cels and, after integrating over k_p', we are left with

$$M=C\langle\Psi_p^{(-)}\varphi_f,(V_n+V_p)\Psi_0\rangle.$$

This is the prior form of the Born approximation and is equal to the post form (8) by Hermiticity. The operator T_p is Hermitian between the final-state wave function and Ψ_0 (in contrast to Ψ), since their overlap is bounded at infinity in the variable r_p. Thus operation of $H-E$ on the two wave functions gives equal prior and post forms of the Born approximation with distorted waves in the final state.

In the above we have avoided integrating over r_p before integrating over k_p'. Thus the "sudden" approximation leads to zero for the direct-reaction amplitude even when M_2 is evaluated correctly.

After making the two approximations, the neglected terms in Eq. (6) are given by Eq. (5). Another way to show that these do not correspond to a direct reaction is to examine the neutron matrix element in Eq. (5). We may regard $\Psi_n^{(+)}(Q',r_n)$ as the projection on χ_0 of the complete wave function $\Psi_i(\xi,r_n)$ for a neutron incident on the target nucleus with wave function χ_0. Both φ_f and Ψ_i then represent eigenstates of $H_0+T_n+V_n$ with different energies and are thus orthogonal. Introducing the complete set of states χ_λ, we have

$$\langle\langle\varphi_f,\chi_0\rangle,\langle\chi_0,\Psi_i\rangle\rangle=-\sum_{\lambda\neq 0}\langle\langle\varphi_f,\chi_\lambda\rangle,\langle\chi_\lambda,\Psi_i\rangle\rangle.$$

Thus the comments after Eq. (6) apply and M_2, given by Eq. (5), does not represent a direct reaction.

In conclusion we see that the "sudden" approximation for Ψ is invalid for rearrangement collisions when used in matrix elements such as given by Eq. (3). It could be used for Ψ in matrix element (2), but then the transition to Eq. (3) is no longer possible and further evaluation is difficult. The use of the sudden approximation in elastic scattering[8] is not invalidated by the above arguments.

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THRESHOLD PHOTONEUTRON CROSS SECTIONS FOR IRON AND BISMUTH*

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Photoneutron cross sections were measured for iron and bismuth for photon energies up to 15 keV above threshold by the neutron time-of-flight technique. A number of nuclear levels were observed. Nuclear properties which can be derived from the data include ground-state gamma-ray transition widths, gamma-ray strength functions, and average level spacings.

This Letter presents the results of a first attempt to make use of the time-of-flight technique to measure photoneutron cross sections near threshold with good resolution. Such measurements allow one to explore in detail the properties of many individual nuclear levels just above the neutron separation energy in all stable nuclei, and thus to investigate several classes of systematics of the excited nucleus. Also, the multipolarity and strength of the electromagnetic transitions which excite the nuclear states can be determined when the technique is applied properly. Such information is difficult to obtain in the 6- to 10-MeV energy range.

Previous studies of neutron-capture gamma-ray spectra,[1] scattering of nearly monoenergetic photons,[2] and resonance fluorescence with a continuous bremsstrahlung source[3] all suffer from inadequate gamma-ray resolution;

and although the resolution required can be obtained by varying the energy of neutron-capture gamma rays from a source inside a reactor,[4,5] the range of energy variation possible with these techniques is small.

Consider the case of the reaction $Fe^{56}(\gamma,n)Fe^{55}$ (see Fig. 1). If we irradiate Fe^{56} with bremsstrahlung having a maximum energy between 11.21 and 11.62 MeV, we can identify unambiguously all resonances seen in the neutron energy spectrum as representing levels in Fe^{56} having an excitation energy equal to the neutron binding energy plus the neutron energy (corrected for the photon and neutron momenta and the recoil of the residual Fe^{55} nucleus). Thus, we can examine in great detail the band of levels just above the (γ,n) threshold in Fe^{56} by the well-developed time-of-flight technique of neutron spectroscopy. The incident gamma-ray intensity is nearly the same for all resonances in this interval, since the photon energy changes by only 0.2%. The idea is not entirely a new one and there has been an attempt to exploit it before[6]; the new departure introduced here is to look for resonances in the neutron energy spectrum in the very low-energy region from zero to a few tens of kilovolts with a highly efficient neutron detector. This method, as applied here, is capable of neutron energy resolution of a few tens of electron volts for incident photon energies of about 10 MeV. Since the s-wave neutron strength function peaks near $A=50$ and the p-wave strength function is a minimum there,[7] p-wave neutron emission is strongly inhibited relative to s-wave, particularly if the studies are restricted to neutrons with energies of only a few keV. The $\frac{3}{2}^-$ ground state of Fe^{55} then can be reached only by neutron transitions from 1^- or 2^- states in Fe^{56}. This implies either electric dipole or magnetic quadrupole photon absorption by the 0^+ Fe^{56} target. The Moszkowski transition rates[8] predict that the latter will be inhibited by a factor of 10^4 relative to electric dipole absorption. Therefore, the states seen in this experiment can be assigned a spin and parity of 1^-; in this way it is possible to use the electromagnetic selection rules as a spectroscopic tool.

