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ANGULAR DISTRIBUTIONS FOR THE INVERSE PHOTONUCLEAR PROCESS IN Si^{28} IN THE EIGENCHANNEL REACTION THEORY*

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Using the eigenchannel reaction theory we performed coupled-channel calculations for Si^{28} and computed the differential cross section for Al$^{27}(p,\gamma_0)$Si^{28} over the energy range 6 MeV $< E_p <$ 16 MeV. The obtained angular distributions are nearly constant over the whole energy range and agree with the experiment in that they are almost isotropic. Thus, it seems that in this framework we can give a natural explanation for the peculiar behavior of the Al$^{27}(p,\gamma_0)$Si^{28} cross section.

During the past four years the inverse photonuclear process in Si^{28}, and, in particular, the reaction Al$^{27}(p,\gamma_0)$Si^{28} leading to the ground state of Si^{28} has gained great interest because of its surprising feature that the gamma-ray angular distribution approximately remains constant throughout the region of the giant resonance, in spite of the fact that the yield curves show considerable structure, especially for high-energy resolution.[1-3] As a matter of fact, the Al$^{27}(p,\gamma_0)$Si^{28} angular distributions are almost isotropic through the whole energy range. This behavior distinguishes them clearly from γ-ray angular distributions observed for B$^{11}(p,\gamma)$C^{12,12*}[4] or F$^{19}(p,\gamma)$Ne^{20,20*},[5] for example, showing a rather pronounced energy-dependent peaking.

It was demonstrated in Ref. 3 that the Al$^{27}(p,\gamma_0)$Si^{28} 90° yield curve exhibits Ericson fluctuations which can be characterized by peaks of 50-keV widths which are spaced about 100 keV apart. Figure 8 of Ref. 3 shows that the integrated (p,γ_0) cross section smoothed by using an averaging interval of 600 keV has a remarkable intermediate structure with peaks at 18.2-, 19.0-, 19.8-, and 21.3-MeV excitation energy, respectively. These intermediate-resonances are expected to be predictable by a 1p-1h treatment of the compound nucleus. From the conventional shell-model calculation of Bolen and Eisenberg,[6] however, one could

obtain no indication for the constancy of the γ-ray angular distribution. Therefore, Singh et al.[3] concluded that the 1$^-$ nuclear eigenstates of Si^{28} which produce the intermediate resonances should not be responsible for the angular distribution, but that it would result from some sort of single-proton configuration, characteristic for the giant resonance as a whole.

We do not agree with this view, but intend to show that the observed angular distribution can, indeed, be explained by a shell-model calculation in the 1p-1h Tamm-Dancoff approximation provided that the particle continua are treated carefully. The procedure we actually use for accurately solving the coupled-channel-continuum problem is known as the eigenchannel method[7] and was first worked out and successfully employed in the case of O^{16}.[8-10]

The basic idea of the eigenchannel method is to construct a complete set of degenerate nuclear scattering states to a given excitation energy E_{exc} of the compound system; thus they are eigenfunctions of the nuclear 1p-1h Hamiltonian as well as of the S matrix. These eigenchannel functions contain real radial wave functions in the various channels. Therefore, boundary conditions on a distant surface can easily be formulated and a discretization of the particle continuum states can be obtained. Then, the nuclear Hamiltonian can be diagonalized similarly as for pure bound configura-

tions. The coupling between the diverse channels occurs via the residual interaction. The S matrix for particle-particle reactions can be expressed in terms of the "eigenphases" $\delta^{(\nu)}$ and asymptotic amplitudes $V_c{}^{(\nu)}$ of the eigenchannel functions (which are actually the eigenvectors of the S matrix) as follows:

$$S_{cc'} = \sum_\nu V_{c'}{}^{(\nu)} \exp[2i\delta^{(\nu)}] V_c{}^{(\nu)}.$$

The eigenphases $\delta^{(\nu)}$ are determined by those common phases δ in the various open channels for which the given excitation energy E_{exc} coincides with some eigenvalue of the nuclear problem. The amplitudes $V_c{}^{(\nu)}$ follow simultaneously.[7,10]

