DIRECT NEUTRON CAPTURE IN $Co^{59}(n,\gamma)Co^{60}$†

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The existence of a direct reaction mechanism in competition with compound nucleus formation in the radiative capture of slow neutrons has been predicted by several authors.[1-3] Experimental evidence for this process and a measurement of the direct capture cross section is presented here for the reaction $Co^{59}(n,\gamma)Co^{60}$.

Co^{59} lies in the region of the periodic table where the direct neutron capture is expected to be large. From (d,p) work[4] it is known that Co^{60} has several low-lying p states which are expected to be populated strongly in the direct capture process. From observation of the interference between direct capture and the resonance capture from the 132-eV resonance, the value of the direct capture cross section for the ground-state transition has been measured.

The experiment was performed at the new high-flux beam reactor fast-chopper facility at Brookhaven National Laboratory. Captures were observed in a Co-metal sample 3 in. by 3 in. by 0.25 in. thick, orientated at 45° in the chopper neutron beam, 22m from the chopping point. Events were detected in a 10-cm^3, ac-drifted Ge(Li) detector, positioned 19 cm from the midpoint of the sample. The incident-neutron flight time and the pulse amplitude for each event were recorded on magnetic tape and subsequently analyzed. Events for neutron energies between 2 and 300 eV and γ rays above 4.5 MeV were examined. A typical pulse-height spectrum is shown in Fig. 1. The peak numbers were chosen to correspond to the thermal-capture γ-ray spectrum of Shera and Hafemeister,[5] and peak 1 is the 7.490-MeV ground-state γ ray. The variation with neutron energy of the peak areas of nine of the stronger γ rays, shown in Table I, was determined.

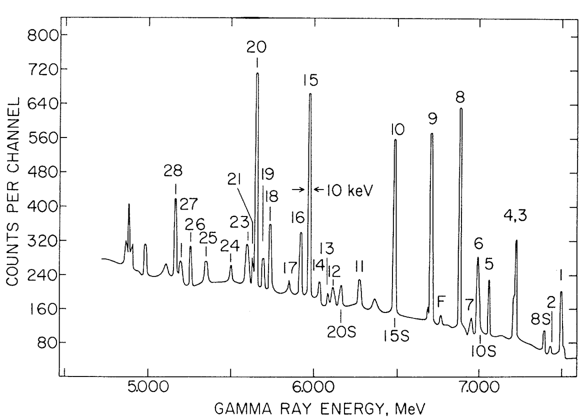

FIG. 1. The $Co^{59}(n,\gamma)Co^{60}$ γ-ray spectrum from 2.2- to 5.5-eV incident neutron energy. The peaks shown are mostly two-escape peaks, except for peaks labeled F and S, which correspond to full energy and single escape. The line numbering is chosen to agree with the thermal capture work of Shera and Hafemeister.

Let us denote by R the ratio of the peak area of a single γ ray to the total γ-ray spectrum for $E_\gamma > 4.5$ MeV. Since this total spectrum contains contributions from at least 40 γ rays, it is assumed to be proportional to the capture cross section. If $\sigma_{n\gamma f}$ is the partial cross section for emission of the γ ray to the final state f, and $\sigma_{n\gamma}$ is the capture cross section, then

$$R \propto \sigma_{n\gamma f}/\sigma_{n\gamma}.$$

If R is normalized to unity at the position of the 132-eV resonance, the resultant data points of Fig. 2 are obtained for the ground-state γ ray. For seven of the γ rays, little variation with energy is observed. For the ground-state γ ray and the 7.21-MeV doublet, however, the relative intensity is significantly larger at a few electron volts than in the 132-eV resonance.

Let us interpret the energy variation of R for the ground-state transition: According to

Table I. Relative γ-ray intensities for the 2- to 5-eV region. Each γ-ray intensity was normalized to unity in the 132-eV resonance.

