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Spectrum of the Reaction $^{208}\mathrm{Pb}(n, \gamma)^{209}\mathrm{Pb}$ and Semidirect Capture Theory[*]

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Measurements of the spectrum of γ rays from the reaction $^{208}\mathrm{Pb}(n,\gamma)^{209}\mathrm{Pb}$ have been made at incident neutron energies of 9.2, 11.2, and 13.2 MeV. The observed spectral shapes disagree strongly with the predictions of compound-nuclear theory and agree quite well with those predicted by semidirect (collective) capture theory.

The earliest theory of radiative nucleon capture involved the *compound-nuclear* reaction mechanism. This theory explained the capture of low-energy nucleons quite well. However, the situation for the capture of nucleons with energies greater than 4 or 5 MeV is not as satisfactory. Upon comparing the results of the theoretical calculations with experiment, particularly measurements of 14-MeV neutron capture cross sections, serious discrepancies were found.[1] The calculated magnitude of the total radiative cross sections was usually 1 or 2 orders of magnitude low for low-mass nuclei and falls below the observed values by 4 to 5 orders of magnitude for heavy nuclei. In order to explain these differences, several authors[2-5] proposed a reaction mechanism based on a *direct* capture process, in which an incident nucleon moving in the optical potential of the target nucleus plus nucleon makes a radiative transition to a lower state. Unfortunately, this mechanism leads to a cross section about an order of magnitude lower than the lowest neutron capture cross section.[6] To overcome this, a collective *semidirect* capture mechanism was proposed.[7-9] This theory assumes that the incident nucleon is captured into a lower orbit with the excitation of the target nucleus into its giant-dipole resonance as an intermediate state from which it decays radiatively with a collective enhancement. Evidence is now beginning to accumulate favoring this process.[10]

It has recently been claimed that compound-nuclear theory can predict the right order of magnitude of the neutron capture cross section for intermediate energies around 10 MeV.[11] A sensitive test of the relative importance of the compound-nuclear process to this reaction is to measure the shape of the spectrum of γ rays emitted in the capture process.

The purpose of the present experiment was to investigate the spectrum from the reaction $^{208}\mathrm{Pb}(n, \gamma)^{209}\mathrm{Pb}$ at several energies and to compare the observed shapes with the predictions of compound-nuclear and semidirect capture theories. If direct capture theories hold, we expect transitions to lower states which are well described as single-particle states. Hence, we chose ^{208}Pb since the wave functions of the lower excited states of ^{209}Pb are very well established. This Letter is a report on portions of a more extensive experiment covering measurements over the entire giant dipole resonance of ^{208}Pb.[12]

Neutrons were obtained from the reaction T(p, n)^{3}He using the Los Alamos Scientific Laboratory tandem Van de Graaff to accelerate pulsed and bunched protons. The 1.5-nsec bunched beam permitted unwanted background to be rejected utilizing standard time-of-flight technique. The target consisted of 490 g of pure ^{208}Pb formed in the shape of a cylinder 3.3 cm in diameter and 5.0 cm long. Its long axis was located at 0° to the incident beam with a distance from the center of the tritium gas target to the front face of the ^{208}Pb cylinder of 7.7 cm. The capture γ rays were detected with a 6-cm-diam, 12.5-cm-long NaI(Tl) crystal surrounded by a NaI(Tl) annulus operated in anticoincidence whenever a pulse greater than 0.7 MeV was detected. The efficiency of this detector, along with the remainder of the pertinent experimental details are described elsewhere.[12]

In Fig. 1 are shown the spectra obtained at E_n = 9.2, 11.2, and 13.2 MeV. The experimental points shown in the figure were obtained by subtracting the results of a run with the ^{208}Pb sample in and the sample out, after first correcting both spectra by subtracting out counts due to high-energy neutrons. The results for each energy were normalized to the total charge collected.

The solid curves through the spectra represent the predictions of semidirect capture theory.[8] The relation used for capture into a particular single-particle orbit is

$$\sigma_{n\gamma}=\frac{\pi}{K'^2}\sum_{l'j'}(2l'+1)\frac{\Gamma_\gamma\Gamma_{\mathrm{in}}}{(\epsilon_{l'}-\epsilon_r)^2+(\frac{1}{2}\Gamma)^2}. \qquad (1)$$

The symbols used here are defined in Clement, Lane, and Rook[8] except for the modification needed to include a spin-orbit term in the potential. The numerical evaluation for the $g_{9/2}$, $i_{11/2}$, $j_{15/2}$, and $d_{5/2}$ single-particle states were taken from previous work.[10-13] The position of the giant-dipole resonance was taken as 13.5 MeV and the width as 3.5 MeV. For the $s_{1/2}$, $g_{7/2}$, and $d_{3/2}$ states we have utilized the calculations of Longo and Saporetti[14] to obtain ratios of these cross sections to those of the other states. The positions of these states are shown at the top of Fig. 1. A spectroscopic factor of 1 was assumed for all states except for the $j_{15/2}$ state for which a value of S = 0.60 was used.[15,16] The numerical results for the γ-ray transitions were then folded in with the response function of the detector to give the theoretical pulse-height spectrum as shown by the solid curves on the figure. These curves were then normalized to the experimental data over the upper portion of the spectra.

