fined LEOR in spite of a large spread in single particle-hole energies.

On the basis of general considerations one expects an octupole phonon to yield four states characterized by angular momentum projections $K$ ranging from 0 to 3 with excitation energy increasing as $K$ for a nucleus with a permanent prolate deformation. In Fig. 1 it is apparent that the transition from spherical $^{148}$Sm to deformed $^{154}$Sm does indeed produce a splitting of the LEOR. Whether the two peaks seen in $^{154}$Sm contain some or all of the expected $K$ components is not clear on the basis of the present data. The observed reduction of the EWSR strength due to the lowering of the centroid energy in $^{154}$Sm suggests that one or more $K$ components (not observed) may lie at higher excitation energies. One must await further experimental evidence and more sophisticated theoretical work on the splitting of the LEOR before its exact nature is understood.

In summary, evidence has been presented of a large concentration (16–22%) of isoscalar octupole EWSR strength in a relatively narrow low-energy octupole resonance at $\sim 32/A^{1/3}$ MeV in medium-mass nuclei. Comparison with RPA calculations indicates that most or all of the $1\hbar\omega$ oscillator strength has now been located in the nuclei studied. Approximately $\frac{1}{2}$ to $\frac{2}{3}$ of this strength is concentrated in the LEOR. Preliminary evidence indicates a large effect on this resonance due to nuclear deformation.

The authors would like to thank T. Kishimoto for many informative discussions about the theoretical aspects of this work and for performing the RPA calculations for $^{90}$Zr.

*Work supported in part by the National Science Foundation and the Robert A. Welch Foundation.

[1]G. E. Brown and M. Bolsterli, Phys. Rev. Lett. 3, 476 (1959).

[2]Aage Bohr and Ben R. Mottelson, *Nuclear Structure* (Benjamin, Reading, Mass., 1975), Vol. II.

[3]K. Hosoyama and Y. Torizuka, Phys. Rev. Lett. 35, 199 (1975).

[4]D. H. Youngblood, J. M. Moss, C. M. Rozsa, J. D. Bronson, A. D. Bacher, and D. R. Brown, Phys. Rev. C 13, 994 (1976).

[5]Calculations were made using the DWBA code DWUCK from P. D. Kunz of the University of Colorado.

[6]A. M. Bernstein, Adv. Nucl. Phys. 3, 325 (1969).

[7]J. H. Barker and J. C. Hiebert, Phys. Rev. C 4, 2256 (1971).

[8]G. R. Satchler, Nucl. Phys. A195, 1 (1972).

[9]G. F. Bertsch and S. F. Tsai, Phys. Rep. 18C, 125 (1975).

[10]Calculations are similar to those described in R. J. Lombard and X. Campi-Benet, Nucl. Phys. 83, 303 (1966).

[11]T. Kishimoto, private communication.

# Reaction $^{12}C(\gamma, \pi^-)^{12}N$ near the Threshold

A. M. Bernstein, N. Paras, and W. Turchinetz
*Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139**

and

B. Chasan and E. C. Booth
*Physics Department, Boston University, Boston, Massachusetts 02215†*

(Received 15 March 1976)

The total cross section for the reaction $^{12}C(\gamma,\pi^-)^{12}N$ has been determined by observation of the residual $^{12}$N radioactivity. The cross section was extracted from the bremsstrahlung excitation function which was measured in the region between 3.6 and 12.6 MeV above the threshold, with one point 33.5 MeV above the threshold. The variation of the measured cross section with energy is far more rapid than is predicted by calculations using the $\vec{\epsilon}\cdot\vec{\sigma}$ interaction. Even when the full interaction Hamiltonian is used, the experimental cross section rises somewhat more rapidly than predicted.