E_γ (MeV)	I_γ(2-5 eV)
7.49	1.35 ± 0.08
7.21(2)	1.48 ± 0.05
7.055	1.02 ± 0.05
6.985	0.97 ± 0.04
6.877	1.06 ± 0.04
6.705	0.91 ± 0.04
6.485	1.05 ± 0.03
5.743	0.98 ± 0.04
5.662	1.00 ± 0.04

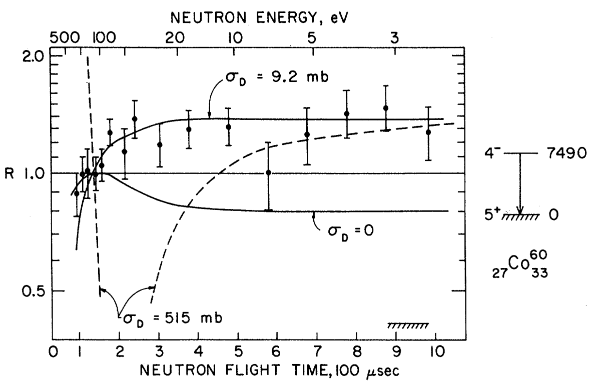

FIG. 2. The energy variation of $R \propto \sigma_{n\gamma f}/\sigma_{n\gamma}$ for the ground-state transition. The curve $\sigma_D = 0$ would be the expected variation after correction for the presence of the 3^- bound state, with no interference assumed between the resonance and direct reaction amplitudes. The curves $\sigma_D = 9.2$ mb and $\sigma_D = 515$ mb result from constructive and destructive interference below the 132-eV resonance.

polarized-neutron measurements of Schermer,[6] 22% of the thermal absorption cross section is due to a bound state with spin and parity 3^-. The remainder, due to 4^- capture, is almost entirely accounted for by the 132-eV 4^- level, other known states contributing less than $\frac{1}{2}$%.[7] If electric dipole transitions are assumed, 3^- capturing states cannot contribute to $\sigma_{n\gamma f}$ for the ground-state transition. Correcting for the bound-state contribution to $\sigma_{n\gamma}$, the variation of R should follow the solid curve $\sigma_D = 0$ of Fig. 2 using the usual Breit-Wigner single-level formula. The failure of the data to follow that curve indicates the presence of an interference effect.

We assume that the partial capture cross section contains a direct-interaction amplitude which interferes with the 132-eV resonance amplitude according to the form

$$\sigma_{n\gamma f} = \pi \lambda_0 \lambda g \left| A_0 + \frac{(\Gamma_n{}^0 \Gamma_{\gamma f})^{1/2}}{(E - E_\gamma) + i\Gamma/2} \right|^2,$$

where A_0 is the direct amplitude and the index 0 means evaluation at 1 eV, and that the interference terms are negligible in $\sigma_{n\gamma}$. The value of the direct capture cross section with constructive interference is

$$\sigma_{n\gamma f}(1\ \mathrm{eV}) = 9.2 \pm 2.4\ \mathrm{mb}$$

and gives the upper solid curve of Fig. 2. The dotted curve, assuming destructive interference, is ruled out by the data.

According to the calculations of Lane and Lynn,[1] the direct capture cross section for cobalt at 1 eV is

$$\sigma_{\mathrm{direct\ capture}} = 39.2\theta_n{}^2\ \mathrm{mb}$$

where $\theta_n{}^2$ is the final state reduced width. Using (d,p) results[4] which indicate that about $\frac{1}{4}$ to $\frac{1}{3}$ of the $P_{3/2}$ strength resides in the ground state, we conclude that the experimental result is in excellent agreement with this calculation.

No strong statement can be made about the behavior of the 7.21-MeV γ-ray doublet because of the unknown contribution of the 3^- bound level.

Can any interference mechanism other than direct capture explain this experiment? One possibility is resonance-resonance interference between the 132-eV 4^- level and a bound level of the same spin. However, no such 4^- bound level is required to fit the total cross-section measurements to several kilovolts.[8] Furthermore, a strong argument against the presence of a nearby 4^- bound state is presented by the failure to observe an interference effect for seven of the strongest γ rays observed in the present experiment. Such interference effects would be expected to be present for all γ rays, not just the ground-state γ ray. Thus, there is strong evidence against the presence of a 4^- bound level whose amplitude could simulate a direct amplitude in the region just above the neutron binding energy.

The present experiment, therefore, constitutes unequivocal evidence for the presence of a direct capture component in the radiative capture cross section.

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COMPOSITE MODELS OF HADRONS AND HIGH-ENERGY SCATTERING*

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We have applied the assumptions of simple additivity of quark amplitudes and SU(2) invariance to derive relations among hadron total cross sections, assuming hadrons to be composites of integral charge particles. Our results are compared with those obtained from the conventional quark model.

