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Neutron resonance spectroscopy: Calcium*

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Results are presented to 550 keV of high resolution time of flight neutron total cross section measurements using various sample thicknesses of natural calcium. An R-matrix analysis was made to fit the results for the nine strong s levels in ^{40}Ca above 100 keV. A transmission area analysis was made for the 22 weaker observed levels which are also mainly due to ^{40}Ca, but have $l > 0$. We obtain $10^4 S_0 = (2.97^{+1.95}_{-1.05})$ for ^{40}Ca.

[NUCLEAR REACTIONS $^{40}Ca(n, n)$, (n, γ), $E = 0$–550 keV; measured $\sigma_t(E)$; deduced E_0, Γ_n, $ag\Gamma_n$, S_0.]

I. INTRODUCTION

This paper reports the results of the high resolution measurements of the neutron total cross section on natural calcium to 550 keV. It is one of a series of papers[1-9] reporting the results of neutron time of flight spectroscopy measurements using the Columbia University Nevis synchrocyclotron.

The data, to 300 keV, were first analyzed by Singh using an R-matrix formalism for his Ph.D. thesis.[10] Analysis has been subsequently extended to 550 keV. The total cross section data were analyzed using R-matrix multilevel formalism which has been discussed in earlier papers.[1,7] Levels other than the main strong broad ^{40}Ca s levels were analyzed making use of the transmission area analysis which takes into account the Doppler broadening effects and is not affected by the instrumental energy resolution. For some resonances both the techniques of area and shape analysis were used and the results are in agreement within the experimental uncertainty.

These measurements, which emphasize the principal isotope of mass 40 (abundance 96.94% in natural calcium), are of interest since it is a doubly magic nucleus with $Z = N = 20$. Some measurements[11-14] of the total and partial neutron cross section have been reported in the literature using natural and separated isotopes of calcium. Our purpose in making these measurements has been the systematic investigation of the neutron total cross section vs E of the nuclei across the Periodic Table with great precision and to extract the resonance parameters with sophisticated analytical techniques in order to make comparisons with the theoretical predictions as well as with the measurements of other workers where available.

II. EXPERIMENTAL DETAILS AND ANALYSIS PROCEDURES

The data were obtained using our 202.05 m flight path for transmission measurements. A description of the cyclotron operation, the flight path and detector station, and the time of flight (TOF) analyzer was given in our K paper[8] for which data was taken at the same period. The spectrum was covered using 16 000 detection channels, using 40 ns channel widths for the first 1024 channels above ~1290 eV where all of the resonances are situated.

The samples were high purity metallic calcium sealed in polyethylene bags. The thickness of the samples corresponded to $1/n = 1.413$, 4.207, 11.21, and 33.60 b/atom of natural Ca. A spectroscopic analysis of these samples was made by Lucius Pitkin Inc. This analysis showed negligible amounts of impurities, mainly Mg(0.18%) and Sr (less than 0.05%).

In addition to transmission measurements using the above Ca samples, we also made "standard filter" measurements with and without the thickest Ca sample. These filters were 7.6 cm thick iron, 1.3 cm thick copper, and 1.3 cm thick cobalt. They are characterized by having numerous strong s-level transmission dips. Where there is no coincident Ca structure at a filter dip, the Ca cross section at the energy region of the filter-element dip is obtained from the reduction in the (count) area of the filter dip on adding the thick Ca sample. These results are given in Table I. The method has been previously used and described in our paper.[7] It enables proper background subtracted counts vs channel to be made for the measurements for all sample thicknesses of Ca. The σ_t vs E between levels and for the "wings" of the resonances used the thickest sample results, with

TABLE I. σ_t values for Ca resulting from standard filter measurements.

