# NEW RESONANCES IN PHOTON TRANSITION STRENGTH FUNCTIONS*

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Variable-energy photons of about 1% resolution[1] were used to measure quasi-elastic scattering cross sections for Pb, Bi, Sn, and Zr. The results give the energy dependence of the ground-state photon transition strength functions below the neutron threshold for the first time. Sometimes these strength functions were concentrated in only a few hundred keV, as contrasted with several MeV predicted by accepted optical model parameters.

Rapid variations in photon cross sections have been reported previously,[2,3] but they were not attributed to fluctuations in the strength function (i.e., the ratio of the average ground-state radiative width, $\overline{\Gamma}_0$, to the average level spacing, $D$). The significant variation of $\Gamma_0$ between neighboring levels is now well established,[4,5] and it has been shown[6] that this distribution of $\Gamma_0$ values does not weaken the intimate relation between the scattering cross section and $\overline{\Gamma}_0/D$. However, before these effects were established, anomalously large level spacings were thought to be involved in photon interactions.[2,7,8] For these reasons, and because neither the magnitude nor the energy dependences of the cross-section variations were known, level density variations were thought to be responsible for cross-section variations.[3,9]

The results reported below, which establish strength function concentrations, merit immediate attention for three reasons:

(1) Data about strength concentrations can help extend the optical model to lower excitation energies. These data should be particularly informative about both the energy dependence and the spatial distribution of the imaginary part of the optical potential, $W$.

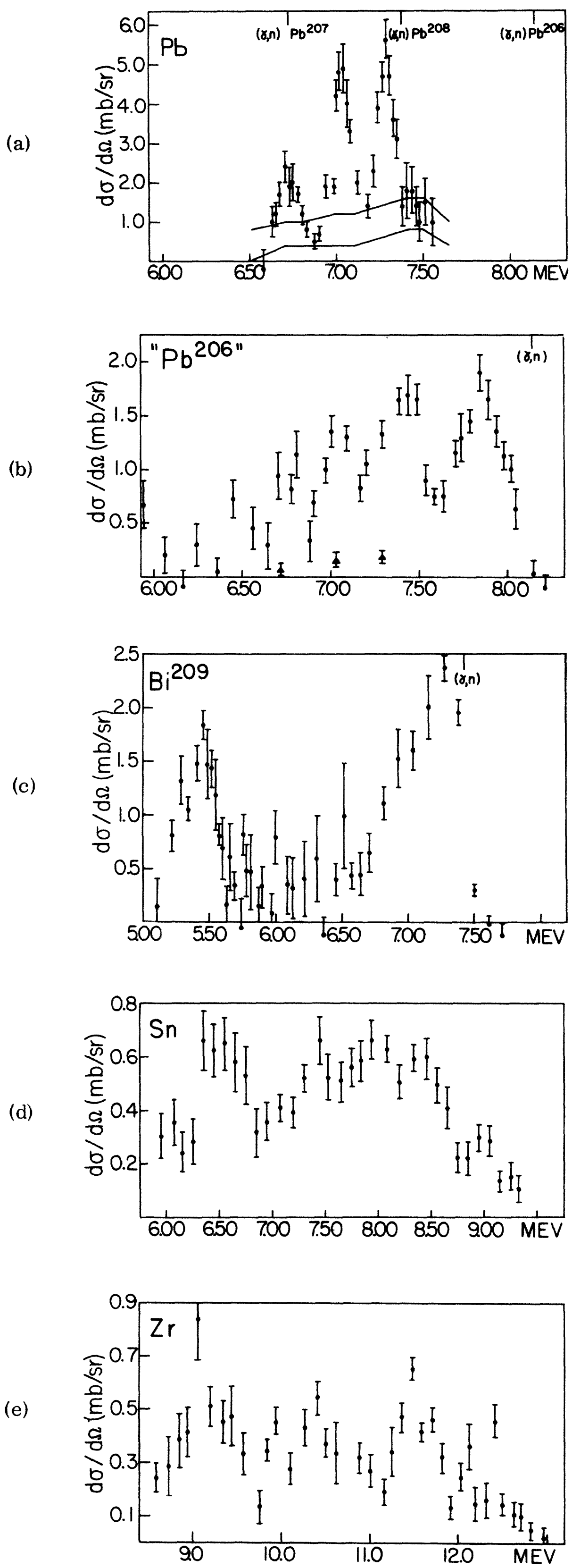
(2) Additional experiments are needed to determine the spreading of strength in other nuclei and at other energies. Stripping (or pickup) reactions can give information about the strength associated with a single particle (or hole), whereas photon absorption probably involves the simultaneous excitation of a hole and a particle.

