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THRESHOLD PHOTONEUTRON ANGULAR DISTRIBUTION AND POLARIZATION STUDIES OF NUCLEI

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by

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Summary

The photoneutron method was applied to the study of (i) deuteron photodisintegration, (ii) giant magnetic dipole resonances in heavy nuclei, (iii) mechanism of radiative capture in light nuclei and (iv) isospin splitting of the giant dipole resonance in ^{60}Ni. These studies were performed with the pulsed bremsstrahlung beam and high-resolution spectrometer available at the Argonne high-current electron linac. A threshold photoneutron polarization method was developed in order to search for the giant M1 resonance in heavy nuclei. A surprisingly small amount of M1 strength was found in ^{208}Pb. Furthermore, the M1 strength for the 5.08-MeV excitation in ^{17}O, the best example of a single-particle M1 resonance in nuclei, was found to be strongly quenched. In addition, the $^{17}O(\gamma,n_o)^{16}O$ reaction was found to provide an ideal example of the Lane-Lynn theory of radiative capture. The interplay among the three components of the theory, internal, channel and potential capture, were evident from the data. An electron beam transport system was developed which allows the bremsstrahlung to impinge on the photoneutron target on an axis perpendicular to the usual reaction plane. This system provides an accurate method for the measurement of relative angular distributions in (γ,n) reactions. This system was applied to a high-accuracy measurement of the relative angular distribution for the $D(\gamma,n)H$ reaction. The question of isospin-splitting of the giant dipole resonance in ^{60}Ni was studied by using the unique "pico-pulse" from the accelerator and the newly installed 25-m, neutron flight paths. The results provide clear evidence for the effect of isospin splitting.

Introduction

The prospect of a giant magnetic dipole resonance (GMDR) in ^{208}Pb has led to intense experimental and theoretical development during the past decade. One would expect ^{208}Pb to provide an ideal example of a GMDR since both proton ($h_{11/2} \rightarrow h_{9/2}$) and neutron ($i_{13/2} \rightarrow i_{11/2}$) transitions can contribute to the excitation. Interest in this subject was spurred when Mottelson[1] and Bohr[2] first suggested a simple model for the GMDR, and Bowman et al.[3] claimed experimental evidence for the effect in ^{208}Pb. Photoneutron polarization and high-resolution photoneutron spectroscopy[4] revealed that the amount of M1 strength in ^{208}Pb was much smaller than previously believed below an excitation energy of 8.4 MeV. These results led Brown et al.[5] to hypothesize that the empirical particle-hole energies should not be used as the unperturbed energies in the schematic particle-hole model. Rather, these particles and holes are coupled to nuclear vibrations, and the unperturbed energies can deviate significantly from the empirical values. This hypothesis would place the GMDR at a higher energy, ~10 MeV, where further experimentation would be extremely difficult. The photoneutron experiments which led to these results will be discussed briefly in the following section.

Since there was difficulty with understanding the apparent ideal collective M1 excitation, it was interesting to focus on an ideal single-particle M1 excitation. The $^{17}O(\gamma,n_o)^{16}O$ reaction should provide a good example since the 5.08-MeV excitation is a $d_{5/2} \rightarrow d_{3/2}$ transition. Here, the $5/2^+$ ground state and $3/2^+$ (5.08 MeV) excited states are believed to have spectroscopic factors of near unity. Furthermore, the magnetic moment of ^{17}O is extremely close to that of a free neutron. Thus, one would expect this M1 excitation to be described accurately by the single-particle model. In reality, the B(M1) was measured[6] to be only ~1/3 of the single-particle value. The source of this quenching of M1 strength remains unknown.