E (keV)	σ_t (b) b/atom	E	σ_t (b)	E	σ_t (b)	E	σ_t (b)
		Using iron filter					
375.3	2.09	270.5	3.02	81.6	1.03	63.8	1.02
273.6	2.47	180.7	1.09	72.7	0.87	23.0	1.72
		Using cobalt filter					
124.0	0.59	39.5	1.27	23.7	1.62	15.3	1.90
49.1	1.24	29.1	1.51	21.3	1.67	12.6	1.98
43.5	1.17	28.6	1.42	21.1	1.71		
		Using copper filter					
9.65	1.94	5.73	2.30	4.30	2.58	2.43	2.55
7.76	2.10	5.15	2.46	3.78	2.39	1.82	2.78
7.44	2.07						

the thinner samples contributing to the behavior of σ_t vs E at resonances. Proper correction was made for the polyethylene wrappers. The resulting σ_t vs E results were analyzed using R-matrix shape fitting, except at the positions of the narrow (or weak) resonances. These latter resonances (usually $l > 0$) were analyzed using our standard area analysis methods[2] which take account of Doppler broadening, and are independent of the experimental energy resolution. The levels analyzed by R-matrix methods were all in the 100 keV to 550 keV region and were mainly broad relative to the experimental energy resolution. The form of the R-matrix treatment is the same as has been described previously.[1,7]

III. RESULTS AND DISCUSSION

Figure 1 shows the measured σ_t vs E below 100 keV for the thick sample. Many channel averages are used to emphasize the σ_t vs E behavior between levels. The curve is an aid to viewing and

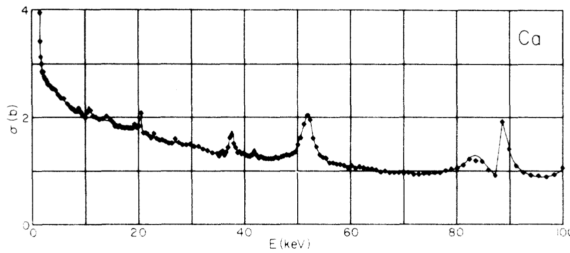

FIG. 1. A plot of a multichannel average σ_t vs E for our thick sample ($1/n = 1.413$ b/atom) data. The emphasis is on the between level σ vs E behavior below 100 keV and not on the weak resonances. The curve is a guide only.

not a theoretical fit. The parameters for all of the levels below 100 keV and for the weaker levels above 100 keV are given in Table II. They were all obtained using our usual area analysis[2] since they are all relatively weak levels.

Figure 2 shows the measured σ_t vs E from 100 to 550 keV, using data for all sample thicknesses as described above. The R-matrix parameters used for the fitting to the behavior of the strong levels are given in Table III, and the "fitted curve" is shown in Fig. 2. These nine levels have Γ_n large compared to the Doppler width ($\Delta \simeq 30$ eV at 400 keV) and usually large relative to the experimental energy resolution. The size of these levels is such that they must all be due to the main isotope, ^{40}Ca, and be $l=0$, $J=\frac{1}{2}$ for which the peak resonance cross section contribution, $0.97\,(4\pi\lambda\!\!\!^{-2})$ $= 2.65/E_0$ (MeV) b/atom. There is a small contribution from the other Ca isotopes, and from ^{40}Ca, $l \neq 0$. Besides the level energy, the main free parameter for each of these strong levels is Γ_n, to fit the level width, the $l=0$ potential scattering, and the $l=0$ resonance-potential interference asymmetry for ^{40}Ca.

Except at the weaker levels, treated in Table II, the fit is good except for a tendency of the experi-

TABLE II. Resonance parameters (using transmission area analysis) for levels (mainly weak) observed in neutron interaction with natural calcium below 550 keV.