The photon channels are included by perturbation theory. For the integrated dipole disintegration cross section, one obtains, e.g.,

$$\sigma_{\alpha,\text{dis}}$$

$$= 4\pi^2 (e^2/\hbar c)\hbar\omega \sum_{lj} |\sum_\nu \exp[i\delta^{(\nu)}] V_{\alpha l j}{}^{(\nu)} \mathfrak{M}^{(\nu)}|^2,$$

where $\mathfrak{M}^{(\nu)}$ is the dipole matrix element for a transition from the νth eigenchannel state into the particle vacuum. The subscript α characterizes the residual nucleus, i.e., a $1d_{5/2}$ proton hole (with -11.6-MeV energy) for the (γ, p_0) cross section in the case of Si^{28}. The radial single-particle wave functions have been computed in a Woods-Saxon potential

$$V(r) = V_c \rho(r) - U_{\text{so}} (\vec{l}\cdot\vec{\sigma})\frac{1}{r}\frac{d\rho(r)}{dr} + V_{\text{Coul}},$$

where

$$\rho(r) = \{1 + \exp[(r-R_0)/t]\}^{-1}.$$

The depth $V_c = -55$ MeV and the radius $R_0 = 3.85$ F. The diffuseness was chosen to be $t = 0.75$ F and the strength of the spin orbit force was $U_{\text{so}} = -11.3$ MeV. The obtained level scheme for the bound proton and neutron states, together with the empirical[6] neutron level scheme, is presented in Fig. 1. For the comparison of the theoretical and empirical level positions, only states above the Fermi surface are of significance, since the hole energies in the energy matrix are replaced by the empirical values anyhow. The matching radius was chosen as large as 12 F and, therefore, should not affect the results. The total number of particle-hole channels considered was 14, i.e., sev-
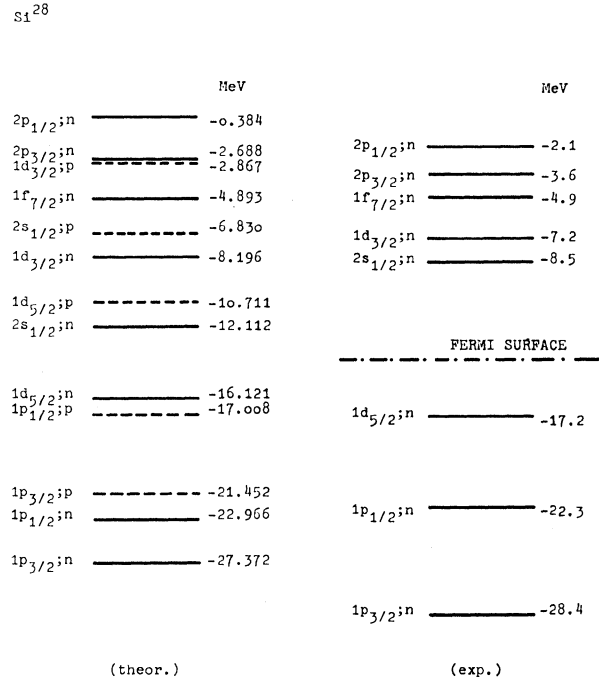
Si^{28}

FIG. 1. Theoretical single-particle level scheme for the employed Woods-Saxon potential specified in the text compared with the empirical neutron level scheme.

en neutron and seven proton configurations. They are the same configurations as considered in Ref. 6. In each channel three different radial quantum numbers were admitted leading to a 42×42 energy matrix. The strength of the zero-range two-body residual force was chosen to be -1000 MeV F^3. A Soper-type exchange mixture was used.

Gamma-ray angular distributions for the reaction $Al^{27}(p, \gamma_0)Si^{28}$ have been calculated in steps of 0.5-MeV excitation energy (Fig. 2). They vary little with energy, especially for the higher proton energies E_p. Besides, they are isotropic within about 20%. Thus our results strongly resemble those of Fig. 5 in Singh et al.[3] However, since we did not account for the small admixtures of quadrupole radiation, the calculated angular distributions are exactly symmetric about 90°. In addition, there is also the difference that the maximum of the angular distribution does not move to 90° at higher excitation energy. But, this, of course, can simply be a consequence of our special parameter choice.