A long-standing goal of nuclear physics is a complete understanding of the deuteron. The $D(\gamma,n)H$ reaction is the simplest process for studying the deuteron. Although it has long been believed that the theory could provide a good explanation of the photodisintegration of the deuteron, it turns out not to be true. Recently, Hughes et al.[7] have measured the cross section for $D(\gamma,p)n$ at 0°. No theory of the deuteron can explain these data. Moreover, Hadjimichael[8] has shown that the predictions of conventional theory are ~20% lower than the total photoabsorption cross section. Hadjimichael has hypothesized that the theory can be brought into agreement with the experiment if the deuteron alters its nature at distances smaller than 1.5 fm. These findings emphasize the need for high-accuracy angular distribution measurements for the $D(\gamma,n)H$ reaction. Measurements are presently underway at the ANL linac and some of the results will be presented here.

Gell-Mann and Telegdi[9] first derived isospin selection rules for the giant electric dipole resonance (GDR). In particular, for a non self-conjugate nucleus of isospin T, the giant dipole resonance is expected to exhibit two components of isospin T ($T_<$) and T + 1 ($T_>$). Fallieros and Goulard[10] developed expressions for the amount of splitting and relative strengths of these two components. The photoneutron method provides a unique method for the study of this phenomenon in nuclei. Whereas, the (γ,p_o) reaction can excite both isospin components, the (γ,n_o) reaction selects only $T_<$. Results for ^{60}Ni will be shown.

Collective M1 Excitation in ^{208}Pb

The ANL photoneutron facility is centered around a 4 - 20 MeV travelling wave electron accelerator. For the purpose of high-resolution photoneutron time-of-flight spectroscopy the accelerator can be operated in modes that produce pulses at 800 Hz with a pulse duration of 35 ps to 4 ns and with peak currents of 200 A to 10 A, respectively. A schematic diagram of the facility is shown in figure 1. The energy analyzed electrons strike a bremsstrahlung converter and stop in a water-cooled Al block. The bremsstrahlung then irradiates the (γ,n) target. The key to threshold photoneutron spectroscopy is to adjust the electron energy so that only the narrow band of levels above the threshold are excited and so that decay neutrons from these resonances can proceed only to the ground state of the daughter nucleus. In this way neutron energy is related simply to the incoming photon energy. The neutron energies are determined with high resolution by the time-of-flight method. The photoneutrons travel along two, well-collimated 25-m flight paths which are at angles of 90° and 135° with respect to the photon axis.

Typical high-resolution time-of-flight spectra are shown in figure 2 for the $^{208}Pb(\gamma,n_o)^{207}Pb$ reaction.

