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Single-particle $2d_{5/2}$ strength in the ^{48}Ca + n reaction

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The neutron total cross section of ^{48}Ca + n has been measured up to 10 MeV and analyzed up to 4 MeV using the R-matrix formalism to obtain resonance parameters and potential scattering phase shifts. Very little s-wave neutron strength was observed, and the small cross section $(0.5 \pm 0.2$ b) observed for low-energy neutrons (< 150 keV) can be described by a real Woods-Saxon potential with $V_0 = 47.3 \pm 0.7$ MeV, $r_0 = 1.21$ fm, and $a = 0.66$ fm. Three strong $d_{5/2}$ resonances amounting to 45% of the single-particle width were found in the 0.8- to 2.0-MeV energy region. These results compare well with cross-section predictions from two microscopic calculations. The $p_{1/2}$, $p_{3/2}$, and $d_{3/2}$ resonance strengths are very weak (much smaller than the $d_{5/2}$ strength).

Neutron spectroscopy in the resonance energy region is a sensitive probe[1] of single particle strength for light and closed-shell nuclei. In that context the ^{48}Ca + n reaction is interesting since both particle-core excitation and two-particle–one-hole[2] models predict the occurrence of $\frac{5}{2}^+$ states with large neutron widths for neutron energies below 2 MeV and an absence of s-wave strength, which is in contrast to the situation for lighter Ca isotopes. Several years ago Seibel *et al.*[3] reported neutron total cross-section measurements of ^{48}Ca + n up to 1.4 MeV neutron energy, which did indeed establish the existence of one strong $d_{5/2}$ resonance at 0.956 MeV and did not detect any s-wave resonances. In this paper we present neutron total cross-section measurements for the ^{48}Ca + n reaction which extend the neutron energy range up to 10 MeV. An R-matrix analysis of the data yielded three strong $d_{5/2}$ resonances in the 0.8- to 2.0-MeV neutron energy region, as well as a very small s-wave strength. The results are consistent with those of two microscopic calculations of the ^{48}Ca + n system, one described here and the other by Divadeenam *et al.*[2]

Two neutron total cross-section measurements of ^{48}Ca were performed over the energy interval from 10 keV to 10 MeV by the time-of-flight method using 8-ns bursts and the 200-m flight-path station of the Oak Ridge Electron Linear Accelerator (ORELA). The sample consisted of CaCO$_3$ $(1/N = 126 b/a)$ enriched to 96.0% ^{48}Ca. One measurement used neutrons emitted directly from the ORELA Ta target and was analyzed for energies greater than 500 keV, while the other used water-moderated neutrons and was analyzed below 500 keV. The energy resolution $\Delta E/E$, where ΔE is the full width at half maximum, was ~ 0.0011 $(E + 0.04)^{1/2}$, where E is in MeV. The experimental data corrected for the oxygen and carbon cross sections are shown with statistical uncertainties in Figs. 1 and 2.