Photomeson production in complex nuclei can be used as a probe of the nuclear mesonic field. Because of its fundamental importance, this process and its inverse, radiative capture, have received considerable theoretical attention.[1-5] This reaction has, in addition, considerable potential for applications in studies of the isospin analogs of nuclear vibrations.[3,6] However, because of the experimental difficulties, only a few experiments have been performed in which transitions to discrete nuclear states are observed.[6,7]

Current theoretical calculations of these processes are based on the impulse approximation,[2,5] which assumes that the interaction Hamiltonian for bound nucleons is identical to the free nucleon case. Radiative pion capture and photoproduction proceed through an interaction Hamiltonian whose leading term is proportional to $\vec{\epsilon}\cdot\vec{\sigma}$, where $\vec{\sigma}$ is the nucleon spin operator and $\vec{\epsilon}$ is the photon polarization vector. Other terms in the Hamiltonian depend on the pion momentum.[8] They may be important at the threshold because of the Fermi motion of the nucleons and should contribute at higher photon energies.

In order to test the reaction mechanism, it is important to minimize nuclear-structure uncertainties by choosing transitions which have been studied by means of magnetic electron scattering[9] which measures the axial form factor at the momentum transfer appropriate to threshold meson photoproduction ($q \cong 0.75$ fm$^{-1}$). However, the knowledge of the magnetic form factor does not eliminate all nuclear structure uncertainties because it contains contributions from both the orbital and spin magnetization and a model-dependent extraction of the spin part must still be made.

In a first approach to the study of threshold photoproduction, the reaction $^{6}$Li$(\gamma,\pi^+)^{6}$He was measured at the Saclay linac between 0.3 and 3 MeV above the threshold.[7] After an initial result 60% lower than the then current theoretical predictions had been reported, the extraction of the nuclear form factors from electron scattering has been re-examined[10,11] and the theoretical predictions have subsequently been revised downward. The experiment has been repeated with an improved technique,[12] and there is now agreement within the combined theoretical and experimental uncertainty of 20%.

There is no simple connection between the negative and positive pion threshold photoproduction. Because of the Coulomb interaction between the emitted pion and the daughter nucleus, $\pi^-$ production is characterized by a step-function cross section at the threshold, while the $\pi^+$ production cross section rises slowly with energy.[4,5] The negative pion wave function is pulled in by the Coulomb interaction resulting in a larger overlap with the nuclear interior than in positive pion photoproduction. As a consequence, the strong final-state interaction is correspondingly more important for the negative pions. For the same reason the pion wave function has a larger curvature in $\pi^-$ photoproduction than in $\pi^+$ photoproduction. Therefore $\pi^-$ photoproduction may be more sensitive to momentum (gradient) dependent terms in the interaction Hamiltonian.[13] Another motive for studying negative pion production is that this process can reach nuclear states not accessible to radiative pion capture.

We report a study of the total cross section for the reaction $^{12}$C$(\gamma,\pi^-)^{12}$N by observing the 16.3-MeV end-point, 11-msec $\beta^+$ radioactivity of $^{12}$N. Since there is only one particle-stable state[14] in $^{12}$N, this technique measures photoproduction to that one state only; and the experiment reported here was not limited to the extreme threshold region, but explored the energy region where the momentum-dependent terms in the Hamiltonian become important.

The detection apparatus is shown in Fig. 1. Electrons from the Massachusetts Institute of Technology Bates Linear Accelerator impinged on a radiator consisting of 2.6% radiation length of Ta and 0.6% radiation length of Al. The emerging electrons were then deflected with a bending magnet and dumped. The entire photon beam irradiated a target whose thickness was 1 g/cm$^2$. $\beta^+$ rays emerging from the target were counted between beam bursts. The detection system consisted of two wire chambers (each used as a thin counter with its wires tied together) and two $\frac{1}{8}$-in. plastic scintillators. Fourfold coincidences were required to reduce the background from delayed neutron capture $\gamma$ rays. The magnet was used as a charge separator and did not transmit $\beta^+$ rays below 5 MeV. The background with the target removed was typically 10% or less of the yield below the threshold.