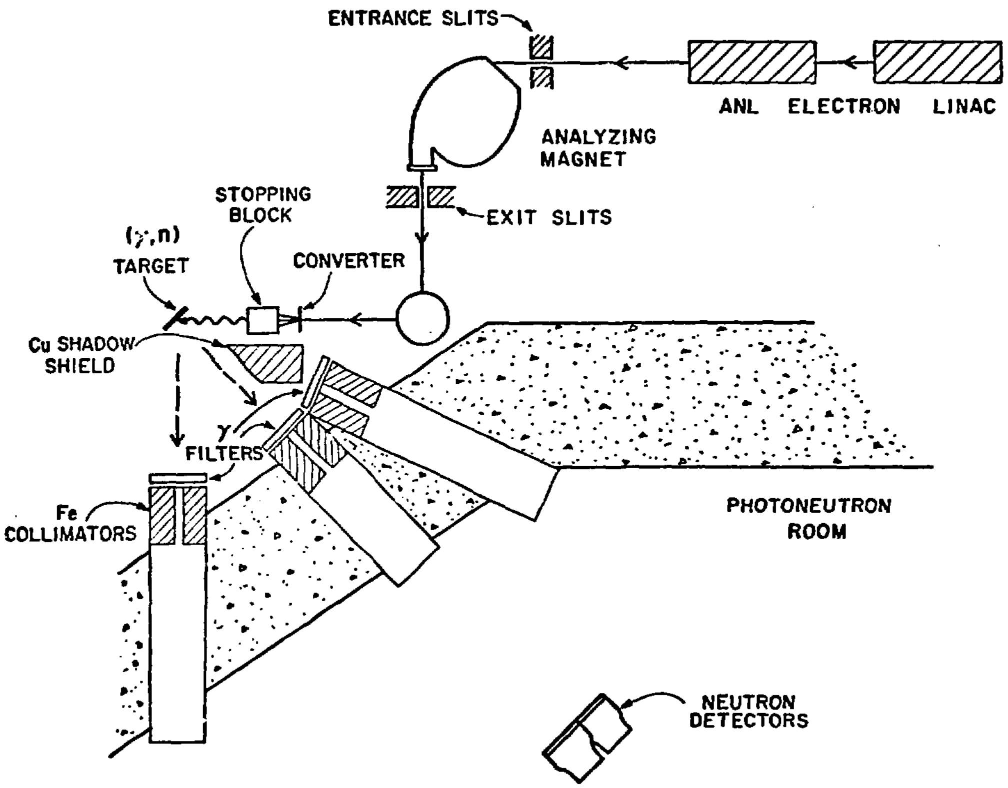

Figure 1. Schematic diagram of the ANL photoneutron facility.

In this example, the high resolution was essential in order to resolve the 600 and 610-keV resonances, shown in the inset figures. The filled-in region between the two resonances is indicative of constructive level-level interference, and thus, these two resonances have the same spin and parity. This result in conjunction with the photoneutron polarization data indicates that these resonances are E1 in nature and not M1 as previously believed. In fact, at one time it was believed that many of the large resonances shown in figure 2 were M1 excitations.

In order to study these resonances in more detail a threshold photoneutron polarimeter[11] was developed. A schematic diagram of this new experimental arrangement is shown in figure 3. A solenoid was placed along the neutron flight path in order to precess the neutron spins, and consequently, minimize false asymmetries in the polarization measurement. At the end of the neutron flight path the neutrons scattered from targets of known analyzing powers (Mg below 300 keV, ^{16}O between 400 keV and 1.2 MeV, ^{12}C above 1.2 MeV) and into pairs of either left-right or up-down detectors. Up-down detectors were used for neutron spins that were precessed through ∿90°; whereas, left-right counters, for those that precessed near 180°. The results from these measurements are shown in figure 4 for the $^{208}Pb(\gamma,\vec{n}_o)^{207}Pb$ reaction and a ^{16}O analyzer. In this instance the solenoidal field was adjusted so that the spin of a 600-keV neutron was precessed through 180°. The lower two panels of that figure illustrate the data for a reaction angle of 135° and with and without the solenoidal fields for the right and left detectors individually. Clearly, the major resonances in this energy region yield polarized neutrons at 135°. The final polarizations for reaction angles of 90 and 135° are shown in the upper panels. All except one of the large resonances in this energy region exhibit a sin(2θ) angular dependence which is characteristic of E1 excitations. No polarization would be expected for isolated M1 excitations, since the nonresonant p-wave phase shifts for the $^{207}Pb + n$ system almost exactly cancel in the expression for the differential polarization. Overlapping E1 and M1 or E2 excitations would give rise to a sin(θ) dependence as observed in the vicinity of the 610-keV resonance. From neutron scattering[12] it is believed that a small E2 excitation resides on the high-energy side of the 610-keV resonance. We also found that the 179-, 254- and 314-keV resonances exhibit a sin(2θ) dependence. We conclude from these studies that no large M1 excitations exist between threshold and 8.4 MeV. Presently, the only M1 strength in ^{208}Pb occurs in a small grouping