Measurements were made on both iron and bismuth. The beam from the Livermore electron linear accelerator was collimated and energy analyzed with a bending-magnet-and-slit arrangement and then allowed to strike a bremsstrahlung-producing target thick enough so that

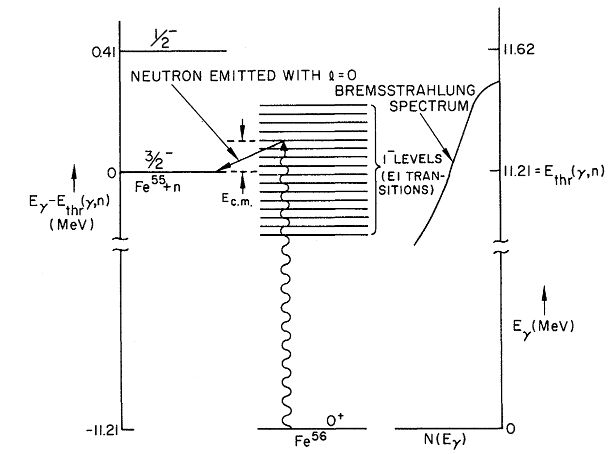

FIG. 1. Schematic energy-level diagram for idealized threshold photoneutron experiment on Fe^{56}.

the primary electron beam was stopped completely in the target. This insulated target then was used as a crude beam monitor as well. The bremsstrahlung photons in turn irradiated the neutron-producing sample, which was placed along the line of sight of the neutron detector. The angle between the neutron flight path and the bent electron beam (and hence the photon beam) was 135°. The 3-in. diam. sample was placed at an angle of 67.5° with respect to each of the above. The neutron detector consisted of a B^{10}-loaded liquid scintillator 5 in. in diameter by 0.625 in. thick which was viewed by a 5-in. EMI 9579B phototube. The detector efficiency varied from 0.30 at $E_n=1$ keV to 0.21 at 15 keV.[9] In this first attempt to apply the method, the ideal conditions on the bremsstrahlung end-point energy shown in Fig. 1 were not achieved completely. The energy resolution of the electron beam is determined mainly by the magnet and slit parameters, and was chosen such that, for example, for a mean electron kinetic energy $E_e=12.5$ MeV (the iron case), half of the electrons which strike the bremsstrahlung target are within 200 keV of E_e. For further experimental details see Table I.

The data are presented in Figs. 2(a) and 2(b) which show the (γ,n) cross section versus neutron energy, E_n, for iron and bismuth, respectively. The background under the resonance structure is felt to be caused chiefly by gamma rays from activation of the target, and probably could be reduced substantially by means of pulse-shape discrimination. The absolute cross-section determination might contain sys-

Table I. Experimental parameters.

Neutron sample	Sample thickness (in.)	$E_{thr}(\gamma,n)$ (MeV)	Bremsstrahlung target	Target thickness (in.)	E_e (MeV)	Bremsstrahlung conversion efficiency (10^{-8} photon/electron sr eV)	Ω_γ (sr)	Average beam current (μA)	W (μsec/channel)	Beam burst width (nsec)	Run time (h)
Fe	1.017	11.21[a]	Al	1.015	12.5	1.57	0.025	36.8	0.125	500	4
Bi	0.502	7.43	Ag	0.249	11.0	4.64	0.133	6.4	0.0625	40-100	34

[a] Fe^{56} (isotopic abundance 91.7%).