E_0 (keV)	A	l	$ag\Gamma_n$ (eV)	E_0 (keV)	A	l	$ag\Gamma_n$ (eV)
10.827 ± 0.006	40	≥1	0.65 ± 0.15	121.3 ± 0.2	40	≥1	14 ± 4
20.404 ± 0.016	40	(0)	6.0 ± 1.0	145.1 ± 0.3	40	≥1	170 ± 40
37.43 ± 0.04	(42)		7.0 ± 3.0	151.0 ± 0.3	40	≥1	23 ± 5
42.04 ± 0.05	40	(0)	0.85 ± 0.20	160.5 ± 0.4	40	≥1	26 ± 6
51.80 ± 0.20	(44)		25.0 ± 5.0	185.1 ± 0.4	40	≥1	29 ± 6
82.55 ± 0.20			20.0 ± 10.0	210.2 ± 0.5	40	≥1	180 ± 40
84.80 ± 0.14	(40)	≥1	3.4 ± 0.7	229.1 ± 0.6	40	≥1	300 ± 60
88.75 ± 0.15	40	0	140 ± 30	385.0 ± 1.3	40	≥1	450 ± 90
90.93 ± 0.15	(40)	≥1	9 ± 2	466.3 ± 1.8	40	≥1	450 ± 100
101.0 ± 0.2	40	≥1	17 ± 4	476.1 ± 1.8	40	≥1	600 ± 125
103.0 ± 1.0			40 ± 10	535.4 ± 2.2	40	≥1	1000 ± 300

mental cross section to be $\lesssim 1$ b/atom above the curve in the regions near the interference minima on the low sides of the levels where $\sigma \approx 0$ for ^{40}Ca, $l = 0$, with only a small contribution ($\ll 1$ b) due to the $l \neq 0$ and from the other isotopes. This effect of the theoretical curve being below the experimental σ_t vs E curve where $\sigma \lesssim 1$ b at minima has also been seen in the results of other workers.[12,13] Table III includes a comparison of our fitted Γ_n values with those of Bowman, Bilpuch, and Newson (Duke).[12]

The measurement of σ_t vs E using an enriched ^{40}Ca sample above 550 keV, and its analysis by R-matrix methods has been reported by Nebe and Kirouac[13] (Karlsruhe cyclotron). Their R-matrix analysis was from 0.55 to 1.26 MeV. They obtain $10^4 S_0 = (2.92^{+1.25}_{-0.67})$, $10^4 S_1 = (0.35^{+0.15}_{-0.08})$, and $10^4 S_2 = (1.9^{+1.0}_{-0.5})$ for the $l = 0$, 1, and 2 strength functions.

Recently, high resolution measurements have been made using the Oak Ridge electron linear accelerator (ORELA) by Johnson *et al.*[15] for σ_t vs E and by Allen and Macklin[16] for the capture cross section vs energy. These results[15,16] were made available to us as plots of σ_t vs E and relative capture yield vs E after our analysis was completed. Johnson *et al.*[15] measured σ_t vs E from 50 keV to about 1 MeV and Allen and Macklin[16] obtained counts vs E from ~3 to 600 keV using a capture detector.

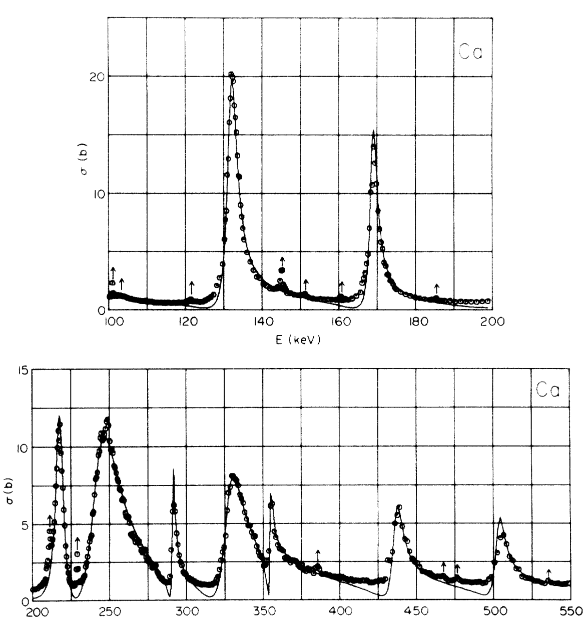

FIG. 2. The R-matrix fit (Table III) to the observed σ vs E from 100 keV to 550 keV emphasizing only the strong $l = 0$ levels in ^{40}Ca. The experimental points use our thick sample results for $\sigma \lesssim 3$ b/atom, but the thinner sample values at the resonances.