Fourfold coincidences were time sorted with

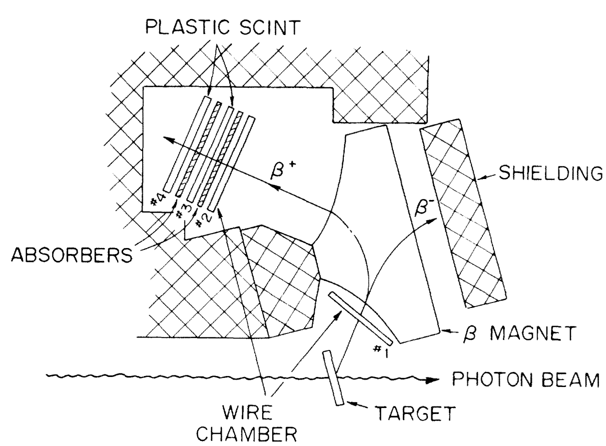


FIG. 1. Layout of the detection system.

respect to the beam pulse; and the 11-msec component was extracted with a typical accuracy of 5%. The time distribution also contained long-lived activities which were consistent with 127-msec $^{9}$C produced via the reaction $^{12}$C($\gamma$, $3n$) and 774-msec $^{8}$B produced via the reaction $^{12}$C($\gamma$, $3np$). A pulse rate of 7.5 Hz was small enough to allow an accurate determination of these long-lived components.

The cross section as a function of photon energy must be extracted from a measurement of the yield,

$$Y(E_0) = \int_{E_T}^{E_0} \sigma(E)\Phi(E_0,E)\,dE,$$

where $E_0$ is the end-point bremsstrahlung energy, $E_T$ is the threshold energy, $\sigma(E)$ is the total cross section, and $\Phi(E_0,E)$ is the Bethe-Heitler spectrum function modified near the end point.[15] The extracted cross section is insensitive to this modification. The accelerator energy calibration was determined within an accuracy of ± 250 keV in separate electron-scattering measurements involving both the ground state and the 15.11-MeV level of $^{12}$C.

The ($\gamma$, $\pi$) yield was normalized to the yield from the reaction $^{14}$N($\gamma$, $2n$)$^{12}$N. Since both processes result in the same final state, a measurement of the ratio of the 11-msec components for the two reactions was independent of the counter geometry and efficiency, while alternation of the carbon and Melamine ($C_2N_3H_2$) targets minimized the effect of beam fluctuations.

In order to determine the excitation function for the reaction $^{12}$C($\gamma$, $\pi^-$)$^{12}$N, it was necessary to take into account the nonmesic production of $^{12}$N through the two-step process $^{12}$C($\gamma$, $p$)$^{11}$B followed by $^{12}$C($p$, $n$)$^{12}$N. This was done by measuring the $^{12}$N activity below the meson threshold and extrapolating this background above the threshold. Figure 2 shows the linear fit to the background obtained by this procedure. Only when $E_0$ is 3.6 MeV above the threshold is the meson yield significantly above the background.

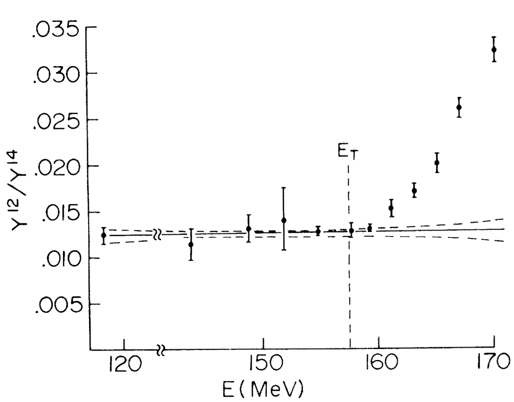


FIG. 2. Relative yield of the $^{12}$C → $^{12}$N to the reaction $^{14}$N($\gamma$, $2n$)$^{12}$N versus the end-point bremsstrahlung energy.