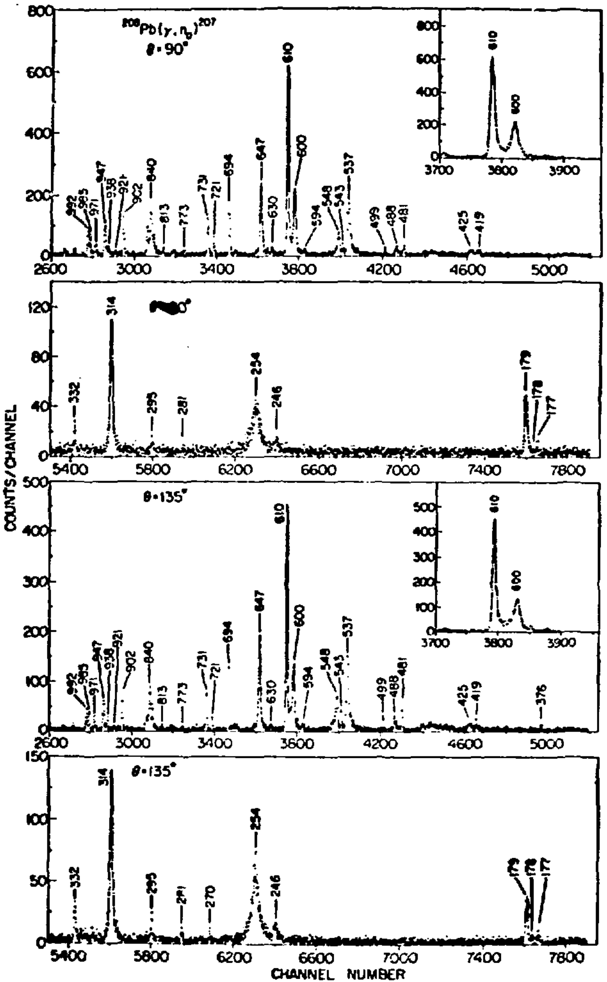

Figure 2. High-resolution time-of-flight spectra for the $^{208}Pb(\gamma,n_0)^{207}Pb$ reaction at angles of 90° and 135°.

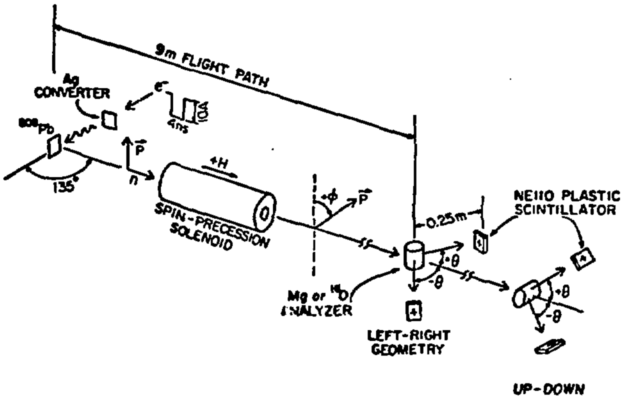

Figure 3. Schematic diagram of the threshold photoneutron polarization experiment.

of levels near 7.6 MeV. The known M1 strength accounts for only 10% of the sum rule for the GMDR. Perhaps Raman will speak more about this problem in the following talk.

Single-Particle M1 Excitation

The threshold (γ,n) method was applied to the study of the $^{17}O(\gamma,n_0)^{16}O$ reaction. Here, the primary interest is the photoexcitation of the $d_{5/2} \rightarrow d_{3/2}$ transition at 5.08 MeV. The single particle model yields a reduced transition probability of

$$B_\gamma(M1;\ell-1/2\rightarrow\ell+1/2) = \frac{3(\ell+1)}{(2\ell+1)\pi}\,\mu_n^2\left(\frac{e\hbar}{2M_pC}\right)^2\left|\int_0^\infty u_{\ell-1/2}u_{\ell+1/2}dr\right|^2$$

where μ_n is the magnetic moment of the neutron and u(r) is the single-particle radial wave function. For the $d_{3/2} \rightarrow d_{5/2}$ spin-flip transition this expression gives a ground-state radiative width $\Gamma_{\gamma 0} = 3.17$ eV. The empirical value of 1.0 eV was deduced from the spectra illustrated in figure 5. A multi-channel R-matrix analysis based on the theory of radiative