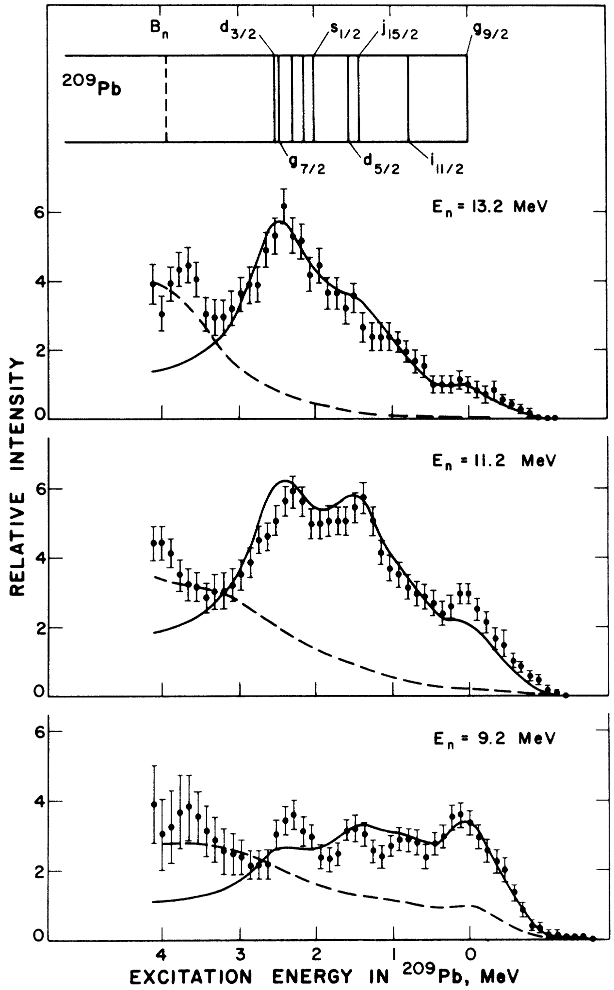

FIG. 1. Neutron radiative capture spectra for ^{208}Pb at incident energies of 9.2, 11.2, and 13.2 MeV. The experimental points are only relative, but the separate spectra at each energy are normalized to the total accumulated charge. The solid curves show the predictions of semidirect theory and the dashed lines represent the compound-nuclear prediction. Normalization of both curves is described in the text.

The dashed curves show the spectra obtained using the statistical predictions. The number of γ's per unit energy interval, N_γ, was obtained from

$$N_\gamma\, dE_\gamma \sim \Gamma_\gamma(E_\gamma)\rho(E_x - E_\gamma)\, dE_\gamma, \tag{2}$$

where E_x is the excitation energy of the compound nucleus and $\rho(E_x - E_\gamma)$ is the number of levels per unit energy interval[17] to which transitions can occur. Γ_γ is the partial radiative width and was calculated using a giant-dipole-resonance form factor. After folding in the response function of the detector, the statistical spectra were normalized to the low-energy portion of the pulse-height distribution shown in Fig. 1.

It is clear that the statistical-theory calculations of the spectrum shape fails in two ways irrespective of questions about magnitude. First, it predicts a sharp fall-off with energy, which is not observed. Also, it predicts a relatively smooth behavior with energy, whereas the observed spectra show definite structure at high γ-ray energies. On the other hand, the semidirect capture theory predicts closely the observed spectral shape. In particular the transitions to low, excited single-particle states as a function of energy are predicted very well by this collective excitation process. It can be seen from Fig. 1 that the predicted shape in the region of excitation of the residual nucleus of 2.5–4.0 MeV does not agree with the observed spectra. The latter can expect contributions due to single-particle strength (particularly $j_{15/2}$) being spread over this energy interval. In conclusion it would appear that the semidirect capture theory adequately describes the shape of the γ-ray spectra produced by neutron capture in the giant-dipole-resonance region of ^{208}Pb.

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Bremsstrahlung in Proton–α-Particle Scattering

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An experiment to determine the bremsstrahlung cross section in proton–α-particle scattering was performed for incident proton energies between 7.0 and 12.0 MeV. It was found that in order to obtain agreement with the measured coplanar values, the theoretical calculation must include the contribution of the so-called "rescattering term."

An experiment to determine the bremsstrahlung cross section in the scattering of protons on ^{4}He nuclei was performed at the Eidgenössische Technische Hochschule tandem accelerator for incident proton energies from 7.0 to 12.0 MeV. The energies of the scattered protons and the recoil α particles, as well as the time difference between the two detector signals, were measured simultaneously by means of a triple-parameter system.[1] This information, with a resolution of $256\times256\times512$ channels, was recorded on magnetic tape and analyzed off line with a