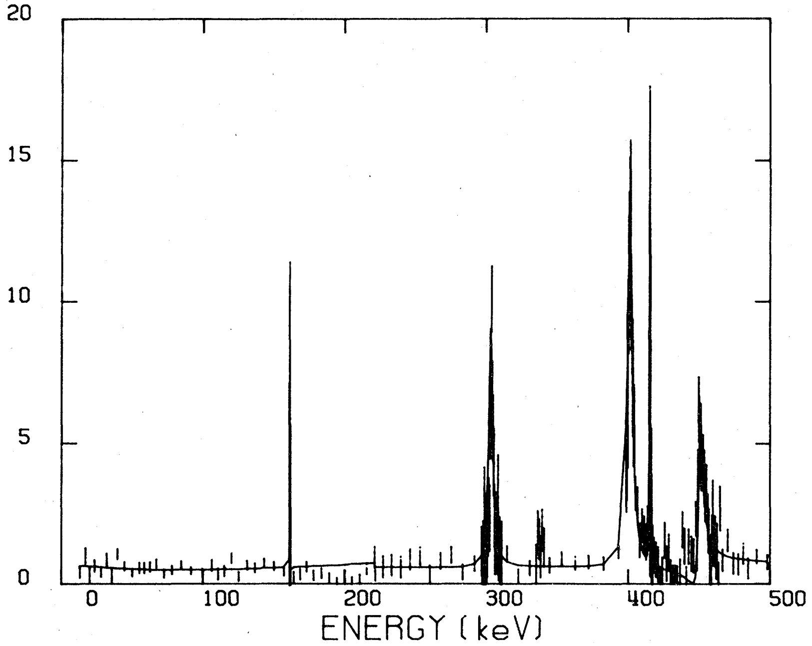

FIG. 1. Neutron total cross section of ^{48}Ca from 10 to 500 keV using water-moderated neutrons. The data are shown with statistical uncertainties; the solid line represents R-matrix parametrization.

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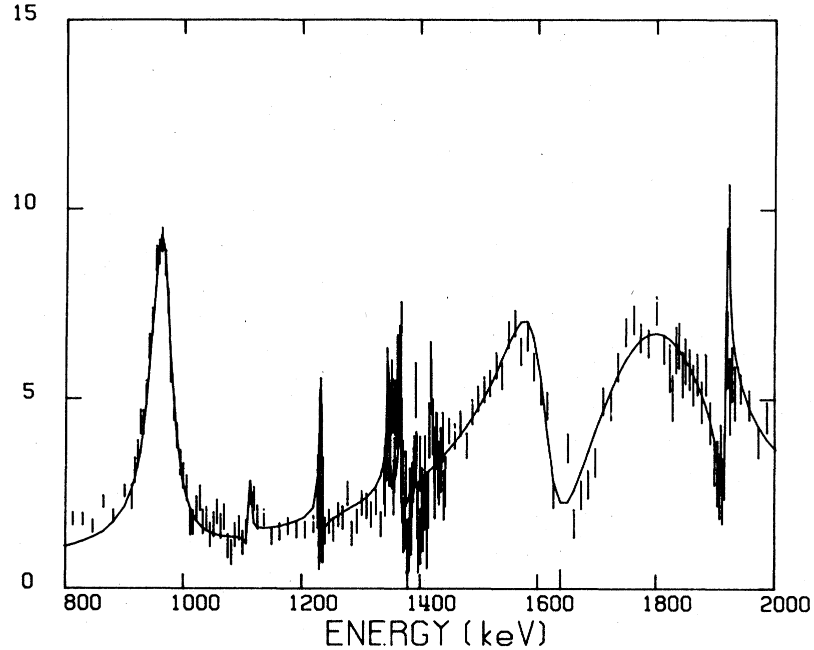

FIG. 2. Neutron total cross section of ^{48}Ca from 0.08 to 2 MeV using Ta target neutrons. The data are shown with statistical uncertainties; the solid line represents R-matrix parametrization.

We fit these data in the R-matrix formalism using the program SAMMY (Ref. 4) for adjusting the off-resonance phase shifts and the widths and energies of the resonances. Values for J and l are assigned for each resonance consistent with the peak-to-valley cross sections and the observed widths. Such assignments are uncertain for resonances narrower than the resolution width, but these are not important for the present discussion. For broad resonances the J values can be assigned at once from the fact that $4\pi g/k^2$ must equal the observed peak-to-valley cross sections. Given J, the l value (i.e., $J\pm\frac{1}{2}$) can usually be assigned from the observed interference pattern or from reasonable limits to the reduced width for the larger l value.

Of particular interest are the J and l assignments for the three broad resonances in Fig. 2 at 0.94, 1.56, and 1.77 MeV. Their peak-to-valley cross sections require all to have $J=\frac{5}{2}$ and their interference patterns require that all have the same l value, either 2 or 3. The $l=3$ or f-wave assignment is ruled out because the resulting sum of reduced widths would exceed the single-particle limit. Hence, these three are each $d_{5/2}$.

