigma_0 = 0.541(3)$ b was determined from both prompt and delayed γ-ray measurements. This value is 4.4% higher than the recommended value of Mughabghab [40] but consistent with numerous earlier measurements. The neutron separation energy, S_n-6959.352(18) is slightly lower and more precise than the recently adopted value in the latest Atomic Mass Evaluation publication [43]. New spin and parity assignments have been made here on the basis of a more complete level scheme and the systematics of primary γ-ray transition probabilities.

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[1] T. Belgya, Z. Révay, I. H. B. Fazekas, L. Dabolczi, G. Molnár, J. O. Z. Kis, and G. Kaszás, *Proceedings of the 9th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Budapest, Hungary, Oct. 8–12*, edited by G. Molnár, T. Belgya, and Zs. Révay (Springer Verlag, Budapest, Berlin, Heidelberg, 1997).

[2] R. Firestone, H. Choi, R. Lindstrom, G. Molnár, S. Mughabghab, R. Paviotti-Corcuera, Z. Revay, V. Zerkin, and C. Zhou, *Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis* (International Atomic Energy Agency, Vienna, 2007).

[3] *Handbook of Prompt Gamma Activations Analysis with Neutron Beams*, edited by G. Molnár (Kluwer Academic Publishers, Boston, 2004).

[4] G. Molnár, Z. Revay, and T. Belgya, Nucl. Instrum. Methods Phys. Res., Sect. A **489**, 140 (2002).

[5] B. Fazekas, J. Óstór, Z. Kis, G. Molnár, and A. Simonits, *Proceedings of the 9th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Budapest, Hungary, Oct. 8-12*, edited by G. Molnár, T. Belgya, and Zs. Révay (Springer-Verlag, Budapest, 1997), p. 774.

[6] Z. Révay and G. Molár, Radiochim. Acta **91**, 361 (2003).

[7] G. Molnár, Z. Revay, and T. Belgya, Nucl. Instrum. Methods Phys. Res., Sect. B **213**, 32 (2004).

[8] *Table of Radionuclides*, edited by M.-M. Bé (Bureau International des Poids et Mesures, Sevres, France, 2013).

[9] R. Firestone, Nucl. Data Sheets **108**, 2319 (2007).

[10] P. Hungerford, T. von Egidy, H. Schmidt, S. Kerr, H. Borner, and E. Monnand, Z. Phys. A **313**, 325 (1983).

[11] R. Firestone, Nucl. Data Sheets **108**, 2319 (2007).

[12] L. V. Groshev, Conf: 1st UN Conf. Peaceful Uses Atomic Energy, Geneva **2**, 39 (1966).

[13] K. Alexander, Ann. Phys. (Berlin, Ger.) **12**, 225 (1963).

[14] H. Matsue and C.Yonezawa, J. Radioanal. Nucl. Chem. **262**, 49 (2004).

[15] L. Szentmiklosi, Z. Revay, and T. Belgya, Nucl. Instrum. Methods Phys. Res., Sect. A **622**, 468 (2010).

[16] J. Meadows, Nucl. Sci. Eng. **9**, 132 (1961).

[17] H. Pmerance, Phys. Rev. **83**, 641 (1951).

[18] W. Brooksbank, *Conf: Nuclear Sci. and Engineering Congress, Cleveland, 1955* (Pergamon Press, New York, 1955), p. 203.

[19] W. Koehler, Z. Naturforsch., Sec. A **18**, 1339 (1963).

[20] N. Yamamuro, Nucl. Sci. Eng. **41**, 445 (1970).

[21] S. Harris, Argonne National Laboratory report series, No. 5031 p. 68 (1953).

[22] F. D. Corte and A. Simonits, At. Data Nucl. Data Tables **85**, 47 (2003).

[23] G. Kennedy and J. St-Pierre, J. Radioanal. Nucl. Chem. **257**, 475 (2003).

[24] B. Grimeland, J. Nucl. Energy **1**, 231 (1955).

[25] R. Heft, *Proceedings of Computers in Activation Analysis and Gamma-ray Spectroscopy, Mayagues, Puerto Rico, 30 April to 4 May* (National Technical Information Service, U.S. Dept. of Commerce, Washington D.C., 1978), p. 495.

[26] T. Ryves, J. Nucl. Energy **24**, 419 (1970).

[27] L. Szentmiklosi, Z. Revay, and T. Belgya, Nucl. Instrum. Methods Phys. Res., Sect. A **564**, 655 (2006).

[28] E. Jozefowicz, Nukleonika **8**, 437 (1963).

[29] G. Wolf, Nukleonika **2**, 255 (1960).

[30] S. Cocking, J. Nucl. Energy **4**, 33 (1957).

[31] H. Rose, Second Internat. Atomic Energy Conf., Geneva 1958 **16**, 34 (1958).

[32] D. Kappe, Dissertation Abstracts B (Sciences) **27**, 919 (1966).

[33] D. Popovic, J. Nucl. Energy **1**, 286 (1955).

[34] G. Gleason, Radiochem. Radioanal. Lett. **23**, 317 (1975).

[35] R. Bartholomew, Can. J. Chem. **31**, 204 (1953).

[36] B. Grimeland, Phys. Rev. **86**, 937 (1952).

[37] K. Kaminishi and T. Shuin, Jpn. J. Appl. Phys. **21**, 636 (1982).

[38] J. Coltman, Phys. Rev. **69**, 411 (1946).

[39] L. Seren, H. Friedlander, and S. Turkel, Phys. Rev. **72**, 888 (1947).

[40] S. Mughabghab, *Atlas of Neutron Resonances, Fifth Edition* (Elsevier, New York, 2006).

[41] R. Firestone, V. Shirley, C. Baglin, F. Chu, and J. Zipkin, *Table of Isotopes*, 8th ed. (John Wiley and Sons, Inc., New York, 1996).

[42] E. T. Jurney, J. W. Starner, J. E. Lynn, and S. Raman, Phys. Rev. C **56**, 118 (1997).

[43] M. Wang, G. Audi, A. Wapstra, F. Kondev, M. MacCormick, X. Xu, and B. Pfeiffer, Chin. Phys. C **16**, 1603 (2012).

[44] I. Tomandl, J. Nóvak, V. Burjan, S. Raman, T. von Egidy, H.-F. Wirth, U. Koster, W. Schauer, J. Starner, E. Jurney *et al.*, Phys. Rev. C **69**, 014312 (2004).