An absolute determination of the $^{12}$C($\gamma$, $\pi^-$)$^{12}$N yield depends on the $^{14}$N($\gamma$, $2n$)$^{12}$N yield. This was determined in a separate measurement of the $^{12}$N activity from a liquid nitrogen target using a thick plastic scintillator in coincidence with a wire chamber. The solid angle and efficiency were well known in this measurement, which yielded the result $Y_{2n}$(153 MeV) = 13.4 ± 1.9 $\mu$b per equivalent quantum (Q). This is in agreement with the result of Panofsky and Reagan,[16] $Y_{2n}$(120 MeV) = 14.6 ± 5.3 $\mu$b/Q.

The ($\gamma$, $\pi$) yield measured at 191 MeV allows a comparison with the measurements of Epaneshnikov, Kinzetsov, and Stukov[17] who were mainly interested in the region of the (3, 3) resonance. From their published yield curve we obtain the value $Y$(191) = 0.9 ± 0.2 $\mu$b/Q which is in good agreement with our measurements, $Y$(191) = 0.89 ± 0.13 $\mu$b/Q.

The yielded for the reaction $^{12}$C($\gamma$, $\pi^-$)$^{12}$N is shown in Fig. 3(a) along with the theoretical predictions. The calculation of Koch[5,18] uses the $\vec{\sigma}\cdot\vec{\epsilon}$ interaction with a coupling strength adjusted to fit the ($\gamma$, $\pi^-$) production on the neutron. Only $s$-wave pions, distorted in a Kisslinger-type optical potential,[19] are considered. Because of these approximations, this calculation was performed on-

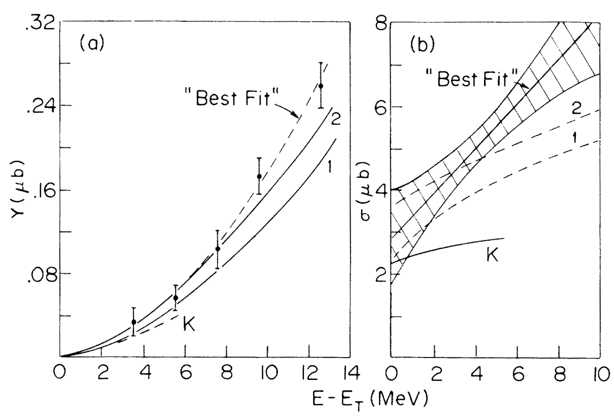


FIG. 3. (a) Yield and (b) cross section versus energy above threshold. The theoretical curves are from Koch (K) and from Ref. 19; curves 1 and 2 are from Nagl and Überall (Ref. 21). The best fit is a two-parameter fit with a step at the threshold and a linear increase with energy above the threshold. The shaded zone shows the errors in the best fit.

ly in the near-threshold region. The nuclear wave functions are obtained from the electron scattering data[20] for the 15.11-MeV, $1^+$ state of $^{12}C$ which is the isospin analog of the ground state of $^{12}N$. The calculation of Koch gives a result which is in agreement with experiment up to 4 MeV above threshold, but is too small above that energy.

The calculation of Nagl and Überall[21] uses the full interaction Hamiltonian[8] and includes $s$-, $p$-, and $d$-pion waves distorted in a Kisslinger-type optical potential. The nuclear transition density is obtained from the electron scattering data to the $1^+$ state of $^{12}C$ and is parametrized by the Helm model. The differences between the curves in Fig. 3(a) are due to different choices for the pion momentum in the coefficients of the interaction Hamiltonian. In curve 1, the asymptotic pion momentum is used. In curve 2, the local pion momentum is used. In the curves shown, a correction for the Lorentz-Lorenz effect has been made. If this correction is omitted the results lie between curves 1 and 2.

A two-parameter best fit to the data was made assuming a step at the threshold, which is the effect of the final-state Coulomb interaction in the $(\gamma, \pi)$ reaction,[4] and a linear rise above threshold. This curve is shown in Fig. 3. This does not imply that the data exclude curvature in the cross section, but because of the limited number of data points a fit with more unknown parameters is not justified.