(3) Where important strength concentrations exist, none of the conventional measurements provide the average values needed for comparison with calculations of nuclear electromagnetic transition probabilities. Even recent attempts to treat photon transitions systematically[4-7] contain previously unrecognized ambiguities. The required averages cannot be obtained from studies of either neutron-capture gamma rays[4,5,7] or the interactions of photons in a narrow, fixed energy band.[2,10] Poor-resolution measurements made with bremsstrahlung photons[3,11,12] do not provide an adequate average if the relative sensitivity to different energies is unspecified.

The pertinent experimental results which display strength function concentrations consist of the 135° quasi-elastic scattering cross sections of $Pb^{206}$, $Bi^{209}$, Sn, and Zr. The results for $Pb^{208}$, however, show that for this special case the participating levels have spacings much greater than the experimental resolution. They represent an extreme example of fluctuations in quasi-elastic scattering caused by level density. The scattering is called quasi-elastic because the poor resolution (15%-20%) of the photon detector did not separate high-energy inelastic scattering from elastic scattering.

The data obtained with a natural mixture of Pb isotopes are shown in Fig. 1(a). Each of the three resonances exhibits the monochromator resolution and is therefore consistent with the scattering from a single energy level. Additional data with enriched $Pb^{206}$ and $Pb^{208}$ targets indicated that these three strong levels at 6.72 MeV, 7.03 MeV, and 7.29 MeV are in $Pb^{208}$. Auxiliary absorption experiments implied ground-state radiative widths of about 15 eV, 30 eV, and 40 eV, respectively, and total widths between one and a few times as large. These levels undoubtedly dominated the scattering observed from natural Pb targets with poor resolution[3,11,12] near 7 MeV and caused the large difference reported[2] between "6.92 MeV" and "7.12 MeV." The 7.29-MeV level may also be responsible for the large $Pb^{208}$ scattering recently observed[13,14] using the 7.285-MeV $\gamma$ ray produced by neutron capture in Fe.

The cross sections measured with the other targets include at each energy the unresolved contributions of many narrow, isolated nuclear energy levels. For $Pb^{206}$ and $Bi^{209}$ there are only about 15 contributing levels at each energy. Although statistical fluctuations in this small num-




ber could produce noticeable effects, they could not account for the large variations in cross section nor its relatively smooth gross structure. For Sn and Zr, hundreds or thousands of levels contribute at each energy, and the effects of variations in these numbers are negligible.

Competition due to inelastic scattering may be in evidence in Fig. 1, but it is not the primary cause of the rapid fluctuations with energy. Inelastic scattering probably increases slowly with energy, and this increase may explain why the general trend in the elastic scattering of Sn and Zr does not increase. Competition effects also probably produce in the elastic scattering a somewhat exaggerated reflection of the ground-state transition strength fluctuations.

Neutron emission competition causes an obvious decrease in the elastic scattering of Fig. 1 only for $Bi^{209}$ just above 7.4 MeV. Neutron emission effects are obscured for the other samples because the scattering happens to be low at the energies of the $(\gamma, n)$ thresholds of dominant isotopes. The existence of other important energy-dependent factors near the $(\gamma, n)$ threshold will require the reinterpretation of data previously used[15] to infer the neutron competition by studying only the photoneutron cross section in $Zr^{90}$. These additional energy-dependent factors will also make it more difficult to establish the continuity of the photoabsorption cross section across the $(\gamma, n)$ threshold. The elastic scattering of $Bi^{209}$ shown in Fig.