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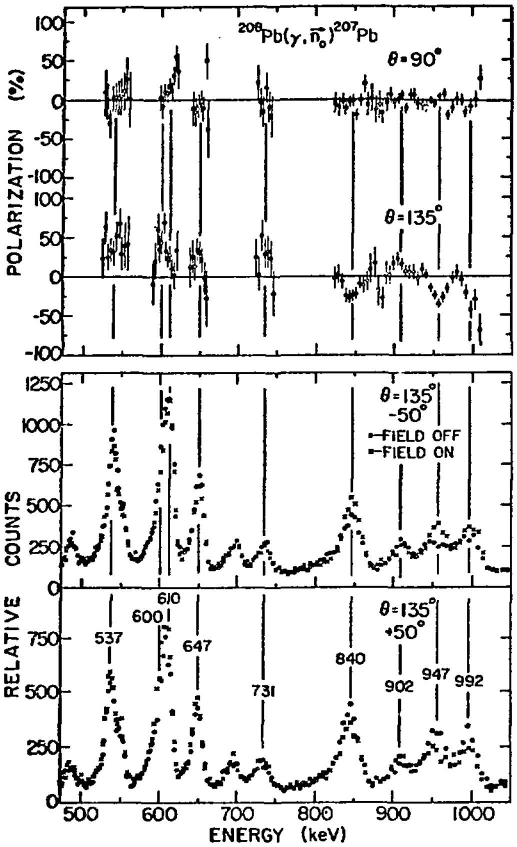

Figure 4. Polarization results for the $^{208}Pb(\gamma,n_0)^{207}Pb$ reaction. The lower two panels show the data at 135° with and without the effect of the spin precession solenoidal field.

capture of Lane and Lynn[13] was developed[6] in order to more accurately deduce the ground-state radiative widths from the data. The curves in figure 5 represent the result of that analysis.

In the Lane-Lynn theory radiative capture is comprised of three components: (i) internal capture (resonant capture which occurs within the channel radius), (ii) channel capture (resonant capture outside the channel radius), and (iii) potential capture (nonresonant capture). The spectra of figure 5 are characterized by a large nonresonant cross section, a prominent resonance at 5.08 MeV, an asymmetric resonance at 4.56 MeV, and a symmetric minimum at 5.38 MeV. This symmetric minimum will be demonstrated to arise from channel capture. For example, if we consider only a single level and a direct component D, then the (γ,n) collision matrix becomes

$$U_{\gamma n} = ie^{-i\phi_\ell}\left[\frac{\Gamma_n^{1/2}[\Gamma_{\gamma f}{}^{1/2}-(\delta\Gamma_{\gamma f})^{1/2}]}{E_r - E - i\Gamma/2} + D\right]$$

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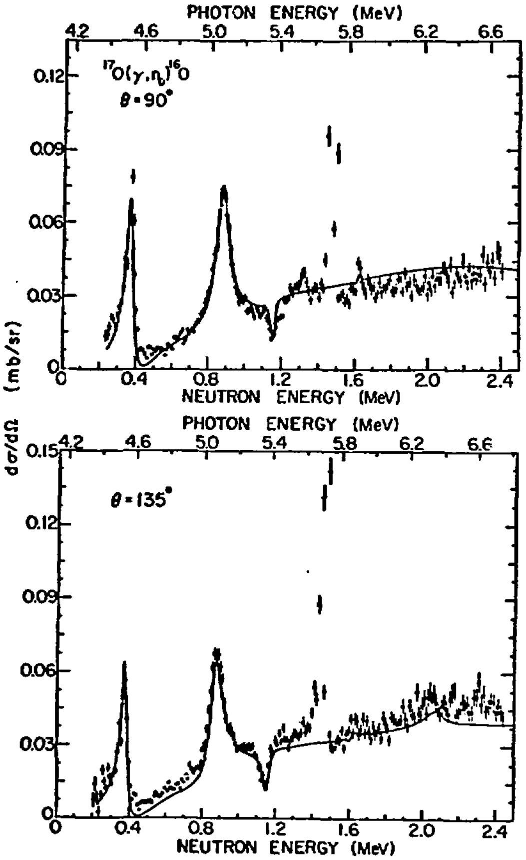