The cross section as a function of energy is shown in Fig. 3(b). The indicated errors include the uncertainty in the energy scale as well as statistical and systematic errors. It can be seen that the best fit extracted from the excitation function has a threshold value of $2.9 \pm 1.1$ $\mu$b, consistent with all of the theoretical calculations. The Nagl-Überall result is characterized by a larger slope than the Koch result, reflecting the added terms in the Hamiltonian and the emission of $p$-wave pions. But it can be seen that the best-fit cross section obtained in this experiment rises somewhat more rapidly than any of their theoretical curves. It would be of interest to extend these measurements to higher energies. It is also important to re-examine the accuracy of the wave functions and transition densities obtained from electron scattering, the nuclear final-state interaction, and the significance of hitherto-neglected terms in the $(\gamma, \pi)$ production amplitude.

We would like to thank the staff of the Massachusetts Institute of Technology Bates linac for their support during the difficult initial running period of the accelerator. We would also like to thank Dr. J. Koch and Dr. H. Überall for numerous discussions and for communicating their results before publication.

*Work supported in part by the U. S. Energy Research and Development Administration under Contract No. E(11-1)-3069.

†Work supported in part by the National Science Foundation.

[1]M. Ericson and M. Rho, Phys. Rep. 5C, 59 (1972), and references quoted there.

[2]L. M. Saunders, Nucl. Phys. B7, 293 (1968).

[3]F. J. Kelly, L. J. McDonald, and H. Überall, Nucl. Phys. A139, 329 (1969); K. S. Rao, V. Devanathan, and G. N. S. Prasad, Nucl. Phys. A159, 97 (1970), and references quoted there.

[4]C. Tzara, Nucl. Phys. B18, 246 (1970).

[5]J. E. Koch and T. W. Donnelly, Nucl. Phys. B64, 478 (1973), and Phys. Rev. C 10, 2618 (1974).

[6]H. W. Baer *et al.*, Phys. Rev. C 12, 921 (1975); H. W. Baer, K. M. Crowe, and P. Truöl, in "Advances in Nuclear Physics" (Plenum, New York, to be published), Vol. 9.

[7]J. Deutsch *et al.*, Phys. Rev. Lett. 33, 316 (1974).

[8]G. F. Chew, M. L. Goldberger, F. E. Low, and Y. Nambu, Phys. Rev. 106, 1345 (1957); F. A. Berends, A. Donnachie, and D. L. Weaver, Nucl. Phys. B4, 1 (1967).

[9]J. S. O'Connell, T. W. Donnelly, and J. D. Walecka, Phys. Rev. C 6, 719 (1972).

[10]J. C. Bergstrom, I. P. Auer, and R. S. Hicks, Nucl. Phys. A251, 401 (1975).

[11]J. B. Cammarata and T. W. Donnelly, to be published.

[12]C. Tzara, in Proceedings of the International Topical Conference on Meson-Nuclear Physics, Pittsburgh, Pennsylvania, May 1976 (to be published).

[13]J. H. Koch, in Proceedings of the International Topical Conference on Meson-Nuclear Physics, Pittsburgh, Pennsylvania, May 1976 (to be published).

[14]F. Ajzenberg-Selove, Nucl. Phys. A248, 1 (1975).

[15]J. Matthews and R. O. Owens, Nucl. Instrum. Methods 91, 37 (1971).

[16]W. K. H. Panofsky and D. Reagan, Phys. Rev. 87, 543 (1952).

[17]V. D. Epaneshnikov, V. M. Kinzetsov, and O. I. Stukov, Yad. Fiz. 19, 483 (1974) [Sov. J. Nucl. Phys. 19, 242 (1974)].

[18]J. H. Koch, private communication.

[19]L. Tauscher and W. Schneider, Z. Phys. 271, 409 (1974).

[20]A. Yamaguchi, T. Terasawa, K. Nakahara, and Y. Torizika, Phys. Rev. C 3, 1750 (1971), and references contained therein.

[21]A. Nagl and H. Überall, private communication, and to be published; A. Nagl, F. Cannata, and H. Überall, Phys. Rev. C 12, 1586 (1975).