The resulting R-matrix parametrization to the total cross section is shown as a solid line in Figs. 1 and 2. The parameters for the $d_{5/2}$ resonances are listed in Table I. Definitive spin and parity assignments could not be made to a few of the very narrow resonances observed below 2 MeV as explained above. The experimental data above ~ 2 MeV are inadequate for a definitive analysis, since spin and parity assignments could not be made from the present data to many of the resonances. The two resonances at 2.4 and 3.1 MeV could be assigned $d_{5/2}$, but there may be other $d_{5/2}$ resonances from 2 to 4 MeV.

Only three small resonances at 161, 304, and 450 keV may be due to s-wave neutrons. The nonresonant cross section for low-energy neutrons (<150 keV) is very small (0.5 ± 0.2 b), corresponding to an R' of 2.0 ± 0.4 fm. This low value for R' can be described by scattering from a real Woods-Saxon potential with $V_0=47.3\pm0.7$ MeV, $r_0=1.21$ fm, and $a=0.66$ fm. The widths of the $p_{1/2}$, $p_{3/2}$, and $d_{3/2}$ resonances are very small (much smaller than the widths of the $d_{5/2}$ resonances).

A more meaningful way of describing the reduced neutron widths is in terms of the single-particle widths and we now describe our method of calculating these quantities using the R-matrix formalism. The boundary radius in the R-matrix formalism is arbitrary, but should be large enough to be outside of the neutron-nucleus polarizing forces. For the present analysis we choose $R=7.5$ fm or $2.05\,A^{1/3}$fm, a radius at which a typical phenomenological Woods-Saxon potential is 1% of its central value. Also, we use constant boundary conditions in order to include the energy-dependent effects of the shift factor. To calculate the $2d_{5/2}$ single-particle (sp) width we use a Woods-Saxon real potential, but modify it by setting the potential to zero for radii >7.5 fm. The $d_{5/2}$ scattering function is calculated for a series of central well depths, which place the $2d_{5/2}$ resonance at several energies within our experimental region. Each function is then expanded in terms of an R function. The $2d_{5/2}$ reduced width is

$$\gamma_{\mathrm{sp}}^2=\frac{\hbar^2}{2\mu r}u^2\ ,$$

where μ is the neutron-reduced mass and u is the value of the radial part of the $2d_{5/2}$ regular wave function evaluated at $r=7.5$ fm and at the resonance energy. The resulting values of γ_{sp}^2 are found to increase with neutron energy, approximately as $\gamma_{\mathrm{sp}}^2=320$ keV + $0.17E_\lambda$, where E_λ is in keV. (At 2540 keV, γ_{sp}^2 equals the Wigner limit, $\hbar^2/\mu r^2$.)

TABLE I. $d_{5/2}$ resonances in ^{48}Ca + n.

Experiment[a]				Theory	
E_λ (keV)	γ_λ^2 (keV)	$\gamma_\lambda^2/\gamma_{\rm sp}^2(E_\lambda)$[b]	$\gamma_\lambda^2/\gamma_{\rm sp}^2(1600)$[c]	E_λ (keV)	Fraction of sp strength
414	2.1	0.006	0.004		
940	63	0.131	0.106		
				1210	0.12
1366	2.3	0.004	0.004		
1560	84	0.142	0.144		
1770	108	0.174	0.182		
				1850	0.21
1923	8.0	0.012	0.014		
				2090	0.25
2440	19	0.026	0.032		
3117	23	0.027	0.039		
Sum of eight resonances		0.52	0.53		
Sum of three strong resonances		0.45	0.43		0.58

[a] The boundary condition B has been set equal to the shift factor S at 1560 keV and the R-matrix radius to 7.50 fm.

[b] $\gamma_{\rm sp}^2(E_\lambda) = 320$ keV $+ 0.17E_\lambda$.