FIG. 1. 135° differential quasi-elastic photon scattering cross sections. The energy resolution values irregularly from about 75 keV to 200 keV because some measurements were combined. Relevant $(\gamma, n)$ thresholds are shown along upper abscissa in 1(a)-1(c). (a) The target consisted of a natural mixture of Pb isotopes ($Pb^{204}$, 1%; $Pb^{206}$, 25%; $Pb^{207}$, 22%; $Pb^{208}$, 52%). The cross-section scale assumes that the observed scattering was due entirely to $Pb^{208}$. The solid lines show the limits of the cross section attributable to $Pb^{206}$. The data are consistent with three very narrow nuclear levels at 6.72 MeV, 7.03 MeV, and 7.29 MeV; the apparent cross sections are a function of the resolution. (b) The target was enriched $Pb^{206}$ ($Pb^{206}$, 88%; $Pb^{207}$, 9%; $Pb^{208}$, 3%). The cross-section scale assumes all the scattering is due to $Pb^{206}$. The triangles indicate the energies of and the contributions attributable to the three levels in $Pb^{208}$. (c) The target was $Bi^{209}$. (d) The target consisted of a natural mixture of Sn isotopes. The cross-section scale assumes that only 71% of Sn contributes (i.e., $Sn^{116}$, $Sn^{118}$, $Sn^{120}$). (e) The target contained a natural mixture of Zr isotopes. The cross-section scale assumes that all of the scattering comes from $Zr^{90}$.

1(c) is consistent with continuity when compared with the reported photoneutron cross section.[3] However, these scattering data are quite different from those used previously to show that the average absorption cross section is continuous across the $(\gamma, n)$ threshold.[3,16] Proof of continuity will not be available until good-resolution experiments are available below and above the threshold, and until quantitative values are available for the inelastic scattering.

The narrowest strength concentrations appear at about 7.85 MeV in $Pb^{206}$ and at about 5.45 MeV in $Bi^{209}$; these have full widths at half-maximum of about 350 keV (uncorrected for the finite spread in incident photon energies). Peaks near 7.85 MeV have also been reported[3] in the photoneutron cross sections of $Pb^{207}$ and $Pb^{208}$. Both $Pb^{206}$ and $Bi^{209}$ have considerable transition strength in the energy region where the three strong $Pb^{208}$ levels occur. There is too much statistical uncertainty to decide whether $Pb^{206}$ has partially resolved peaks at about 6.75 MeV, 7.1 MeV, and 7.45 MeV. No similar substructure is evident in the $Bi^{209}$ data, possibly because three different spin states participate in the absorption.

Inasmuch as inferences about energy structure in scattering cross sections have been based[3] on comparing absolute values obtained in poor-resolution[3,11] and good-resolution[2] experiments, it is worth noting that the structure shown in Fig. 1 does not explain the past discrepancies. Our data for Bi and Sn agree with (or are slightly higher than) the values reported near 7 MeV with comparable resolution.[2] When reasonable energy averages are taken, our data also agree with (or are slightly lower than) poor-resolution results for[11,12] Bi and for[12] Sn. However, our averaged absolute cross sections are less than 50% of other poor-resolution results for[3] $Pb^{206}$, for[3] $Bi^{209}$, and for[11] Sn. It therefore would be premature to infer cross-section fluctuations near 7 MeV in Mn, Ni, Cu, and I, even though poor-resolution values[11] are more than twice the good-resolution values.[2]

The data for Sn show that strength concentrations are strong enough or regular enough to persist even though several isotopes contribute. The most distinctive features are the sharp drop beyond 8.5 MeV, and the valley near 7.1 MeV. The five Sn isotopes with $(\gamma, n)$ thresholds above 9.1 MeV are $Sn^{120}$ (33%), $Sn^{118}$ (24%), $Sn^{116}$ (14%), $Sn^{114}$ (0.65%), and $Sn^{112}$ (0.95%). The $(\gamma, n)$ thresholds between 6.5 MeV and 9 MeV are in $Sn^{117}$ (8%, 6.94 MeV), $Sn^{115}$ (0.3%, 7.54 MeV), $Sn^{124}$ (6%, 8.44 MeV), and $Sn^{122}$ (5%, 8.84 MeV). There is no evidence that these thresholds play a significant role in the data of Fig. 1(d).