The resonances observed below 100 keV, except for that at 88.75 keV, which are narrow are probably due to $l \geq 1$ in ^{40}Ca. The broader weak levels are due to another Ca isotope. Because of the small values of Γ_n for these narrow resonances and the small σ_p, the characteristic $l = 0$ interference effect is likely to be too small to observe. A J^π assignment is however possible via the investigation of radiative resonance capture spectra. Such capture studies using the Ge(Li) detectors have been made by Chan and Bird.[14] On the basis of their γ yields to various known (J, π) low lying levels of ^{41}Ca, they assign the levels at 19 keV and at 39 keV to $l = 0$ in ^{40}Ca, the level at 51 keV to $l = 1$ in ^{40}Ca, and the level at 88 keV to $l = 2$ in ^{40}Ca. Their 19 keV level is probably our 20.4 keV for which we obtain $\sigma_{max} \sim 19$ b/atom and a decrease to half value at ~20 eV on either side. It is hard to explain such a "large" observed σ_{max} for the resonance except for ^{40}Ca. Our weak level at 37.4 keV is spread over many channels with a peak only ~0.4 b/atom above the potential σ in this region. It thus cannot be due to ^{40}Ca since $ag \sim 0.006$ [a = isotopic abundance, g = spin weight factor $(2J+1)/2(2I+1)$]. The experimental level full width is ~1.2 keV. It may correspond to the level at 40 keV in ^{42}Ca (for which $a = 0.0065$) reported by the Duke group[12] for which they give $\Gamma_n = 5.0$ keV. Their Γ_n value is inconsistent with the observed width of our 37.4 keV level.

We identify our level at 42.04 keV as the 39 keV level of Ref. 14. Our 51.80 keV level is the 53.0 keV level in ^{44}Ca of Ref. 12 rather than the "51 keV" level of Ref. 14 which we cannot associate with any of our levels. The 88 keV level of Ref. 14 is probably our 90.93 keV level and our 88.75 keV level is probably the same as the 88 ± 0.25 keV lev-

TABLE III. The multilevel R-matrix fit to the data from 100 keV to 550 keV, shown in Fig. 2, has $\ll 1$ b/atom contribution from other than ^{40}Ca, $l = 0$, $J = \frac{1}{2}$. All fit levels are for ^{40}Ca, $l = 0$, $J = \frac{1}{2}$ for which the following potential scattering parameters (Refs. 1 and 7) were used: channel radius = 4.8 fm, $E_{1/2} = 245$ keV, $A = 0.25$, $B = 0.22 \times 10^{-5}$. The estimated uncertainty in the Γ_n values is <10% for the stronger levels and <15% for the weaker levels. The Γ_n values in the last column are from Ref. 12 for comparison.

E_0 (keV)	Γ_n (keV)	Ref. 12 Γ_n (keV)	E_0 (keV)	Γ_n (keV)	Ref. 12 Γ_n (keV)
131.60	3.17	2.54	326.35	14.2	14.0
168.57	2.44	2.49	354.50	1.61	2.00
216.15	7.37	7.80	435.00	8.24	9.50
241.80	20.0	18.5	501.50	8.11	8.00
290.95	1.80	2.40			

el of Ref. 12. Our levels at 82.55 and 103.0 keV are too broad and weak to be due to ^{40}Ca.

As mentioned above, all of our other weak levels above 100 keV must be due to ^{40}Ca and are probably $l>0$. A calculation of the s-strength function for ^{40}Ca using the 88.75 keV level from Table II, and the levels in Table III, gives $10^4 S_0 = (2.97^{+1.95}_{-1.05})$ for $0 \leq E \leq 550$ keV. This is in excellent agreement with other reported results. Nebe and Kirouac[13] obtain $(2.92^{+1.25}_{-0.67})$ for 28 levels to 1.3 MeV. Bilpuch *et al.*[12] obtain (2.8 ± 1.8) to 280 keV and later results of Duke group by Wilenzick *et al.*[12] obtain (3.4 ± 1.6) for 230 keV $\leq E \leq$ 630 keV. Our quoted uncertainty in S_0 is based on the 0.841 to 0.159 confidence limits as described in Ref. 17.

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