Thermal-neutron scattering length and capture by ^{46}Ca

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We have deduced the coherent scattering amplitude of ^{46}Ca as 3.55±0.21 fm by measuring the neutron-diffraction patterns of calcite enriched to 32% in ^{46}Ca. We have employed this value in calculating the direct-capture cross sections of the primary electric-dipole γ transitions in ^{47}Ca using optical-model potentials with physically realistic parameters. The calculated cross sections agree reasonably well with measurements showing that thermal-neutron capture by ^{46}Ca is controlled largely by a simple direct mechanism.

Although low-energy neutron capture can be regarded as *the* classical compound-nuclear process, it has been known for nearly three decades that far from resonances a direct form of radiative capture, not involving the compound nucleus, can exist. In this process, the neutron-target interaction is represented in zero order by a potential well, and the neutron in its initial scattering orbital simply falls into a bound single-particle state. The calculation of the cross sections for individual primary electric-dipole ($E1$) transitions becomes relatively simple because the major component of the radial factor of the $E1$ matrix element arises outside the potential radius where the relevant wave functions are well known, being dependent only on the neutron scattering length (for the initial state) and the binding energy plus single-particle spectroscopic factor (for the final state).

In our preliminary analysis [1] of the available data on the primary $E1$ transitions in the thermal-neutron capture by even isotopes of calcium, we found strong indications that the above direct mechanism played a major role. However, this analysis was not definitive enough because a key parameter required for the calculation—the coherent scattering length for each calcium isotope—was either unknown or poorly known. We remedied this situation [2] substantially by measuring the neutron-diffraction patterns of isotopically enriched calcite samples and analyzing these patterns to deduce the scattering lengths of the individual calcium isotopes. A reanalysis of the capture data showed that in three cases (^{40}Ca, ^{42}Ca, and ^{48}Ca) the agreement between theory and data was good and that in one case (^{44}Ca) the relatively poor agreement could be explained by considering the modifications to the theory due to collective vibrations of the core.

Of all six naturally occurring calcium isotopes, ^{46}Ca is the rarest (0.004% of natural Ca). Except for its scattering length, other data such as partial $E1$ cross sections [3,4] and (d,p) spectroscopic factors [5,6] were available, and an analysis was therefore attempted in Ref. [1] by varying the scattering length a to find a "best fit" between the calculated and experimental cross sections. The deduced value was $a=3.0$ fm.

Scattering-length measurements of ^{46}Ca were not attempted in Ref. [2] because a sample of adequate size, purity, and isotopic enrichment was not available at that time. Subsequently a single 0.5-g sample of $CaCO_3$ powder with a 32% enrichment of ^{46}Ca became available by combining four smaller samples that were originally part of the Research Materials Collection maintained by the Oak Ridge National Laboratory. Measurements with this sample and a reanalysis of the capture process are reported in this paper.

Integrated intensities for the first eight diffraction peaks were collected using the HB-3 spectrometer at the High-Flux Isotope Reactor. The analysis of the data was as described in Ref. [2] and gives a value for the average bound coherent length $\bar{b}_{Ca}$ for Ca in this sample as 4.05±0.06 fm. From the isotopic composition (^{40}Ca-59.18%, ^{42}Ca-0.75%, ^{43}Ca-0.19%, ^{44}Ca-5.89%, ^{46}Ca-32.13%, ^{48}Ca-1.86%) and the previously measured scattering lengths [2] for the other isotopes, we deduce that $b=3.55\pm0.21$ fm for ^{46}Ca. The rather large uncertainty, compared to the results for the other isotopes tabulated in Table III of Ref. [2], is caused by the low isotopic purity of this sample. As a check of the general method, we also measured a 0.5-g sample of natural $CaCO_3$ and obtained $\bar{b}_{Ca}=4.70\pm0.11$ fm. This value agrees well with the earlier result of 4.71±0.07 fm reported in Table II of Ref. [2].