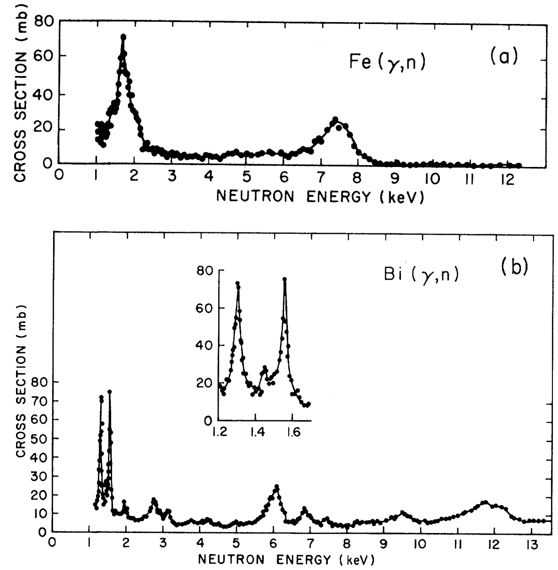

FIG. 2. Absolute cross section for threshold photoneutrons from iron and bismuth as a function of laboratory neutron energy $[\sigma = 4\pi(d\sigma/d\Omega)|_{135°}]$.

tematic errors of up to 50%. The time resolution varies from 15 to 30 nsec/m ($\lesssim$5 channels). An isotropic angular distribution was assumed for the photoneutrons.

We have attempted to extract from these data meaningful values of the ground-state transition width for gamma rays, $\Gamma_{\gamma 0}$; the corresponding gamma-ray transition strength function, $\langle\Gamma_{\gamma 0}/D\rangle$; and the average level spacing of the excited nucleus, D. The analysis for $\Gamma_{\gamma 0}$ is based on the Breit-Wigner single-level formula for photon-induced reactions. The area A under a resonance is given to a good approximation by

$$A = 2\pi^2 \lambda\!\!\!^{-2} g \Gamma_{\gamma 0}\Gamma_n/\Gamma \simeq 2\pi^2 \lambda\!\!\!^{-2} g \Gamma_{\gamma 0},$$

where $\lambda\!\!\!^{-}$ is the photon wavelength divided by 2π, Γ_n is the width for neutron emission, Γ is the total width of the excited state, and g is a statistical factor. Values for A and $\Gamma_{\gamma 0}$ and details of the strength function and average level spacing calculations appear in another report.[10] The value of $\langle\Gamma_{\gamma 0}/D\rangle$ found for iron is comparable in magnitude to that computed from the low-energy wing of a Lorentz-line fit to the giant-dipole resonance, while the value found for bismuth is an order of magnitude lower than that computed from such a fit.

We conclude that the power of this technique is such that even with a crude measurement such as the one described here, worthwhile information can be obtained on the parameters of many individual states just above the photoneutron threshold and on several statistical properties of these states. Bertozzi, Sargent, and Turchinetz,[6] who performed measurements at higher energies, and Bollinger,[11] who has considered the application of this technique to the problems now studied primarily by neutron resonance spectroscopy, have pointed out that nuclei in any mass region can be investigated with adequate precision by using a high-current pulsed electrostatic accelerator operating in the 5- to 8-MeV range as the source of electrons. For light nuclei, however, for which the spacing between the levels near the ground state is large, the poorer electron energy resolution of a linear accelerator is a less stringent restriction on the application of the technique.

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COUPLED-CHANNEL, SEVERAL-FORCE MODEL FOR A BARYON ANTIDECUPLET*

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Recent experiments[1] showing structure in K^+p and K^+d total cross sections have led us to examine in some detail the predictions of dynamical calculations for these systems. We find that two of the usual resonance mechanisms (baryon exchange and inelastic coupling) must be considered and yield a resonant $\underline{10}^*$ SU(3) multiplet with $J^P=\frac{1}{2}^+$ in the mass range 1.5 to 2 BeV.[2]

Baryon (B) and decuplet (D) exchanges in pseudoscalar meson-baryon (PB) scattering were studied by Martin and Wali,[3] who obtained a consistent set of particles, with a limited range of d/f ratios, comprised of the B octet ($\frac{1}{2}^+$), the D decuplet ($\frac{3}{2}^+$), and two unitary singlets, $\frac{1}{2}^-$ and $\frac{3}{2}^-$, all of which can be identified with observed particles. Their forces were attractive in the $\underline{10}^*$ states with $\frac{1}{2}^+$, but a resonant multiplet could not be conclusively established. The phase-shift analysis of Frye and Warnock,[4] based on the KN data of Stenger et al.,[5] allow for a $T=0$, $\frac{1}{2}^+$ phase shift ≈40° around 800 MeV/c. Lovelace[6] suggested that this system should resonate around 1300 MeV/c, and that the associated antidecuplet should include the Roper resonance[7] as well. Lovelace,[6] and others,[8] noted the importance of inelastic effects (notably, production involving a strongly interacting s-wave pion pair) in connection with the Roper resonance.

Cook and Lee,[9] and Auvil and Brehm[10] have proposed various inelastic models of various higher πN resonances. These are based on the effect of strong absorption when the quan-