Multinucleon Removal in a Quasifree Process with a p-γ Coincidence Experiment at 400 MeV

J. Yonnet, M. Louvel, and C. Lebrun
Laboratoire de Physique Corpusculaire associé à l'Institut National de Physique Nucléaire et de Physique des Particules, Université de Caen, 14032 Caen, France

and

G. Roche, G. Landaud, A. Devaux, J. Castor, A. Baldit, and J. P. Alard
Laboratoire de Physique Nucléaire, Université de Clermont-Ferrand II, 63170 Aubière, France
(Received 13 July 1977)

A p-γ coincidence experiment has been performed with 400-MeV protons. The angular and momentum analysis of the scattered proton demonstrates a primary quasifree process. The residual nuclei which have been identified from the γ-ray spectra characterize the final states and indicate an evaporation process or a sequential ejection at low energy of some correlated nucleons. In addition, preliminary results with triple coincidences ($2p$-γ) indicate a promising way to clarify the mechanism of quasifree reactions.

Prompt γ rays arising from the interaction of protons or pions with nuclei[1-14] have been observed in many recent experiments. Much interest has been raised by the profuse production of γ rays corresponding to a removal of one or more "α particles" from the target. In such experiments , the residual nuclei are clearly identified, but this technique cannot distinguish between the detailed reaction processes. The α removal can be explained by an interaction with clusters or $(2p+2n)$ quartets, but, also with separate neutrons and protons. In addition to these poorly understood processes, there are several disagreements between existing experiments with respect to the absolute cross sections and it is possible that the α-cluster removal has been overemphasized. In order to select the initial interaction and, furthermore, to identify the final state of the reaction, we have performed a coincidence experiment at 400 MeV with the proton synchrotron Saturne at Saclay. The wavelength of the incident protons is well suited to generating simple knockout reactions in nuclei. The distortion effects on the incident and outgoing particles weaken our understanding of the interaction but this experiment promises a new and detailed approach to the study of nuclear processes by analysis of both the proton and γ ray. We present here the results of measurements of single γ ray produced in an aluminum target as well as the results for proton-γ-ray coincidences. Some preliminary results of triple coincidences ($2p$-γ) point to a fruitful future for the investigation of $(p,2p)$ quasifree reactions.

A 400-MeV proton beam of 3×10^8 protons per burst was focused on targets of ^{24}Mg, ^{27}Al, ^{28}Si, and ^{60}Ni. The γ rays were detected in a shielded Ge(Li) diode close to the target and set at 120° relative to the beam direction. The main experimental problem was the distortion of the γ-ray spectra due to the rate of large pulses in the Ge(Li) detector. Typically, the energy resolution of the γ rays was 4 keV (full width at half-maximum) at 1 MeV and the ratio of single counting rates on the diode with and without the target was at least equal to 10. The protons scattered between 28° and 42° were detected and analyzed in a large bending magnet equipped with proportional wire chambers. With a 140-mg/cm^2 aluminum target, four coincidences per burst between the γ rays and the scattered protons were detected with 20% random-coincidence rate. Without the target, the accidental coincidences due to the room background contribution was lower than 0.1%. In addition to this p-γ experiment, quasifree reactions $(p,2p\gamma)$ were selected with triple coincidences ($2p$-γ). The recoil protons were detected in a large proportional wire chamber array on the opposite side of the beam to the magnetic spectrometer. The $2p$-γ events represented 20% of the p-γ data. For each proton-γ-ray coincidence, the γ energy, the momentum of the scattered proton, and one (or both) proton angle(s) were stored on magnetic tape for off-line analysis.

The residual states which are reached in the p-γ coincidences are indicated in Fig. 1 by the γ spectra. Each γ-ray line is identified and assigned to a particular final nucleus on the basis of its energy. For each type of events (single γ, p-γ, or $2p$-γ) and for each residual nucleus, the cross sections are estimated from the γ spectra.