The quark model[1] of hadrons,[2] together with the assumption[3] of simple additivity of quark amplitudes, has recently been applied[3] with somewhat remarkable success to the derivation of relations between hadron-hadron total cross sections. Within the framework of SU(3) symmetry, the quark model is the simplest one that can be used to construct hadrons. The price paid for this simplicity is that one has to assume that quarks are fractionally charged.[4] Other fundamental[5] particle models[6] that do not require fractionally charged particles have been suggested. These, on the other hand, require more than just one fundamental SU(3) triplet as building block of hadrons. In these models all hadrons are assumed to be composites of two sets of particles: either an SU(3) singlet b and a triplet t,[7] or two triplets α and β [6] each transforming like an irreducible three-dimensional representation of SU(3). These are the two simplest integral-charge particle models possible. For convenience we have summarized the relevant properties of the quark model, the singlet-triplet model, and the triplet-triplet model in Table I.

The assumption[3] of simple additivity of fundamental particle amplitudes states that the forward scattering amplitude for any reaction is simply the sum of all possible contributing two-body FP-FP scattering amplitudes.[5] This assumption has been discussed in some detail by Kokkedee and Van Hove.[3] We have applied it (together with the optical theorem) to derive relations between hadron-hadron total cross sections assuming hadrons to be composites of integral charge particles, and compared the

Table I. Properties of fundamental particle models. Q = charge; I = isospin; I_3 = third component of isospin; N = baryon number. F and B indicate Fermi and Bose statistics. z is an integer (+, −, or 0). The subscripts 1 and 8 indicate singlet and octet representations, respectively, of SU(3).

	(A) Quark model (q_1,q_2,q_0)	(B) Singlet-triplet model b, (t_1,t_2,t_0)	(C) Triplet-triplet model $(\alpha_1,\alpha_2,\alpha_0)$, $(\beta_1,\beta_2,\beta_0)$
Q	$(\frac{2}{3},-\frac{1}{3},-\frac{1}{3})$	$0,\ (z+1,z,z)$	$(z+1,z,z),\ (z+1,z,z)$
I	$(\frac{1}{2},\frac{1}{2},0)$	$0,\ (\frac{1}{2},\frac{1}{2},0)$	$(\frac{1}{2},\frac{1}{2},0),\ (\frac{1}{2},\frac{1}{2},0)$
I_3	$(\frac{1}{2},-\frac{1}{2},0)$	$0,\ (\frac{1}{2},-\frac{1}{2},0)$	$(\frac{1}{2},-\frac{1}{2},0),\ (\frac{1}{2},-\frac{1}{2},0)$
N	$(\frac{1}{3},\frac{1}{3},\frac{1}{3})$	$1,\ (n,n,n)$	$(n,n,n),\ (n+1,n+1,n+1)$
Statistics	F	F, F or F, B	F, B or B, F
Spin-$\frac{1}{2}$ octet ($N=1$)	$\lvert qqq\rangle_8$	$\lvert b\bar{t}t\rangle_8$	$\lvert\bar{\alpha}\beta\rangle_8$
Spin-0 pseudoscalar mesons	$\lvert\bar{q}q\rangle_{1,8}$	$\lvert\bar{t}t\rangle_{1,8}$ or $\lvert\bar{b}b\rangle_1$	$\lvert\bar{\alpha}\alpha\rangle_{1,8}$ or $\lvert\bar{\beta}\beta\rangle_{1,8}$
$\lvert p\rangle$	$\lvert q_1q_1q_2\rangle$	$\lvert b\bar{t}_0t_1\rangle$	$\lvert\bar{\alpha}_0\beta_1\rangle$
$\lvert n\rangle$	$\lvert q_1q_2q_2\rangle$	$\lvert b\bar{t}_0t_2\rangle$	$\lvert\bar{\alpha}_0\beta_2\rangle$
$\lvert\pi^+\rangle$	$\lvert\bar{q}_2q_1\rangle$	$\lvert\bar{t}_2t_1\rangle$	$\lvert\bar{\alpha}_2\alpha_1\rangle$ or $\lvert\bar{\beta}_2\beta_1\rangle$
$\lvert K^+\rangle$	$\lvert\bar{q}_0q_1\rangle$	$\lvert\bar{t}_0t_1\rangle$	$\lvert\bar{\alpha}_0\alpha_1\rangle$ or $\lvert\bar{\beta}_0\beta_1\rangle$