For almost all of the energy range shown in Fig. 1(e), only 51.5% $Zr^{90}$ would be expected to contribute significantly to the observed scattering. (The highest threshold of the remaining Zr isotopes is 8.68 MeV for 17.7% $Zr^{92}$.) The most obvious concentration of strength occurs near 11.5 MeV; interpreted as a single resonance, it has a full width of less than 500 keV at half-maximum. (Experimental photoneutron data[15] exclude the possibility of significant neutron competition below 12 MeV.) There also appear to be maxima near 9.1 MeV and 10.4 MeV.

The only reported cases of comparable concentrations of transition strength are the sharper ones found[17] in $(p, n)$ reactions. Isotopic spin considerations were invoked to explain why the strength did not spread over a much wider energy range.[18,19] The optical-model parameters used to estimate the expected concentrations in $(p, n)$ reactions would imply widths an order of magnitude larger than we find (since isotopic spin cannot be keeping the strength in Fig. 1 concentrated).

Spreading widths, $\Gamma$, have been reported[20] for Ni from direct nucleon reaction experiments, but they seemed consistent[20] with $\Gamma = 2E/3$ whereas our widths are much smaller.

In an optical model whose imaginary part is spread uniformly over the nuclear volume, $\Gamma = 2W$. However, values such as $W = 3$ MeV used[21] to fit slow neutron data are much too large for our data.

The data of Fig. 1 seem particularly interesting because they (together with additional data and calculations) may be useful for testing three previously suggested modifications of the optical model:

(1) The value of $W$ may be small near closed shells.[22] Explicit shell-dependent values are not available,[19,22] but our data might be useful because shell-dependent effects are probably most noticeable at low energies.

(2) The energy dependence of $W$ might be stronger than apparent from the data available above particle separation energies. The photon excitation energy, $E$, is probably shared between the energies of the hole, $E_h$, and the particle, $E_p$. The concentrations of Fig. 1 require $W$ values considerably below the estimates[23]: $W_p = (1.0\text{ MeV})(E_p/7\text{ MeV})^2$ and $W_h = (1.5\text{ MeV})(E_h/7\text{ MeV})^2$. If $E_p$ and $E_h$ take on all values from 0 to $E$ with equal probability, the above estimates imply $\Gamma = (1.6\text{ MeV})(E/7\text{ MeV})^2$.

(3) The effective value of $W$ appropriate to bound nucleons may be much smaller than the values satisfactory for representing the absorption of nucleons crossing the nuclear surface. The probable dominance of surface absorption[24] is well known. However, some estimates[23] including surface absorption imply increases in the effective value of $W$. On the other hand, some anomalies in slow neutron data were recently explained[25] by moving the absorption beyond the nuclear radius, and if the imaginary potential is concentrated beyond the nuclear surface it will have a smaller effect on bound nucleons.

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# LIFETIME OF HELIUM HYPERFRAGMENTS*

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One of the more interesting parameters involved in the decay of hyperfragments is their lifetimes. Because of the possibility of nonmesonic decay, and the suppression of the mesonic decay modes due to the Pauli principle, it is expected that the lifetimes of hyperfragments will be different from that of the free $\Lambda$ particle. Such considerations have been discussed recently by Dalitz,[1] Dalitz and Liu,[2] and Dalitz and Rajasekharan.[3] Recently data have been presented at the 1962 CERN Conference regarding the lifetimes of $_{\Lambda}H^3$ and $_{\Lambda}H^4$.[4,5]

We exposed a stack of Ilford K5 nuclear emulsion in the 800-MeV/$c$ $K^-$ meson beam of the Bevatron, in the hope that fast hyperfragments which decay in flight mesonically would be produced in sufficient number to obtain some information on hypernuclear lifetimes. As a result of our findings, we are able to present some data regarding the lifetime of helium hyperfragments.

In scanning this stack, each of the pellicles in