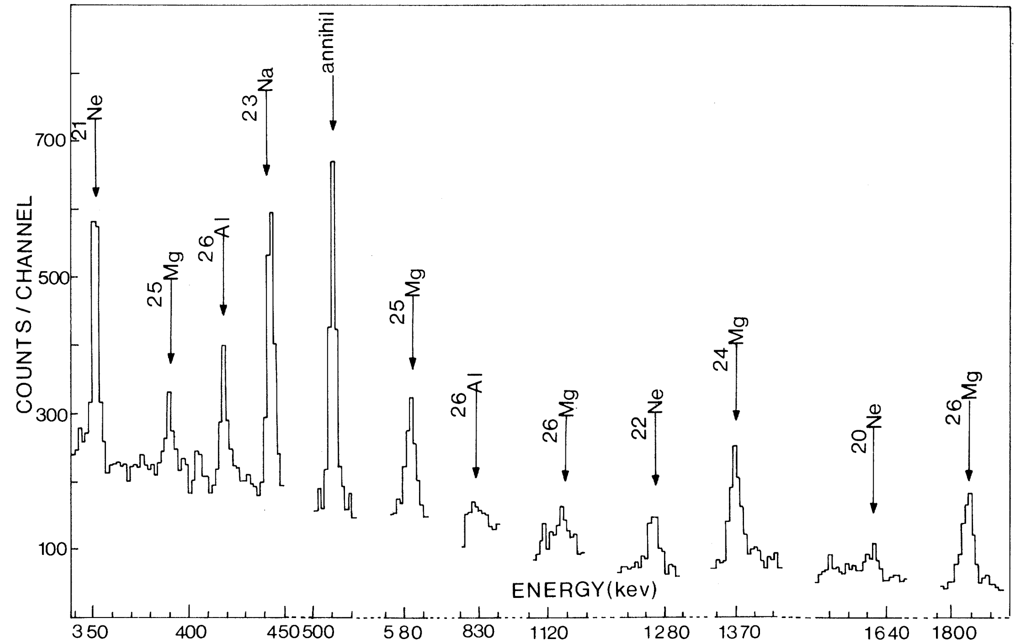

FIG. 1. 400-MeV proton interaction with ^{27}Al. γ-ray spectra issued from the p-γ coincidences.

The γ lines are weighted by the Ge(Li) efficiency. The first results are listed in Table I. In order to facilitate the comparison between the residual nuclei, the cross sections are normalized to the ^{26}Mg line at 1809 keV. For this γ transition, the absolute cross sections σ_γ as well as $\sigma_{p-\gamma}$ are computed assuming isotropy for the γ-ray angular distribution. The absolute cross sections $\sigma_{2p-\gamma}$ are not yet evaluated and will take into account the angular and momentum dependence between the outgoing protons. In order to specify the primary mechanism, the momentum of the scattered proton is compared to that of a free-proton–nucleon collision at the same angle. The distributions of the momentum difference $\Delta P = P_{\text{free}} - P_{\text{expt}}$ are shown in Fig. 2, and suggest that the mechanism is mainly an initial emission of a single nucleon as in quasifree $(p, 2p)$ or (p, pn) reactions. In particular, the 1809-keV γ line from the first excited state of ^{26}Mg indicates a simple quasifree $(p, 2p)$ reaction with a spectator residual nucleon. The width of the mo-

TABLE I. Cross sections for 400-MeV proton interaction with ^{27}Al, for the ^{26}Mg residual nucleus.

Residual nucleus	E_γ (keV)	Nucleon removal	σ_γ	$\sigma_{p-\gamma}$	$\sigma_{2p-\gamma}$
^{26}Mg	1809	$1p$	1^a	1^b	1
^{27}Al	1014	0	0.52 ± 0.03	0	0
^{26}Al	417	$1n$	0.47 ± 0.02	0.13 ± 0.02	0
^{25}Mg	585	$1p + 1n$	0.66 ± 0.02	0.20 ± 0.02	0.14 ± 0.03
^{24}Mg	1369	$1p + 2n$	1.66 ± 0.05	0.74 ± 0.06	0.45 ± 0.06
^{23}Na	440	$2p + 2n$	0.90 ± 0.02	0.34 ± 0.02	0.15 ± 0.02
^{22}Ne	1275	$3p + 2n$	0.38 ± 0.03	0.33 ± 0.05	0.21 ± 0.05
^{21}Ne	350	$3p + 3n$	0.56 ± 0.02	0.19 ± 0.02	0.10 ± 0.02
^{20}Ne	1634	$3p + 4n$	0.76 ± 0.04	0.14 ± 0.06	0
^{19}F	197	$4p + 4n$	0.31 ± 0.01	0^c	0^c

[a]Single–γ-ray $\sigma_\gamma = 21 \pm 1$ mb.
[b]Proton–γ-ray coincidences $\sigma_{p-\gamma} = 16.5 \pm 3$ mb.
[c]Not detected on coincidence. The half-life of the level is 129 ns.