From the measured value of b, the free-nuclear coherent scattering length of ^{46}Ca is deduced as $a=3.50\pm0.21$ fm (see footnote a, Table III, Ref. [2]). With this a value, we have reanalyzed the capture data along the lines described in Refs. [1] and [2]. The results are shown in Table I. The calculated cross section (with the global+valence procedure) for the 5262-keV transition nearly overlaps with the measured value. That for the 4401-keV transition is a factor of 2 low, but those for the 3218- and 2467-keV transitions agree well with measurements. The discrepancies can be attributed to

TABLE I. Direct capture cross sections for primary $E1$ transitions in the ^{46}Ca(n,γ) reaction. Columns 1, 2, and 3 give the energy, J^π value, and the (d,p) spectroscopic factor [multiplied by $(2J+1)$] for the final state. Column 4 is the primary transition energy. Column 5 is the average valency capture width and column 6 the potential capture cross section, both calculated using a global optical potential (see Eqs. (4)–(7) of Ref. [1]). The entries in column 5 do not include the spin-coupling factor and the spectroscopic factor; those in column 6 do. Column 7 is the calculated cross section using the global plus valence $(G+V)$ procedure; the stated uncertainty reflects that in the experimental scattering length. Column 8 contains the calculated cross sections from the specialized optical-model procedure (S). The experimentally determined cross sections are given in column 9. Finally, column 10 gives the hypothesized compound-nuclear contributions deduced from the differences between column 7 and column 9 via Eq. (8) of Ref. [1]. In the table subheading, $a(X)$ refers to the experimental scattering length, while $a(G)$ and $\overline{\Gamma_n^0}/D$ refer to the scattering length and the neutron strength function, respectively, both calculated using the global optical potential.

E_f[a] (keV)	J^π[a]	(d,p)[b] $(2J+1)S$	E_γ (keV)	$(\Gamma_{\gamma,\mathrm{val}}/D)/E_\gamma^3$ (10^{-7} MeV^{-3})	$\sigma_{\mathrm{pot},\gamma}$ (mb)	$\sigma_\gamma(G+V)$ (mb)	$\sigma_\gamma(S)$ (mb)	$\sigma_\gamma(X)$[c] (mb)	$\sigma_{\mathrm{CN},\gamma}$ (mb)
^{46}Ca$(n,\gamma)^{47}$Ca reaction; $a(X)=3.50\pm0.21$ fm; $a(G)=2.59$ fm; $\overline{\Gamma_n^0}/D=5.14\times10^{-4}$									
2014	$\frac{3}{2}^-$	3.60	5262	1.788	624	419±44	423	548±75	<32
2875	$\frac{1}{2}^-$[d]	0.51	4401	1.840	58	40±5	40	77±11	<12
4058	if $\frac{1}{2}^-$[e]	1.10	3218	2.764	90	64±6	65	70±10	<2
	if $\frac{3}{2}^-$			3.284	109	78±8	78		<2
4809	if $\frac{1}{2}^-$	0.28	2467	3.828	17	13±1	13	13±2	<1
	if $\frac{3}{2}^-$			4.459	20	15±1	15		<1

[a] From T. W. Burrows, $A=47$, Nucl. Data Sheets **48**, 1 (1986) except as noted.
[b] The (d,p) strengths are averages of those given in Refs. [5] and [6].
[c] From $\sigma_\gamma=740\pm70$ mb (Ref. [3]) and branchings (Ref. [4]). The 9.5% uncertainty in the σ_γ value is included.
[d] From ^{48}Ca$(\vec{d},t)$ measurements by M. E. Williams-Norton and R. Abegg, Nucl. Phys. **291**, 429 (1977).
[e] Preferred value based on the dip in cross section at back angles in Ref. [6].

compound-nuclear processes, and an estimate of these is provided in the last column of Table I. These estimates are effectively upper limits, obtained by using the most adverse combination of experimental uncertainties. Following the steps outlined in Ref. [1] [see especially Eq. (12) and the definition of various quantities given in that paper], we can extract

$$\frac{\langle\Gamma_{\gamma,\mathrm{CN}}/E_\gamma^3\rangle}{E_\lambda}<-7.3\times10^{-8}\ \mathrm{MeV}^{-3}\ .$$

This estimate is to be compared with the Cameron [7] estimate

$$\frac{\langle\Gamma_{\gamma,\mathrm{CN}}/E_\gamma^3\rangle}{D_{1/2^+}}\approx4.3\times10^{-9}\ \mathrm{MeV}^{-3}\ ,$$

indicating that $E_\lambda>-0.06D_{1/2^+}$ and $\gamma^2_{\lambda(n)}>0.01D_{1/2^+}$ if all compound-nuclear effects can be attributed to a single local level. These are physically reasonable values.

In summary, we have measured the thermal-neutron scattering length of ^{46}Ca and used this value to satisfactorily explain the existing thermal-neutron capture data in terms of a direct neutron-capture mechanism plus small compound-nuclear effects.

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