The result exhibited in Fig. 2 is not trivial, because in the case of O^{16}, for example, we found angular distributions[10] which were high-
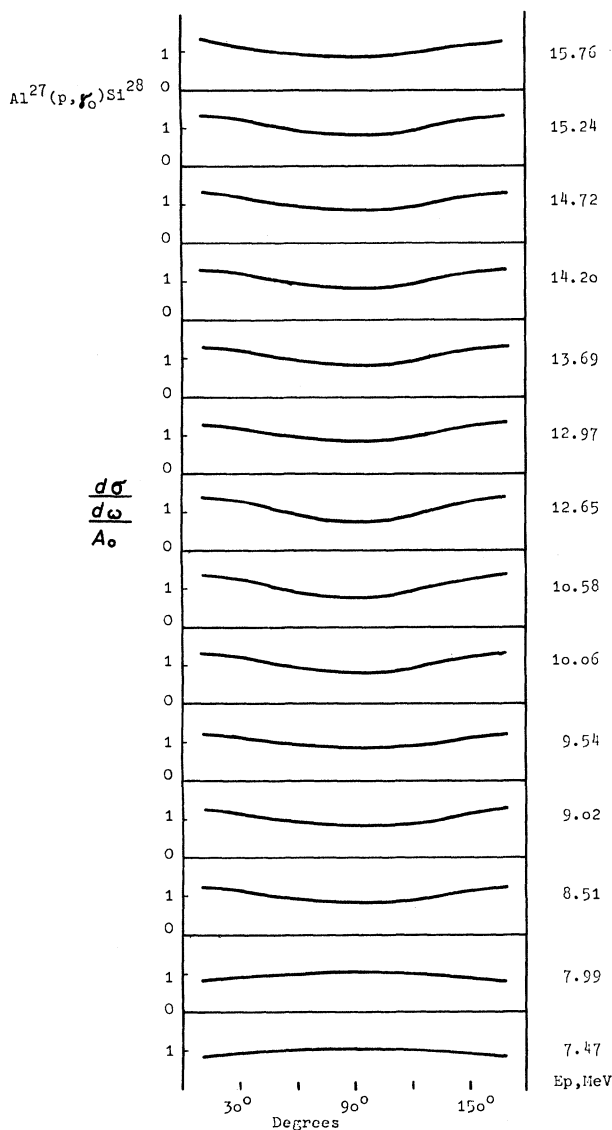
FIG. 2. Calculated angular distributions of the ground state gamma ray from the reaction $Al^{27}(p,\gamma)Si^{28}$.
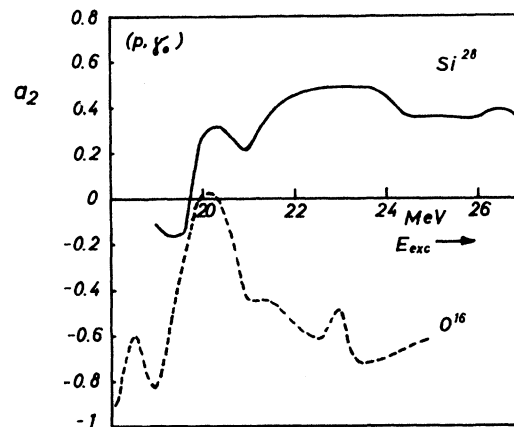

FIG. 3. Comparison of the a_2 parameter of the angular distributions of Si^{28} and O^{16} as a function of energy. Note the relative constancy and smallness of the a_2 parameters of Si^{28}.

these values with energy lead to the energy-dependent angular distributions in this case.

Finally, we mention that for the integrated $Al^{27}(p,\gamma_0)Si^{28}$ cross section we obtained agreement with the smoothed experimental curve of Fig. 8 in Singh et al.[3] in the considered energy range, insofar as our main peak also occurred at about 20 MeV and there seemed to be structure below 19 MeV and between 22 and 24 MeV (instead at 21.3 MeV). However, the theoretical resonance at 20 MeV turned out to be only 0.5 MeV wide, whereas the main experimental peak has a width of about 1 MeV.

Nevertheless, our calculation seems to prove that a careful treatment of the continuum together with the accurate interference of the various resonances allows a natural explanation of the peculiar behavior of the $Al^{27}(p,\gamma_0)Si^{28}$ angular distribution within the framework of the familiar 1p-1h shell model.

ly energy dependent and, to some extent, reflected the intermediate structure of the yield curves. In Fig. 3 this fact is illustrated by a plot of the a_2 angular distribution parameter for Si^{28} and O^{16} as a function of energy. This quantity is a much more sensitive measure for the constancy of the angular distributions. Values of a_2 which are small and nearly energy independent characterize nearly constant energy-dependent angular distributions. It is noticed from Fig. 3 that $a_2 \approx 0.3$ for Si^{28}, while it is varying between $a_2 = -0.8$, $a_2 \approx 0.00$, and again $a_2 = -0.6$ to $a_2 = -0.8$ for O^{16}. The relative large a_2 values for O^{16} and the change of

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