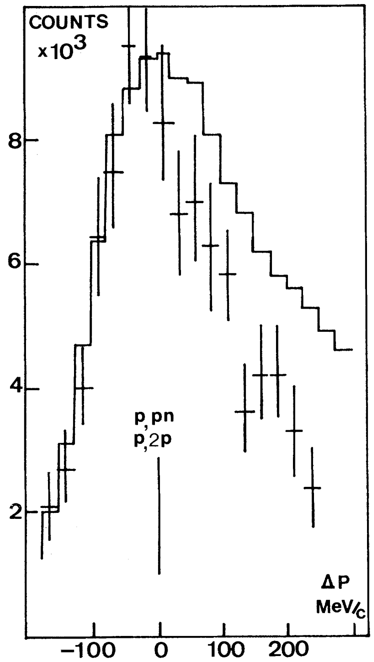

FIG. 2. Distribution of the momentum difference $\Delta P = P_{\text{free}} - P_{\text{expt}}$; P_{expt} = experimental value, and P_{free} = free proton-proton scattering at the same angle. Crosses, experiment. The ^{26}Mg residual nuclei is selected by the 1809-keV γ line. Histogram, momentum distribution without selection in the γ-ray spectrum.

mentum distribution ΔP which corresponds to this γ transition is well explained by knockout protons which would have momenta of about 100 MeV/c before the quasifree reaction. For this ^{26}Mg residual nucleus, the differential cross section $(d\sigma/d\Omega)_{p-\gamma}$ was calculated at the average angle of the magnetic spectrometer. Assuming an isotropic differential cross section $(d\sigma/d\Omega)_{pp}$ in the center of mass, the total cross section $\sigma_{p-\gamma}$ is found to be 16.5 ± 3 mb. This value, compared to $\sigma_\gamma = 21 \pm 1$ mb, tends to demonstrate that knockout interactions are the dominant mechanism when the residual nucleus corresponds to one-nucleon removal.

For all residual nuclei lighter than ^{26}Mg, the momentum distribution (Fig. 2) indicates also that the initial reaction was the ejection of a single nucleon. No evidence for cluster ejection can be detected. Kinematically, a direct cluster ejection or a primary reaction on cluster (for instance, an α cluster leaving ^{23}Na) should be characterized in the momentum distribution by a peak displaced to left by about 150 MeV/c. On the contrary, the contribution on the right tail of the peak is increasing, which could be explained by quasifree reactions $(p,2p)$ or (p,pn), leaving a significant excitation energy in the residual nucleus. After this primary interaction, the multinucleon removal occurs by evaporation or sequential processes. The asymmetric shape of the momentum distribution is well explained by two-step processes with Q values of reactions up to 50 MeV and, therefore, the final process for the lightest residual nuclei is most likely the emission of clusters. Without a measurement of the excitation energy, various combinations of primary processes followed by evaporation can be used to reproduce the data. However, the momentum distribution ΔP suggests, but does not demonstrate uniquely, that the mechanism is a quasifree reaction. In order to enhance this conclusion, primary $(p,2p)$ reactions have been selected and identified by the $2p$-γ coincidences. The ratio between the differential cross sections of the free p-p and p-n reactions is estimated to be 1.7 and the difference between $\sigma_{p-\alpha}$ and $\sigma_{2p-\gamma}$ in Table I can be grossly explained by the number of protons and neutrons among the removed nucleons. This primary emission of a single nucleon is favored in our coincidence experiments by our choice of angle for the scattered protons. For all residual nuclei, the magnitude of such a mechanism, illustrated by $\sigma_{p-\gamma}$ can be compared to σ_γ which represents the total interactions. The variation of $\sigma_{p-\gamma}$ cross sections versus the residual nuclei is weak. On the contrary, the cross sections σ_γ are important along the line of naturally stable nuclei and these data are in good agreement with recent experiments at lower energy. The aluminum target was well suited to detect many exit channels but α removal will be better demonstrated with even nuclei. Our data analysis is in progress with the other targets.

We conclude that the primary interaction of protons with nuclei cannot be explained in a single way but we have shown the important part of initial quasifree reactions. Our p-γ coincidences experiments are the first to demonstrate the magnitude of such primary processes even for quite complex reactions with multinucleon removal. We suggest that a better knowledge of the initial proton-nuclei interactions could be reached with p-γ coincidence experiments at low proton scattering angle.

[1]P. D. Barnes *et al.*, Phys. Rev. Lett. 29, 230 (1972).
[2]H. E. Jackson *et al.*, Phys. Rev. Lett. 31, 1352 (1973).