Figure 5. Differential cross section for the $^{17}O(\gamma,n_0)^{16}O$ reaction. The M1 strength of the 5.08-MeV, $d_{5/2} \rightarrow d_{3/2}$ transition is a factor of three lower than expected.

where $\Gamma_{\gamma f}{}^{1/2}$, $(\delta\Gamma_{\gamma f})^{1/2}$ and D are the internal, channel capture reduced widths and the potential capture component of Lane-Lynn theory, respectively. If we have the condition that $\Gamma_{\gamma f}{}^{1/2} \gtrsim \mathrm{Re}(\delta\Gamma_{\gamma f})^{1/2}$, then a novel interference pattern is possible.

$$\sigma_{\gamma n} = \pi g_J \lambda_\gamma{}^2 \left\{\frac{4[\Gamma_{\gamma o}\Gamma_n + D\Gamma\Gamma_n{}^{1/2}\mathrm{Im}(\delta\Gamma_{\gamma f})^{1/2}]}{\Gamma^2(1 + X^2)} + D^2\right\}$$

where $\Gamma_{\gamma o} \equiv |\,\Gamma_{\gamma f}{}^{1/2} - (\delta\Gamma_{\gamma f})^{1/2}|^2$ and $X = (2/\Gamma)(E_r - E)$. The above expression gives rise to a symmetric resonance and can be a peak or a minimum depending on whether the quantity in brackets is positive or negative. Thus, this symmetric minimum in the cross section is a unique feature of radiative channel capture interfering with potential capture. This work represents the first direct empirical evidence for channel capture.

Photodisintegration of the Deuteron

A high-accuracy measurement of the angular distribution for the D(γ,n)H reaction is necessary in order to test the theoretically predicted multipole contributions to the photodisintegration process. Interest in this problem has become more widespread since Hughes et al.[7] found that the photodisintegration cross section at 0° is ~20% lower than theory in the energy region of 20-120 MeV. Moreover, photodisintegration of the deuteron near threshold depends strongly on the M1 component which is sensitive to meson-exchange effects.

For these reasons we have developed a novel electron beam transport system at the ANL photoneutron facility. With this system the electron beam direction can be altered so that it is normal to the usual *reaction plane. (See figure 6.)* This enables an extremely accurate relative calibration of the neutron detectors. In addition, the beam can be made to reverse its original direction so that it strikes the target from the opposite side. This allows one to make measurements at forward angles. The relative angular distributions measured, thus far, are shown in figure 7.

The solid points in the figure represent results acquired with an electron endpoint energy of 10.0 MeV; while the open circles refer to data, with a 19.0-MeV endpoint. The two separate measurements agree extremely well. The calculations of Partovi[14] and Hadjimichael[15] are compared with the present measurements. The *solid curves* illustrate Hadjimichael's result with only E1 and M1 transitions in the theory; whereas, the dashed curve indicates the result with multipoles up to M4. It is clear from these data that inclusion of only E1 and M1 amplitudes at photon energies as low as 3.5 MeV is not adequate. For the cross section ratio of σ(93.2°)/σ(48.4°) the theory is in remarkable agreement with the experiment. However, for the ratio of σ(91.1°)/σ(135.9°) the slope of the theoretical curve deviates pronouncedly from the data. This is the first evidence that the multipole decomposition for the D(γ,n)H reaction may be incorrect at low energies. Clearly, more data of this kind is necessary in order to determine if this trend of disagreement will continue at higher energies. This work is currently underway at the ANL photoneutron facility.