[c] $\gamma_{\rm sp}^2$ (at 1600 keV) = 592 keV.

The single-particle fraction for an observed resonance is the ratio of γ_λ^2 to the value of $\gamma_{\rm sp}^2$ calculated at the resonance energy. Table I lists the resulting percentages. The three strong states corresponding to $E_\lambda = 940$, 1560, and 1770 keV add up to 45% of the single-particle width as compared with 34% of the Wigner limit. Table I also includes the fragments deduced with $\gamma_{\rm sp}^2$ held constant at its value for $E_\lambda = 1600$ keV. Although the individual fragments are changed, the sum is essentially the same.

Both the very weak s-wave strength and the strong $d_{5/2}$ resonances are predicted by a shell-model-in-the-continuum calculation of the ^{48}Ca + n reaction. The formalism is similar to the one adopted in our previous study of the ^{34}S + n system to which we refer the reader for further detail.[1] Briefly, the nuclear wave function is expanded in terms of a complete set of eigenfunctions of an unperturbed Hamiltonian H_0,

$$\psi_E = \sum_{i=0}^{M} b_i(E)\phi_i + \int a_c(E)\chi_E \, dE \ ,$$

where the ϕ_i's are bound states and the χ_E's are unbound states with one nucleon in the continuum. Two types of configurations for ϕ_i and χ_E are calculated: Those dominated by a single shell model configuration and those belonging to multiplets arising from the coupling of a valence neutron to the excited states of the ^{48}Ca core. The low-lying negative parity states belong to the former category and the calculation indicates that the ground and first excited states exhaust, to a large extent, the p strength, in agreement with (d,p) data.[5] The positive parity states are calculated as a combination of $1g_{9/2}, 2d_{5/2}$, $2d_{3/2}$ single-particle (sp) states; $2p_{3/2}$, $2p_{1/2}$ and $1f_{5/2}$ neutron states coupled to the collective 3^- (4.51 MeV) state in ^{48}Ca; and positive parity states coupled to the 2^+ (3.83 MeV) state. None of the $J = \frac{1}{2}^+$ positive parity states appear in a 3-MeV region above the neutron separation energy, in agreement with the absence of strong s-wave resonances in our experimental data. *However, three strong $J = \frac{5}{2}^+$ states are predicted in this energy region.* They represent a total of 58% of the available sp strength, fragmented by the particle-core interaction. These three unbound states are found at 1.21 MeV (12% of sp strength), 1.85 MeV (21%), and 2.09 MeV (25%). These last two resonances have large components of $(3^- \otimes 1f_{5/2})$ and $(0^+ \otimes 2d_{5/2})$ configurations, whereas the first state has mainly a $(3^- \otimes 2p_{1/2}) + (0^+ \otimes 2d_{5/2})$ configuration. The fact that the energies of these three resonances are each about 300 keV greater than those observed could be an indication that the $2d_{5/2}$ centroid, which we calculate to be at an excitation energy of 7.8 MeV (in ^{49}Ca), is in fact slightly overestimated. The remainder of the strength is predicted to lie concentrated in two broad peaks at 3.85 and 5.15 MeV neutron energy.

Several years ago Divadeenam *et al.*[2] calculated $2p$-$1h$ doorway states that should be observed in the ^{48}Ca + n reaction. These calculations predicted two $d_{5/2}$ resonances below 1.5 MeV, but no s-wave resonances in the region. Thus, the qualitative features regarding $l = 0$ and 2 strengths observed in this experiment are corroborated by two model calculations. However, since the $2p$-$1h$ excitations are calculated within a subspace of the particle-core coupling model, the fact that our results are consistent with Divadeenam's work is to be expected. Both model calculations predict the remainder of the $2d_{5/2}$ strength to be found below 5.5 MeV neutron energy. In order to determine the position of the $2d_{5/2}$ centroid more accurately, additional measurements will be made using a thicker sample and better energy resolution, and the analysis will be extended to higher energies.

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