[3]V. G. Lind *et al.*, Phys. Rev. Lett. 32, 479 (1974).
[4]D. Ashery *et al.*, Phys. Rev. Lett. 32, 943 (1974).
[5]H. Ullrich *et al.*, Phys. Rev. Lett. 33, 433 (1974).
[6]G. L. Chang *et al.*, Phys. Rev. Lett. 33, 1493 (1974).
[7]H. E. Jackson *et al.*, Phys. Rev. Lett. 35, 641 (1975).
[8]O. Artun *et al.*, Phys. Rev. Lett. 35, 773 (1975).
[9]H. E. Jackson *et al.*, Phys. Rev. Lett. 35, 1170 (1975).
[10]R. E. Segel *et al.*, Phys. Rev. C 13, 1566 (1976).
[11]B. J. Leib *et al.*, Phys. Rev. C 14, 1515 (1976).
[12]P. P. Singh *et al.*, Phys. Rev. C 14, 1655 (1976).
[13]M. Sadler *et al.*, Phys. Rev. Lett. 38, 950 (1977).
[14]Y. Cassagnou *et al.*, Phys. Rev. C 16, 741 (1977).

Evidence for a New Symmetry in Nuclei: The Structure of ^{196}Pt and the O(6) Limit

J. A. Cizewski,[a] R. F. Casten, G. J. Smith, M. L. Stelts, and W. R. Kane
Brookhaven National Laboratory, Upton, New York 11973

and

H. G. Börner[b] and W. F. Davidson
Institut Laue-Langevin, 38042 Grenoble, France
(Received 18 November 1977)

^{196}Pt has been investigated with numerous (n,γ) techniques. The structure of the low-spin positive-parity states below the pairing gap shows excellent agreement with the predictions of the O(6) limit of the interacting boson approximation model of Arima and Iachello.

The pure harmonic vibrator and the quadrupole-deformed rotor have long provided two elegant nuclear-structure symmetries or limiting cases. Though few nuclei attain the idealized extremes, these limits are useful in part because their simple energy-level and branching-ratio predictions offer a framework from which deviations, and thereby the forces or interactions that produce them, are more easily identified. A class of nuclei exists toward the end of major shells for which neither limit is applicable. These nuclei are characterized, for example, by low-lying 2_2^+ states and missing or much higher-lying excited 0^+ levels. (The triaxial-rotor model has sometimes been invoked for such cases, but with varying success.) Our purpose here is to summarize a third limiting symmetry, recently proposed,[1] which may characterize such nuclei and, in particular, to propose that ^{196}Pt may be an excellent empirical manifestation of it.

Recently Iachello and Arima have developed an interacting-boson approximation (IBA)[1-3] model in which the Hamiltonian is written in terms of interactions between bosons which can occupy $L=0$ and $L=2$ (s and d) states. This model can be phrased in the group theoretical language of SU(6) in terms of which three natural limits arise for which analytical solutions are obtainable. These limits correspond to three subgroups of SU(6), namely SU(5),[2] SU(3),[3] and O(6).[1,3] The first two correspond to an (anharmonic) vibrator and the quadrupole-deformed rotor (with degenerate "$2_\beta{}^+$" and "$2_\gamma{}^+$" levels), respectively. Many examples of nuclei close to these two limits are well known. The third limit and its application to ^{196}Pt is the subject of this Letter.

In the O(6) limit the energies of collective states are given by[1]

$$E(\sigma,\tau,J)=\tfrac{1}{4}A(N-\sigma)(N+\sigma+4)+B\tau(\tau+3)+CJ(J+1), \qquad (1)$$

where N is the number of bosons, defined as half the sum of the number of protons plus the number of neutrons away from the nearest respective closed shells (for ^{196}Pt, $N=6$); $\sigma=N, N-2, N-4, \ldots, 0$, and $\tau=0,1,\ldots,\sigma$. J takes on the values 2λ, $2\lambda-2$, $2\lambda-3$, $\ldots$, $\lambda+1$, λ, where λ is a nonnegative integer defined by $\lambda=\tau-3\nu_\Delta$ for $\nu_\Delta=0,1,2,\ldots$. An example of a level scheme with $N=6$ is shown in Fig. 1. Each level can be uniquely identified by the quantum numbers $J^\pi(\sigma,\tau,\nu_\Delta)$.

The wave functions of the collective levels may be expanded[1-3] in basis states characterized by their spin, d-boson number n_d, and the numbers of pairs and triplets of bosons coupled to spin zero. In this representation, states with identical J and τ but different σ are composed of identical nonvanishing basis states whose amplitudes are distributed in different (orthogonal) ways. States differing only in τ consist of basis states differing in n_d. Electromagnetic transitions follow the $E2$ selection rules[1] $\Delta\sigma=0$, $\Delta\tau=\pm 1$.