Isospin Splitting of Giant Dipole Resonance

A previous search[16] for isospin splitting in ^{60}Ni relied upon a comparison of (γ,p_0) and (γ,n) results. In that work the ^{59}Co$(p,\gamma_0)^{60}$Ni reaction was studied. The method made use of the fact that both $T_<$ and $T_>$ states should appear in (γ,p_0) data, but only $T_<$ in (γ,n_0) spectra as illustrated in figure 8. Indeed two resonances were seen in the (p,γ_0) spectrum. These resonances were separated by ~3 MeV as expected for isospin splitting. Unfortunately, no (γ,n_0) data

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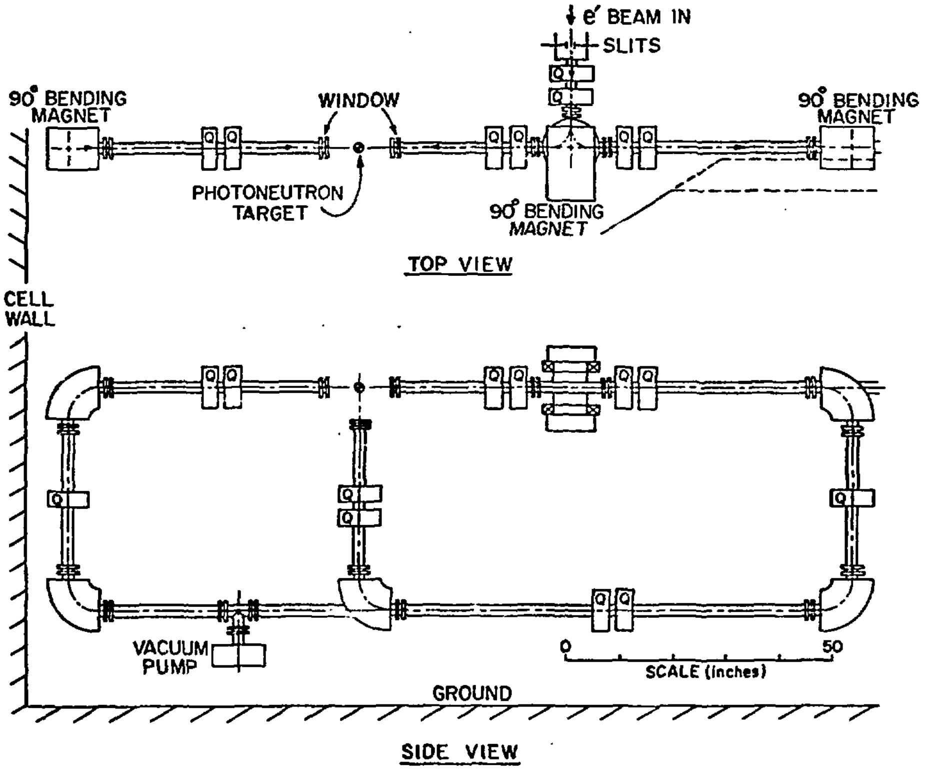

Figure 6. Arrangement of the multi-directional beam transport system at the photoneutron facility.

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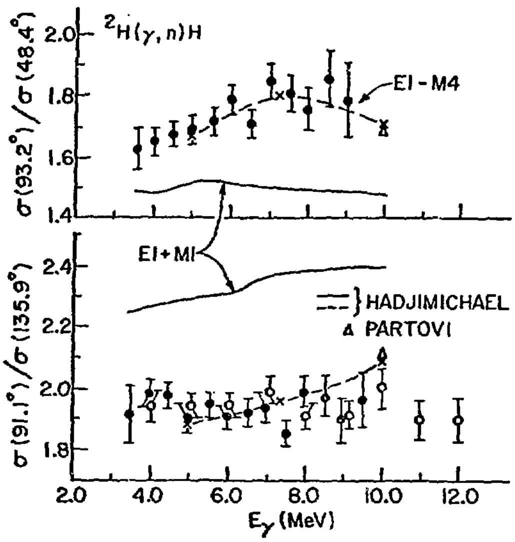

Figure 7. The closed and open circles represent data taken with a 10- and 19-MeV electron en-point energy respectively. The solid curves illustrate the theoretical calculation with only E1 and M1 excitations; whereas, the dashed curves indicate the theory with higher multipoles included.

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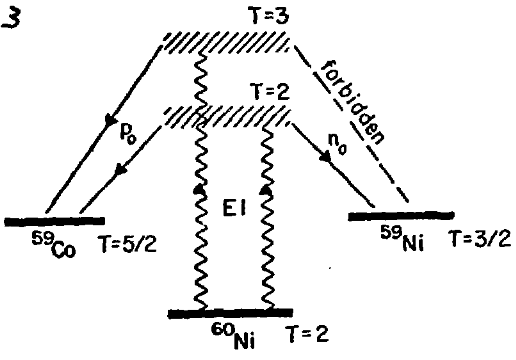

Figure 8. Photo-nucleon processes for the GDR in ^{60}Ni. Neutron decay of $T_>$ is forbidden to the ground state of ^{59}Ni.

existed at that time. Only one resonance, at the location expected for $T_<$, was observed in the early (γ,n) spectra. However, more recent (γ,n) results[18] indicated two resonances at 17 and 20 MeV, respectively.

The major difficulty in observing the $^{60}\mathrm{Ni}(\gamma,n_0)^{59}\mathrm{Ni}$ reaction is that the first excited state in ^{59}Ni is low lying, 340 keV. The picopulse and 25-m flight paths were essential in order to obtain sufficient resolution for this measurement. The final results are shown in figure 9. Here, only one component is consistent with the resonance

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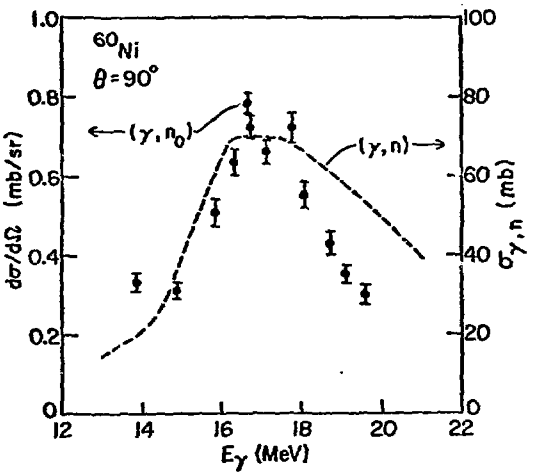

Figure 9. The $^{60}\mathrm{Ni}(\gamma,n_0)^{59}\mathrm{Ni}$ cross section at 90°. The curve represents the observed cross section for $^{60}\mathrm{Ni}(\gamma,n)^{59}\mathrm{Ni}$. Only one resonant component of the GDR is observed in the (γ,n_0) results.

believed to be $T_<$ in the $^{59}\mathrm{Co}(p,\gamma_0)$ data. The curve indicates the results of a (γ,n) measurement[18]. One can readily see that the giant resonance has two components in that data. This is consistent with the resonance thought to be $T_>$ in the (p,γ_0) data. Since the final state in the (γ,n) data was not observed, the (γ,n) spectrum is consistent with $T_>$ decaying by neutron emission to $T \neq 3/2$ states in ^{59}Ni. We conclude that the present (γ,n_0) results support the concept of isospin-splitting of the giant dipole resonance.

Conclusions

Photoneutron spectroscopy is a powerful method for studies of many aspects of photonuclear physics. The high-current and pico-pulse available from the electron accelerator were demonstrated to play an essential part in these studies. In summary, we found that no single, large M1 excitations exist in ^{208}Pb below 8.4 MeV, an energy range previously believed to be the giant M1 resonance region of ^{208}Pb. The 5.08-MeV resonance in ^{17}O was found to have only one-third of the expected single-particle M1 strength. Channel capture, a feature of the Lane-Lynn theory of radiative capture, was demonstrated uniquely for the first time. The importance of including multipoles higher than E1 and M1 for the D(γ,n) reaction at low energies was clearly demonstrated. Isospin splitting was found to be a useful concept for describing the two resonances observed in the GDR region of ^{60}Ni.

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